UNIVERSITY OF HAWAII AT MĀNOA
Institute for Astrononmy

Pan-STARRS Project Management System

Pan-STARRS
System Concept Definition

Grant Award No.	**: F29601-02-1-0268**
Prepared For	**: Pan-STARRS Project Management Office**
Prepared By	**: Pan-STARRS Team**
Document No.	**: PSDC-250-002-DR**
Document Date	**: August 11, 2004**
Revision	**: DR**

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Revision History

Revision Number	Release Date	Description

TBD / TBR Listing

Section No.	Page No.	TBD/R No.	Description
1.2.3.4	2	xxx-xxx	missing TBR

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Acronyms

CAN	Controller Area Network
CCD	Charge Coupled Device
CFHT	Canada-France-Hawaii Telescope
DC	Data Collection - Database or other data storage container.
DML	Device Meta-Language
DMT	Dark Matter Telescope
FOM	Figure of Merit
FOV	Field of View
FWHM	Full-Width at Half-Maximum
GPC	Giga-Pixel Camera
GS	Guide Star
GUI	Graphical User Interface
IAU	International Astronomical Union
IOD	Initial Orbit Determination
IPP	Image Processing Pipeline
KBO	Kuiper Belt Object
LAN	Local Area Network
LSN	Local Solar Neighborhood
LSS	Large-Scale Structure
LSST	Large Synoptic Survey Telescope
MBA	Main Belt Asteroid
MDS	Medium-Deep Survey
MOID	Minimum Orbital Intersection Distance - The minimum distance between two orbits.
MOPS	Moving Object Processing System
MPC	Minor Planet Center (of the IAU)
NEO	Near Earth Object - An asteroid or comet with perihelion ¡ 1.3AU.
OBS	Observation Seqencer
ODA	OTIS Data Archive
OOF	OTIS Observe File
OOT	OTIS Observation Tool
OTA	Orthogonal Transfer Array
OTF	Optical Transfer Function
OTIS	Observatory and Telescope System
OWS	OTIS Weather Server
PHO	Potentially Hazardous Object
PSDC	Pan-STARRS Document Control
PSF	Point Spread Function
PSPS	Published Science Products System
PTS	Pan-STARRS Telescope Scheduler
Pan-STARRS	Panoramic Survey Telescope and Rapid Response System
RFI	Radio Frequency Interference
SCD	System Concept Definition
SDSS	Sloan Digital Sky Survey
SGS	Science Goals Statement
SNe	Supernovae
SRS	Software Requirements Specification
SSS	Solar System Survey
TAC	Time Allocation Committee
TBD	To Be Determined
TBR	To Be Reviewed
TCS	Telescope Control System
TLA	Three Letter Acronym

Acronyms (con't)

TLR	Top Level Requirements
TNO	Trans-Neptunian Object
TTI	Transient Time Interval
UDS	Ultra-Deep Survey
UDS	Ultra-Deep Survey
UET	Unit Exposure Time
WFS	Wavefront Sensor
WFSS	Wavefront Sensor Star
WL	Weak Lensing

Glossary

Subaru	National Astronomical Observatory of Japan's 8.3m telescope
cadence	
Phase 1	IPP image processing preparation stage
Phase 2	IPP image reduction stage
Phase 3	IPP exposure analysis stage
Phase 4	IPP image combination stage
Detection	Identification of a source (real or not) in an image
Observation	In MOPS, a detection that corresponds to a real Solar System object
Designation	The identifying label assigned to newly identified Solar System objects
Orbit Identification	The identification of two separately determined orbits as representing the same object.
Attribution	The identification of a detection with a known orbit.
Linkage	The identification of sets of detections that allow an orbit determination for a Solar System object
Autonomous	operates at night without human intervention for a minimum of three nights out of seven. Daytime summit calibration and maintainance carried out four consecutive days a week (Monday-Thursday).
Robotic	operates at night without human intervention for a minimum of three nights out of seven. Only four days summit maintainence per week necessary, human intervention in calibration not required.
Remote	operates without human intervention at the summit at night.
Transient Time Interval	Time interval between two successive images of the same footprint in order to distinguish between stationary and non-stationary transient detections.
Trans-Neptunian Object	An asteroid or comet that spends most of its time outside Neptune's orbit. Include classical
Sweet Spots	
Potentially Hazardous Object	An asteroid or comet with MOID¡0.05AU with Earth's orbit
Observing Efficiency	ratio of shutter open time to total time in a night excluding weather loss

Notes

[23]Includes FITS Overhead Factor: 1.01

[24]Includes XML Overhead Factor of 2

[25]Includes XML Overhead Factor of 2

[26]Includes XML Overhead Factor of 2

[27]Includes XML Overhead Factor of 2

[28] Includes FITS Overhead Factor of 1.01

1 Scope

1.1 Identification

This document is the System Concept Definition (SCD) for the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS), and is a System-level controlled specification/design description document in the official Pan-STARRS engineering specification tree.

1.2 System Overview

The Institute for Astronomy at the University of Hawaii is developing a large optical synoptic survey telescope system, the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS). The science goals, priorities, top-level concept of operations with associated operational requirements, and system performance drivers with associated system performance requirements are described in the Pan-STARRS Science Goals Statement (SGS). As described in this document, The system conceptual design for Pan-STARRS utilizes an array of four 1.8m telescopes each with a 7 degree^2 field of view, giving the system an étendue larger than all existing survey instruments combined (defined as the product of the collecting area A multiplied by the field-of-view solid angle Ω). Each telescope will be equipped with a 1 billion pixel CCD camera with low noise and rapid read-out, and the data will be reduced in near real time to produce both cumulative static sky and difference images from which transient, moving, and variable objects can be detected. Pan-STARRS will be able to survey up to $\approx 6,000$ degree^2 per night to a detection limit of approximately 24^{th} magnitude. This unique combination of sensitivity and sky coverage will open up many new possibilities in time domain astronomy including a major goal of surveying the Potentially Hazardous Object (PHO) population down to a diameter of ≈ 300 meters. In addition, the Pan-STARRS data will be used to investigate a broad range of astronomical problems of extreme current interest concerning the Solar System, the Galaxy, and the Cosmos at large.

Project sponsor:	AFRL, United States Air Force
Acquirer:	University of Hawaii Institute for Astronomy
User:	Astronomical community
Developer:	University of Hawaii Institute for Astronomy, participating institutions, and associated subcontractors

1.3 Document Overview

The Pan-STARRS System Concept Definition contains a complete conceptual design of the Pan-STARRS system intended to meet the top-level performance and operational requirements contained in the SGS. The requirements flow begun in the SGS is further developed in this SCD to provide additional derived system and subsystem requirements. The SCD also contains a detailed concept of operations, including data products and data flows, required to accomplish the science goals given in the SGS. From the conceptual design of the system architecture described here, major interfaces are identified and characterized.

2 Referenced Documents

This section shall include a list of government and non-government the documents referenced in this document.

2.1 Government Documents

Reference	**Title**

2.2 Non-Government Documents

Reference	**Title**
PSDC-110-001-00	Pan-STARRS Project Management Plan
PSDC-200-001-00	Pan-STARRS - Overview and Status
PSDC-200-002-00	Efficiency Notes
PSDC-200-003-00	What is the Best Filter for Detecting Asteroids?
PSDC-200-004-00	Image Processing Pipeline Draft Requirements
PSDC-200-005-00	IPP Data Flows and Straw Man Design
PSDC-200-006-00	Minimal Functional Data System Requirements and Specifications
PSDC-200-007-00	Asteroid Collision Hazard Reduction Requirements
PSDC-200-008-00	Image Data Simulator and Prototype Pipeline Status
PSDC-200-009-00	Image Quality Forecast
PSDC-200-010-00	The Likelihood of Point Sources in Pixelated Images
PSDC-200-011-00	Addition of Images with Varying Seeing
PSDC-200-012-00	Pan-STARRS - A Wide-Field Optical Survey Telescope Array
PSDC-200-013-00	Performance of NEO Surveys for Reducing Asteroid Collision Risk
PSDC-200-014-00	Death Plunge Objects
PSDC-200-015-00	Pan-STARRS Science Overview
PSDC-200-016-00	Design Reference Mission
PSDC-230-001-00	Pan-STARRS Telescope #1 Reference Mission
PSDC-700-002-00	OTA Documentation

3 System Conceptual Design

3.1 System Overview

The Pan-STARRS System is an astronomical survey system designed to satisfy a broad range of survey programs in order to advance the current state of knowledge in several areas of fundamental astrophysics and cosmology. Those needs are discussed in the Pan-STARRS SGS. It then becomes critical to clearly establish the requirements for the system envisioned to meet these wide-ranging science goals in order to ensure that the requirements of specific programs are blended into a consistent system configuration and operational model. Since even top-level system requirements may be determined by a particular conceptual design, it is reasonable to combine into one document, the "System Concept Definition", a system conceptual design, a concept of operations, and the top-level system design requirements.

The system concept involves state-of-the art detector and detector control technology, high throughput data processing software, large but flexible and fast-access data archives, and a sophisticated observatory and telescope control system sufficent to enable fully robotic observatory operation. Functional capability includes the "hooks" to allow specialized science data processing software to directly interact with appropriate subsystems. Additional user-friendliness is provided through a web-based interface designed to serve a large cross section of the astronomical community with varying needs.

3.2 Design-Independent Top-Level Requirements

This section lists the science requirements and implied (flowed) system requirements established in the Pan-STARRS SGS. In order to maintain numbering consistency within the present document, the requirement numbering here is given internally to this document; however, the associated SGS number is indicated in parentheses.

3.2.1 Science Requirements

In the Pan-STARRS Science Goals Statement (SGS, PSDC-250-001-00), the following science requirements for the Pan-STARRS system are established:

3.2.1.1 For identified solar system objects, a minimum set of object parameters to be calculated for each object shall be the orbital elements and absolute magnitude. (TBR) (SGS-4.2.1)

3.2.1.2 Detections and at least the minimum set of object parameters shall be collected for $> 90\%$ of the PHOs within $\pm 10°$ of the ecliptic plane that reach $\mathrm{R} = 24^{\mathrm{th}}$ magnitude (corresponding to $\mathrm{m}_w \sim$ TBD in the Solar System filter) over the proposed 10 year operational lifetime of the Pan-STARRS system. (TBR) (SGS-4.2.2)

3.2.1.3 The creation of static sky maps shall be such that the cosmological total mass power spectrum P(k) at $z \sim 0.3$ shall be determined to an uncertainty $\sim$ 10% to wavenumbers k corresponding to wavelengths from 100-500 Mpc. (SGS-4.2.3)

3.2.1.4 Galaxy shape parameters Γ_1 and Γ_2 shall be determined to a (TBD) rms value at R ~ 26. (SGS-4.2.4)

3.2.1.5 Photometric redshifts accurate to 10% in a redshift range of $0.5 < z < 1.5$ shall be achievable with (TBD) observations to (TBD) magnitude. (SGS-4.2.5)

3.2.1.6 Detections and photometric redshifts shall be obtained for enough Type Ia SNe to average down the statistical uncertainty in the redshift-distance relation to an uncertainty of $\sim$ 1% in 10 redshift intervals from $0.1 \leq z \leq 1.0$ over a 1 year (TBR) operational period of the Pan-STARRS system. (SGS-4.2.6)

3.2.2 System Operational and Performance Requirements

Supplementing the set of design-independent system operational and performance requirements derived from the Pan-STARRS science requirements presented in the SGS, additional requirements are imposed on the system design. This requirements set is then as follows:

3.2.2.1 The Pan-STARRS system shall be capable of scheduling observations to meet the timing requirements of the science program. (SGS-4.2.1, SGS-4.2.2, SGS-4.2.6).

3.2.2.2 The Pan-STARRS system shall be capable of surveying 2π steradian of the celestial sky in 7 days. (SGS-4.3.1)

3.2.2.3 Image processing shall be completed for transient detections within five minutes. (SGS-4.3.2)

3.2.2.4 The system S/N shall yield a 5σ point source detection at R = 24 in a 30 second integration time under median seeing conditions. (SGS-4.4.1)

3.2.2.5 The system shall achieve an absolute photometric precision of 0.01 magnitude rms in the photometric zero points across the sky. (SGS-4.4.2)

3.2.2.6 Systematic errors in the absolute astrometry shall not exceed 100 milliarcseconds. (TBR) (SGS-4.4.3)

3.2.2.7 The system shall achieve a relative astrometry precision of 30 milliarcseconds. (TBR) (SGS-4.4.4)

3.2.2.8 The system shall use g, r, i, z, y filters. (SGS-4.4.5)

3.2.2.9 The system shall possess a broadband filter approximately equal to a $g + r + i$ filter. (TBR) (SGS-4.4.6)

3.2.2.10 The system shall construct static sky images from the science images. (SGS-4.2.3)

3.2.2.11 The system shall provide data and engineering metadata sufficient to determine the full likelihood of the sky surface brightness $f_\lambda(\alpha, \delta)$ from the data product. (SGS-4.4.7)

3.2.2.12 The system shall provide data and engineering metadata sufficient to determine the effective point spread function (PSF) at each point in the sky. (SGS-4.4.8)

3.2.2.13 The system shall have a false alarm rate (FAR) for transient detections of $<$ 1%. (TBR) (SGS-4.4.9)

3.2.2.14 The telescope system must be fully operational up to zenith angles of 70°. (TBR) (SGS-4.4.10)

3.2.2.15 The system shall be capable of operating robotically. (allocated)

3.2.2.16 The system shall classify detected objects extracted from processed images. (allocated)

3.2.2.17 The system shall possess the capability to identify solar system objects from their attributed detections. (SGS-4.2.1, SGS-4.2.2)

3.2.2.18 The science data products created by the collection and reduction of Pan-STARRS data shall be made available for analysis through an accessible data archive system via the Internet. (allocated)

3.2.2.19 The variance of the PSF across one image shall be less than $0.05\mathrm{arcsec}^2$. (SGS-4.2.4)

3.2.2.20 The system shall provide images with 9 magnitudes of dynamic range from the noise floor to saturation. (allocated)

3.3 System Top-Level Description

At the most basic level, a modern telescope system is based on the integration of a photon guiding device, a photon to electron to raw data converter, a raw data to science data converter, data storage, and an appropriate control system. It is possible to consider further science data processing to support a particular science program as part of a given system or as being system-independent.

For Pan-STARRS, the above considerations results in a system concept possessing these major subsystems:
1. Telescope (TEL, photon guiding device; also presupposes an appropriate enclosure or observatory)
2. Camera (CAM, photon to electron to raw data converter)
3. Observatory, Telescope, and Instrument Software (OTIS, the control system)
4. Image Processing Pipeline (IPP, raw data to science data converter)
5. Data storage (PSPS, or Published Science Products System, composed of dedicated and special purpose databases and data collections)
6. Moving Object Processing Software, MOPS (a type of science data product processor called a "preferred science client").

These subsystems are shown in Figure 1 as forming the foundation of the Pan-STARRS conceptual design that is developed in this document as the preliminary phase of designing a system that meets the design-independent system performance and operational requirements listed above in Section 3.2.2. The inclusion of the MOPS preferred science client is due to it being specifically identified for development with Pan-STARRS grant funds. Additional science clients will be necessary to reach the goals of the various science programs anticipated with Pan-STARRS operations, but they are treated as independent of the Pan-STARRS development effort managed by the PS PMO.

A fundamental aspect of the Pan-STARRS conceptual design is the choice to construct a distributed aperture (multi-telescope) system. This choice is dictated by a strategy of maximizing achievable aperture per fixed cost in the Pan-STARRS budget range and minimizing technical risk for telescope construction. A multi-telescope system naturally possesses many operational, performance, and integration requirements distinct from those of a single telescope system with significant design implications for the Pan-STARRS CAM, OTIS, and IPP subsystems.

Integration of the various subsystems occurs at the major subsystem external interfaces: TEL-CAM, TEL-OTIS, CAM-OTIS, OTIS-IPP, CAM-IPP, IPP-MOPS, IPP-PSPS, and MOPS-PSPS. A summary of interface characteristics for each of these is given in Section 11 with further detail presented in the associated Interface Requirements Specifications and the Interface Control Documents (or Drawings). Interfaces within each major subsystem are considered as subsystem internal interfaces in this document, and are described in the subsystem description sections.

Of particular interest is the TEL-CAM interface, in part because of the close coupling of the optical design of the telescope to the design of the geometric configuration and optoelectronic properties of the camera focal plane. The Pan-STARRS telescopes are conceived to be telescopes dedicated to a single instrument configuration that will not change throughout the observational phase of the project allowing the conceptual design choice adopted for Pan-STARRS to directly mount the camera to the back end of the telescope. Design factors include:
1. Matching the telescope tracking specifications to the guiding bandwidths, range of allowable image motion, and pixel resolution of the cameras,
2. Matching the telescope optical elements to the coverage gaps of the camera arrays,
3. Choosing the telescope focal length and aperture based on the pixel size, charge diffusion in the detectors, and tip-tilt correction capability of the camera arrays.

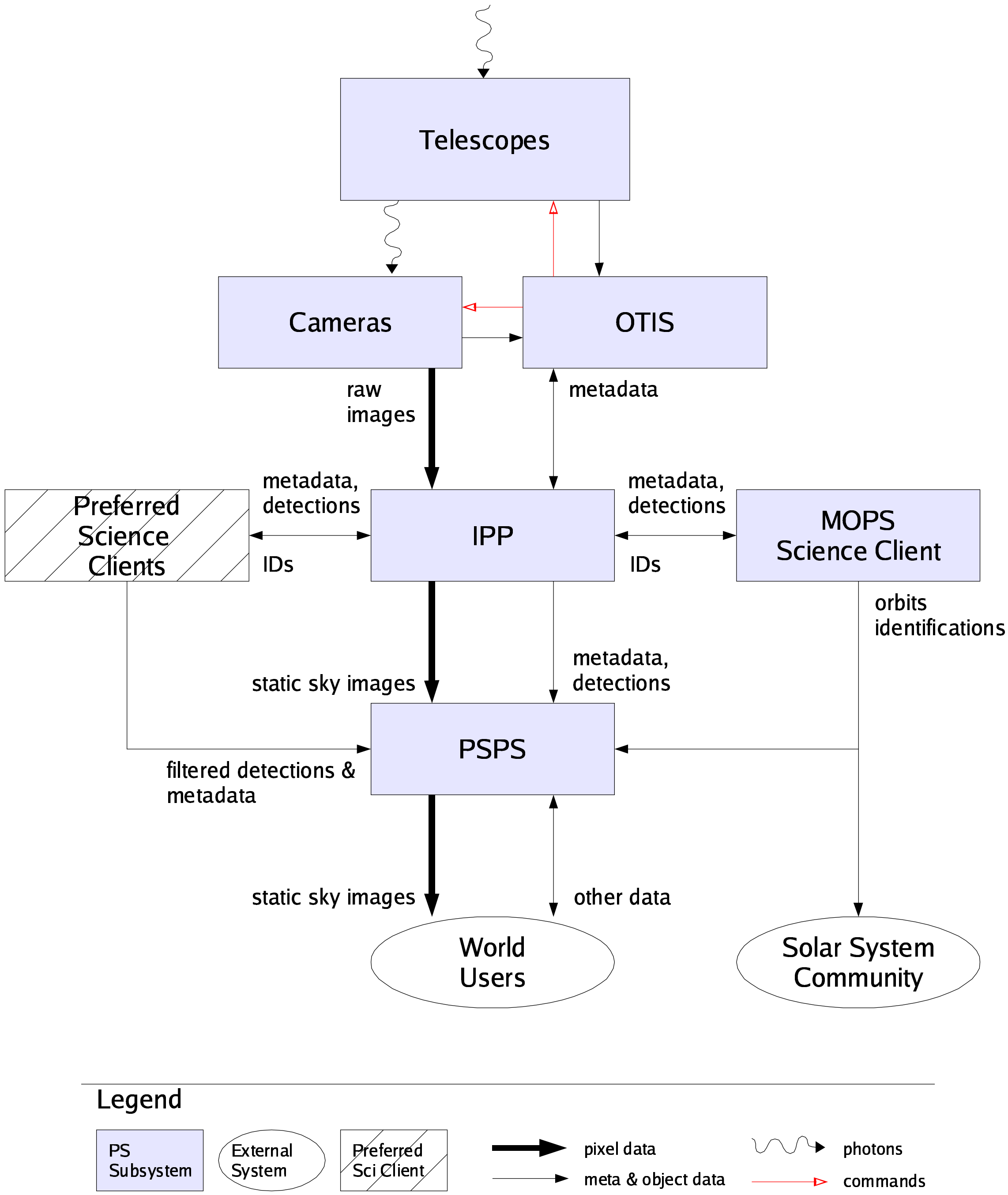

Figure 1: Pan-STARRS Overview

Table 1: Étendue comparison for existing telescopes, Pan-STARRS, and the proposed LSST

Telescope System	$\epsilon = A\Omega$ (m^2 deg^2)
USAF LINEAR	1.5
SDSS	6.0
CFHT Megacam	8.0
Subaru SuprimeCam	8.8
Pan-STARRS	~ 50
(potential) DMT, e.g., the LSST	~ 200

3.4 Design Drivers and Figures of Merit

The purpose of this section is to describe quantitative performance metrics, or "figures of merit" (FOM), used to characterize and compare astronomical survey systems. These FOMs are then used to establish a preferred niche for a new system in terms of both performance capability and scientific potential. Additional details can be found in PSDC-200-002-00.

The most basic quantitative measure of survey system capability is given by the system *étendue*, defined as the product of telescope (or telescope array) collecting area, A, and telescope (or one telescope of an array) field of view (FOV), Ω:

$$\epsilon = A\Omega \tag{1}$$

where the larger the value of $A\Omega$, the better the potential system performance. Table 1 presents the étendue for a number of existing telescopes used for surveying purposes as well as that for a future dark matter telescope (DMT) such as the Large Synoptic Survey Telescope (LSST). Note that existing telescopes such as CFHT and Subaru, while used to achieve some survey goals, also support several different types of programs, and are not exclusively dedicated survey systems.

However, the impressive increase in étendue afforded by an instrument such as the LSST will be unavailable for at least eight more years. As described in the SGS, there are several areas/problems of current astronomical interest that could benefit greatly from a survey system filling an étendue niche intermediate between the currently available systems and that of a future DMT, i.e., there is a specific need to field a survey system with $\epsilon \approx 40 - 50$ within the next 5 – 6 years.

It is possible to extend the preceding discussion concerning the étendue figure of merit (FOM). The next step is to consider the optical point spread function (PSF) that characterizes how electromagnetic energy from a point source is spatially distributed on the focal plane.

To a first approximation, the PSF is determined by the atmosphere, and is the Fourier transform of the free atmosphere long exposure optical transfer function (OTF), $e^{-3.44(z/r_0)^{5/3}}$, where the Fried length r_0 is the scale at which atmospheric phase fluctuations are of order 1 radian. This has a quasi-Gaussian core with a steeply falling power law in the wings that scales as $r^{-11/3}$, and is characterized by a full width at half maximum (FWHM) of FWHM $\sim 0.98\lambda/r_0$. More precisely, the total system PSF is convolution of PSF contributions from atmosphere, optical train, and detector. The smaller the width of the system PSF, the greater the precision with which an object can be detected and the faster it can be located at a given level of significance. Here, the units of the PSF are inverse arcseconds squared with the normalization condition $2\pi \int \theta d\theta \, PSF(\theta) = 1$. Also note that the corresponding optical transfer function (OTF) is simply the Fourier transform of the PSF.

Many of the Pan-STARRS science goals involve the detection of faint point (or nearly point-like) sources against the noise arising from foreground air-glow emission, photon statistics and read noise. For these tasks it is straightforward to define a quantitative FOM that takes into account the sharpness of the image by noting that an optimal way to detect a faint point source in the presence of noise is to convolve the image with its PSF and locate peaks. It then follows that one can write

$$\Delta = \frac{\epsilon}{\delta\omega} \tag{2}$$

where the area of the PSF is defined as

$$\delta\omega = 2\pi \int \theta d\theta \; PSF^2(\theta) \tag{3}$$

The physical significance of this FOM is that it is proportional to the rate at which faint point-like objects can be detected in an exposure. In more practical terms, for a given value of Δ required to accomplish a specific science survey mission, increasing Δ by a factor of two enables the same science to be accomplished in half the time. As constructed here, Δ is an FOM directly related to system photometric performance.

The number of objects detected by a telescope depends on both the number of objects present in the sky at some limiting flux, f_{obj}, that determines the number of available source photons, N_{obj}, as well as the number of noise photons contributed by the background sky, N_{sky}. It is straightforward to show that for a given exposure time, t_{exp}, the photon signal-to-noise ratio is

$$\frac{S}{N} = \frac{N_{obj}}{\delta N_{sky}} \propto \sqrt{\frac{t_{exp}A}{\delta\omega}} f_{obj} \tag{4}$$

In the remainder of this document, an S/N of 5 required for a "5σ object detection" is used to calculate a required limiting magnitude (with the limiting flux, $m_{\rm lim} = -2.5 \log f_{lim}$). Note that the normal dark sky brightness contributes a number of photons per square arcsecond corresponding to a (roughly) 20th magnitude source, so this formula applies only to fainter sources. Further details concerning faint point and extended source detection can be found in PSDC-200-002-00.

The FOM Δ does not account for other factors which may affect the total detection rate of point sources, in particular contributions to the signal-to-noise and the observing efficiency. First, the S/N depends on the filter bandpass as

$$N_{\gamma,\rm obj} = \int d\lambda \; n(\lambda)_{\gamma,\rm obj} \; R_b(\lambda) \tag{5}$$

$$N_{\gamma,\rm sky} = \int d\lambda \; n(\lambda)_{\gamma,\rm sky} \; R_b(\lambda) \tag{6}$$

$$\left(\frac{S}{N}\right)^2_{\rm ideal} = \frac{N^2_{\gamma,\rm obj}}{N_{\gamma,\rm sky}} \tag{7}$$

where $n(\lambda)_{\gamma,\rm obj}$ is the photon flux density in the source, $n(\lambda)_{\gamma,\rm sky}$ is the photon flux density in the sky, and $R_b(\lambda)$ is a filter transmission function. In a real detector, read noise also contributes to the noise term. To account for this, the S/N is modified by the read noise degradation factor,

$$f_{\rm RD} = \left(1 + \frac{\sigma^2_{\rm RD}}{N_{\gamma,\rm sky}}\right)^{-1} \tag{8}$$

where $\sigma^2_{\rm RD}$ is the variance of the detector read noise.

Additional factors which degrade the FOM include the duty cycle,

$$f_{\rm DC} = \left(1 + \frac{t_{\rm open}}{t_{\rm closed}}\right)^{-1} \tag{9}$$

written here as a function of the exposure time or time the shutter is open, $t_{\rm open}$, and the time between exposures or the time the shutter is closed,

$$t_{\rm closed} = t_{\rm read} + t_{\rm slew} + t_{\rm settle} + t_{\rm setup} \tag{10}$$

where $t_{\rm read}$ is the camera readout time, $t_{\rm slew}$ is the telescope slewing time, $t_{\rm settle}$ is the time for the telescope to settle after a slow, and $t_{\rm setup}$ is the time to setup the intrument after a slew. Combining these terms, we find a total FOM of:

$$\Sigma = \Delta \left(\frac{S}{N}\right)^2_{\rm ideal} f_{\rm RD}\, f_{\rm DC} \tag{11}$$

The FOM Σ derived above applies both to individual images and to stacked and/or difference images, with the proviso that the squared PSF be replaced by the mean squared PSF, weighted by the inverse of the noise variance $\sigma^2_{\rm RD} + N_{\gamma,\rm obj} + N_{\gamma,\rm sky}$.

Another factor which degrades the FOM is the observing environment throughput,

$$f_{\rm env} = f_{\rm clear} \left(\frac{t_{\rm dark}}{24h}\right) \tag{12}$$

where $f_{\rm clear}$ represents the fraction of clear nights on which observations may be performed and $t_{\rm dark}$ is the fraction of time during which the sky is sufficiently dark to observe. The final efficiency factor considered here is the detector filling factor,

$$f_{\rm fill} = f_{\rm geom} f_{\rm non-op} \tag{13}$$

the effective photon collecting surface area on the focal plane that factors into the loss of area due to geometrical and layout losses and the losses due to non-operational pixels.

An FOM may be calculated specifically for astrometric observations, in which the goal is precisely determined positions, rather than simply point-source detections. In this case, the ideal FOM is modified to become:

$$\Delta' = \frac{\epsilon}{\delta\omega'} \tag{14}$$

where

$$\delta\omega' = 2\pi \int \theta d\theta \, \frac{\partial^2}{\partial\theta^2} PSF^2(\theta) \tag{15}$$

3.4.1 System Image Size Budget

Initial estimates of the system/subsystem image size budget are based on the faint object detection limit requirement and the adopted design parameters leading to required exposure times ~ 30 seconds. For an assumed median seeing of $0.6''$ FWHM, typical motions of of PHOs and NEOs near the detection limit yield trailing losses equivalent to a degradation of $\approx$ 18% to the natural seeing (see PSDC-200-012-00). This sets the system maximum image degradation requirement to be $\leq$ 20% over a median natural seeing of $0.6''$ FWHM. The subsystem image size requirements are allocations based on minimizing risk.

Table 2 shows the maximum allowable contributions towards the image point spread function (PSF) from the Telescope, Camera, and Image Processing Pipeline subsystems, and the assumed contribution from the atmosphere. These contributions are expressed in three different units and at two different zenith angles, $z = 0^\circ$ and $z = 70^\circ$. The first two columns show the contributions to the image point spread function in terms of an $< r^2 >^{\frac{1}{2}}$, the RMS radius of the contributions in microns with the assumption that the telescope has an 8.0 m focal length, and therefore a plate scale of 38.8μm arcsec^{-1}. These units are useful for quantifying effects on the camera. The second pair of columns give these same contributions in terms of the FWHM in arcseconds. These units are commonly used in the astronomical community. The last two columns show the contributions in terms of the Fried parameter, R_0, for the seeing and the numerical equivalent to the FWHM in units of length, R_{eq}, for the others. Expressing the contributions in this way has advantages for the description of the optical errors allowable in the manufacturing of the mirrors and lenses. Normally, the conversion between a Gaussian

Table 2: System Image Size Budget

Subsystem	$< r^2 >^{\frac{1}{2}}$ (**μm**)		**FWHM (arcsec)**		R_0 **or** R_{eq} **(cm)**	
	$z = 0^\circ$	$z = 70^\circ$	$z = 0^\circ$	$z = 70^\circ$	$z = 0^\circ$	$z = 70^\circ$
Site Seeing	16.50	26.60	0.60	0.97	16.80	10.42
Telescope	8.49	11.76	0.31	0.43	32.64	23.57
Camera	8.94	8.94	0.33	0.33	31.00	31.00
IPP	3.46	3.46	0.13	0.13	80.10	80.10
Total	20.89	30.62	0.76	1.12	13.27	9.05

scale length, σ, and the FWHM that describes the same distribution is given by $\mathrm{FWHM} = 2.354\sigma$. However, the sky follows (to a good approximation) Kolmogorov and not Gaussian statistics. Numerical simulations show that the best-fit Gaussian to a Kolmogorov distribution yields $\mathrm{FWHM} = 2.0\sigma$. This is the conversion used to convert numbers between columns in Table 2. If λ is a reference wavelength then the quantities in the table are related by the following equations:

$$\mathrm{FWHM} = 2.02 \times 10^5 \frac{\lambda}{R_0} = \frac{10.1}{R_0} \tag{16}$$

$$\mathrm{FWHM} = 2.0\frac{\sigma}{38.8} = 0.0607\sigma \tag{17}$$

$$< r^2 >^{\frac{1}{2}} = \sqrt{2}\sigma = \frac{\sqrt{2}}{0.0515}\mathrm{FHWM} = 27.44 \times \mathrm{FWHM} \tag{18}$$

where it is assumed above that R_0 and λ are in the same units, that FWHM is in arcseconds, and that σ is in μm. The second equation relating σ to FWHM also assumes the plate scale of an 8.0 m focal length. The reference wavelength used in Table 2 is $\lambda = 5 \times 10^{-5}$cm. It is assumed in Table 2 that the seeing scales with zenith angle according to the equation $(R_0)_z = (R_0)_{z=0} \times \cos^{\frac{3}{5}} z$, whereas the variation in telescope image size as a function of zenith angle is an estimate due to flexure.

Seeing distributions from two potential locations for the telescopes have been measured where it was observed that the median seeing of $0.65''$ FWHM at a wavelength of 0.5 μm can be expected (see PSDC-200-009-00). A slightly more conservative design specification of a median FWHM seeing of $0.6''$ has been adopted for the Pan-STARRS design. The measured seeing distributions also show that seeing conditions will be better than $1''$ approximately 80% of the time.

3.5 Summary of Derived System Requirements

3.5.1 The system étendue shall be $\gtrsim 40\,\mathrm{m}^2\,\mathrm{deg}^2$.

3.5.2 As measured by the width of the PSF, the System degradation of the image size shall be $<$ 27% relative to median natural seeing of $0.6''$ FWHM, independent of the filter utilized.

3.5.3 The system value of Δ shall be greater than $2.5 \times 10^8\,\mathrm{m}^2$. (TBR)

3.5.4 The system value of Σ shall be greater than $2.0 \times 10^8\,\mathrm{m}^2$. (TBR)

3.5.5 The system value of Δ' shall be greater than (TBD).

3.5.6 The over-sampling of the telescope PSF shall be ≥ 2.

3.5.7 The focal surface field distortions shall be less than 3%.

3.5.8 The focal surface field distortions shall be represented (i.e., possible to fit) by a smooth analytical function with residuals less than 30 mas.

3.5.9 The flatness of the camera focal plane array shall be such that it would not touch at any point either of two coplanar planes separated by 40 μm.

3.5.10 The system shall have the capability to determine the schedulable fraction of a specified science program.

3.5.11 The system shall be capable of allowing interface to preferred science clients at an entry point from the IPP.

3.5.12 The system shall remove the image foregrounds leaving a residual variance of less than 1% of the background level.

3.6 Requirements Trace Matrix

Derived System Requirements		**Top-level System Requirements**	
Number	**Caption**	**Number**	**Caption**
3.5.1	System ´etendue	3.2.2.2	Capability to survey 2π in 7 days
3.5.2	System image size budget	3.2.2.4	S/N for 5σ detection
		3.2.2.6	Absolute astrometry
		3.2.2.7	Relative astrometry
3.5.3	Δ FOM	3.2.2.4	S/N for 5σ detection
3.5.4	Σ FOM	3.2.2.4	S/N for 5σ detection
3.5.5	Δ'	3.2.2.6	Absolute astrometry
		3.2.2.7	Relative astrometry
3.5.6	Over-sampling of the PSF	3.2.2.5	Absolute photometry
		3.2.2.6	Absolute astrometry
		3.2.2.7	Relative astrometry
3.5.7	Allowed focal surface field distortions	3.2.2.10	Construct static sky images
		3.2.2.19	Variance limit of PSF across an image
3.5.9	Flatness of the focal plane array	3.2.2.7	Relative astrometry
3.5.10	Modeling the focal surface field distortions	3.2.2.7	Relative astrometry
		3.2.2.19	Variance limit of PSF across an image
3.5.11	Scheduling capability	3.2.2.1	Scheduling to meet timing requirements
3.5.8	Capability to allow access by preferred science clients	allocated	
3.5.12	Residual variance on image foregrounds removal	3.2.2.10	Construct static sky images
		3.2.2.13	FAR rate limit

4 System Concept of Operations

4.1 Introduction

4.1.1 Overview

The operational function of the Pan-STARRS system is to execute the Pan-STARRS observing program approved by the Pan-STARRS Time Allocation Committee (TAC), and to provide accessibility of the resulting science data products to a specified set of users. This section presents the Pan-STARRS Concept of Operations (ConOps), i.e., the operational model by which the system is operated to meet user requirements. Satisfying significantly different user requirements is accomplished by implementing operational scenarios that utilize combinations of available operational states and modes. Included as part of the ConOps are the identification and description of generalized system operational functions and processes (tasks), their interactions, and information flows (both control and data). Thus, the ConOps flow from beginning to end can be represented as

$$\mathrm{users} \rightarrow \mathrm{user\ needs} \rightarrow \mathrm{operational\ modes} \rightarrow \mathrm{operational\ scenarios} \rightarrow \mathrm{data\ products} \tag{19}$$

The detail given here is at the system level, whereas operational concepts specific to subsystem operations are given in the appropriate subsystem section of this document.

4.1.2 Top-Level Description of Observatory System Operations

The ConOps developed here focuses on the operational characteristics of the “Observatory System” plus the IPP, where the observatory systems refers to those subsystems located at the observatory site (the “summit”). Operational considerations for preferred science sclients (including MOPS) and the publishing process (PSPS) are deferred to the subsystem ConOps descriptions. Figure 2 illustrates the operational interactions between the subsystems involved in observatory operations at the summit and the IPP. Additional details of these command and data flows are given in Section 4.5.

In addition to the tasks and functions executed by the system in the normal course of operations, a set of operational processes and procedures must be implemented to handle emergency situations. In order to meet the requirements of this portion of the operations plan, the system will possess an emergency notification subsystem.

4.2 User Classes

Users and user needs define the ways in which a system is designed to be used and is subsequently used. For a system capable of autonomous/robotic operation, user needs are directly realized by the set of operating programs. In turn, executing the programming instructions associated with a specific survey mode leads to different operational scenarios within the Pan-STARRS ConOps. The operational scenarios associated with each survey program are part of the larger set of scenarios that include calibration and other non-science states and modes.

In general, Pan-STARRS users will conduct research with Pan-STARRS data in one of three broad science areas:

1. Moving object science, e.g. the PHO census or the LSN census,
2. Transient science, e.g., the SNe search or the GRB search,
3. Static sky science, e.g., the WL or LSS programs.

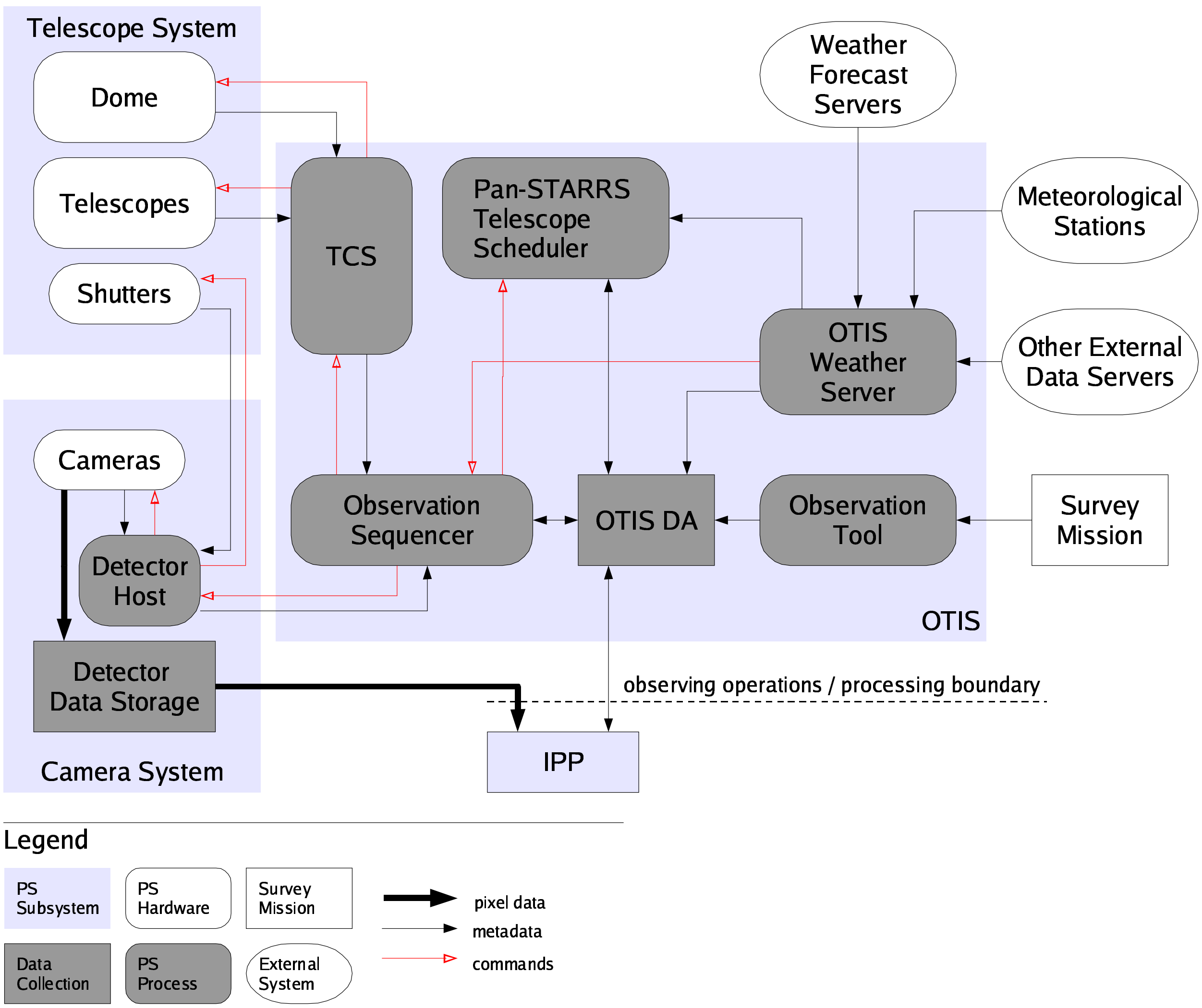

Figure 2: Summit Operations

However, because of the comprehensive set of data products already planned to be archived and accessible with the PSPS, it is more useful from an operational point to classify Pan-STARRS users as follows:

1. Preferred Science Clients - users who require data products produced by the IPP or another Pan-STARRS subsystem at an accesss point prior to publishing to the PSPS,
2. End-users - an individual or group that access the pre-defined set of science data products available through the Internet interface to the PSPS, but who do not require access to any other Pan-STARRS subsystem.

Note that, in addition to the MOPS, the Preferred Science Clients are expected to include a Transient Client that will process and filter stationary transients and publish alerts to the astronomical community.

4.3 Operational States and Modes

As always, the distinction between States and Modes is arbitrary. For the Pan-STARRS ConOps at both the system and subsystem, a State is defined as a particular hardware configuration that allows only certain operations, whereas a Mode is defined as a specific set of operational capabilities or sequences within any one State. Following standard engineering convention, “Off” is not usually considered a state, but may be explicitly included in the list of states when certain operations activities occur only when the System is Off.

4.3.1 Observatory Operational States

The Observatory System operational states are as follows:

1. **Off -** no power but certain subsystem servicing activities may occur.
2. **Initializing -** system power is available to all subsystems, but not all subsystems are ready to operate; this state is further subdivided into
   a. Normal power initialization sequence,
   b. Power initialization following an abnormal shutdown such as a loss of power.
3. **Standby -** system and subsystems are powered but not operating, and subsystem housekeeping functions may be active; this state is further subdivided into
   a. Safe,
   b. Hibernating.
4. **Servicing -** the Observatory System is available for subsystem servicing activities that may allow power to other subsystems in conformance with any necessary Lockout/Tagout procedures.
5. **Ready -** includes subsystem test and calibration capability, but no system capability to execute imaging operations.
6. **Functional -** includes calibration and science imaging operation capability.
7. **Fault -** the system has detected a fault requiring corrrective action.
8. **Shutdown**.

4.3.2 Observatory Operational Modes

When the observatory system is in the Functional operational states described in the Section 4.3.1, it may be operated in one of the following modes:

4.3.2.1 **Summit Interactive.** Night time operations with human operators providing interactive control in an observatory.

4.3.2.2 **Remote Interactive.** Night time operations with humans in the loop remotely, but no human operators issuing commands in an observatory to system control computers.

4.3.2.3 **Autonomous.** No human intervention necessary for 3 consecutive days out of 7 days. Summit daytime support (4 consecutive days per week) includes supporting dome calibration observations as well as standard maintenance.

4.3.2.4 **Robotic.** No human intervention necessary. Summit daytime support of maintenance only and such support required no more than 4 consecutive days per week.

4.3.3 Science Survey Modes

For Pan-STARRS, it has been determined that user science needs can be classified in a way that leads to the creation of the five distinct survey modes discussed in detail in, e.g., PSDC-200-016-00.

4.3.3.1 **Solar System Survey Mode (SSS) -** The PHO, MBA, KBO, and other Solar System science programs as discussed in the SGS possess a common need for maximum detection sensitivity and only a broad passband filter. The primary driver is PHO detection because they have the largest rates of motion. A unique property of this mode is the requirement to observe at small solar elongations (the "sweet spots") with observation times confined to early and late hours of the night. The opposition/ecliptic component of PHO observations can cover most other Solar System science objectives.

4.3.3.2 **The 3π Mode (3π) -** The WL, LSN census, proper motion, and extra-galactic object detection and classification programs discussed in the SGS all require photometrically shallow data over the entire sky visible to Pan-STARRS (3π steradians) in five passbands: g, r, i, z, y. The primary cadence driver in this mode will be the LSN census and proper motion programs.

4.3.3.3 **Medium-Deep Survey Mode (MDS) -** The SNe, LSS, and the extra-galactic object detection and classification programs discussed in the SGS require this mode in five passbands: g, r, i, z, y with the primary driver for the cadence being the SNe program.

4.3.3.4 **Ultra-Deep Survey Mode (UDS) -** The extra-galactic object detection and classification and SNe programs require this mode in five passbands: g, r, i, z, y.

4.3.3.5 **Auxiliary/Object Variability Mode (AUX) -** a user-defined mode designed to support science programs such as the search for extra-solar planets or stellar variability.

4.3.3.1 Survey Depth Requirements

The limiting depths for the 3π Survey, Medium Deep Survey, and Ultra-Deep Survey are shown in Table 3. The required depth for the Solar System Survey Mode is not the integrated static sky depth, but arises from the Science Requirement (3.2.1.2 and SGS-4.2.2) to reach $R = 24$ in thirty seconds to avoid trailing losses.

Table 3: Survey Depth Requirements

Filter	Central wavelength (nm)	Limiting magnitude (5σ) 3π Survey	Medium-Deep Survey	Ultra-Deep Survey
g	475	25.7	27.0	29.0
r	625	25.5	26.8	28.8
i	772	24.3	26.0	28.0
z	890	23.5	24.7	26.7
y	1020	20.5	21.8	23.9

4.3.3.2 Time Domain Requirements

The time domain requirement 3.2.2.1 and the scheduability requirement (3.5.9) place constraints on the timing of observations in each Science Survey Mode. These timing constraints include: (i) $t_{Cadence} \pm \Delta t_{Cadence}$, the time between similar observations and the allowable window of opportunity; (ii) $t_{Duration} \pm \Delta t_{Duration} = n_{cadences} \times t_{cadence}$, the time for which a set of observations of a given cadence is carried out; (iii)t_{Min} and t_{Max} defined such that at least one chronological pair of observations in a duration have a minimum and maximum separation $t_{Min} < t_{n+1} - t_n < t_{Max}$; and (iv) the depth per vistitation, the requirement that in a given night the total exposure time meets the science goals of that survey. Values for these quantities are listed in Table 4 for the above Science Survey Modes.

Table 4: Time Domain Requirements

Survey	Filters	Timescales integer nights $t_{Cadence}$	t_{Min}	t_{Max}	$t_{Duration}$	Depth per Visitation limiting magnitude
Solar System Survey	w	4	8	16	29.5^a	$R = 24$
3π Survey	$grizy$	180	120	270	270	
Medium Deep Survey	$grizy$	4	3	6	180	$r = 23.3, i = 24.1, z = 24.2$
Ultra-Deep Survey	$grizy$	4	3	6	180	$r = 23.3, i = 24.1, z = 24.2$

[a] The value here is for rotating Helio-Ecliptic Coordinates, not RA and Dec.

4.3.3.3 Determination of Science Program Priorities

Further details concerning the science related to these modes can be found in the "Design Reference Mission" (PSDC-200-016). However, it should be recognized that the time spent by the system in any given operational mode is dependent on scheduling feasibility and the science priorities for a given observing period as defined by the Pan-STARRS TAC.

4.4 Operational Scenarios

Maximizing the system throughput and efficiency requires a precise surveying and scheduling strategy. In principle, scheduling is a straightforward optimization problem mathematically expressed as a system of equations containing system parameters and constraints as knowns and scheduled times as unknowns. In one possible realization of this system of equations, allocated time priorities can form part of the set of known parameters. Other parameters can be the system efficiency, cadences, durations, and visitations. An example of a constraint is the total time available to be scheduled. Optimization is achieved by calculating stationary solutions (i.e., solutions for which the global variations are set to zero).

The basic ConOps operational scenario then contains these steps:

1. The Pan-STARRS TAC establishes priorities and allocations for a set of science survey programs to be combined into a master observing program for a specified time interval.

2. A scheduling tool is utilized to determine the feasibility of the proposed master program. Expressed in terms of a schedulable fraction of the master program, the TAC is responsible for determining adjustments when the schedulable fraction falls below some threshold.

3. A scheduling tool prepares an initial night-by-night implementation of the schedulable fraction of the master program, possibly allowing for adverse weather on a statistical basis.

4. The scheduled program is translated into a set of commands and data files to be used as inputs to the executable software controlling the Observatory System.

5. The control software executes the commands yielding the sequence of events that result in image acquisition (including telescope pointing and focus, camera and shutter control, etc.), image processing, and data product input to a preferred science client or the PSPS.

Of course, changing priorities and unanticipated external conditions may force recalculating the master program schedule at any time during the program period. Different operational scenarios then become defined by the amount of rescheduling required, the time spent in a given operational mode, the relative time spent acquiring calibration and science images, and the time spent in a given survey mode.

4.5 Operational Command and Data Flows

The foundation to an operational scenario is represented by the data flow, the functional process flow, a functional timeline, and a processing timeline associated with observatory systems operations.

4.5.1 System Data Flow

Figure 3 shows the flow of photons, pixel data, metadata, object data, and commands from collection of photons by the telescope to the release of data by the PSPS to the Published Data Retriever User Class.

4.5.2 System Functional Process Flow

Figure 4 shows the functional flow of processes. Note the Task Manager of the Summit System is the Observation Sequencer or (OBS) which controls all commandable hardware and software at the summit. The functional flow of the IPP and MOPS are also shown.

4.5.3 Image Acquisition Timelines

Figure 5 shows the timing of the four basic exposure sequences envisioned for Pan-STARRS. In each panel, the dashed line shows the time at which the next exposure sequence may be started. The top part of each panel shows actions taken by the telescope; the bottom shows actions taken by the camera. The time-line is in seconds. Panel A shows the timing for a sequence of exposures of the same field, with only minimal offsets between exposures. Panel B shows the timing

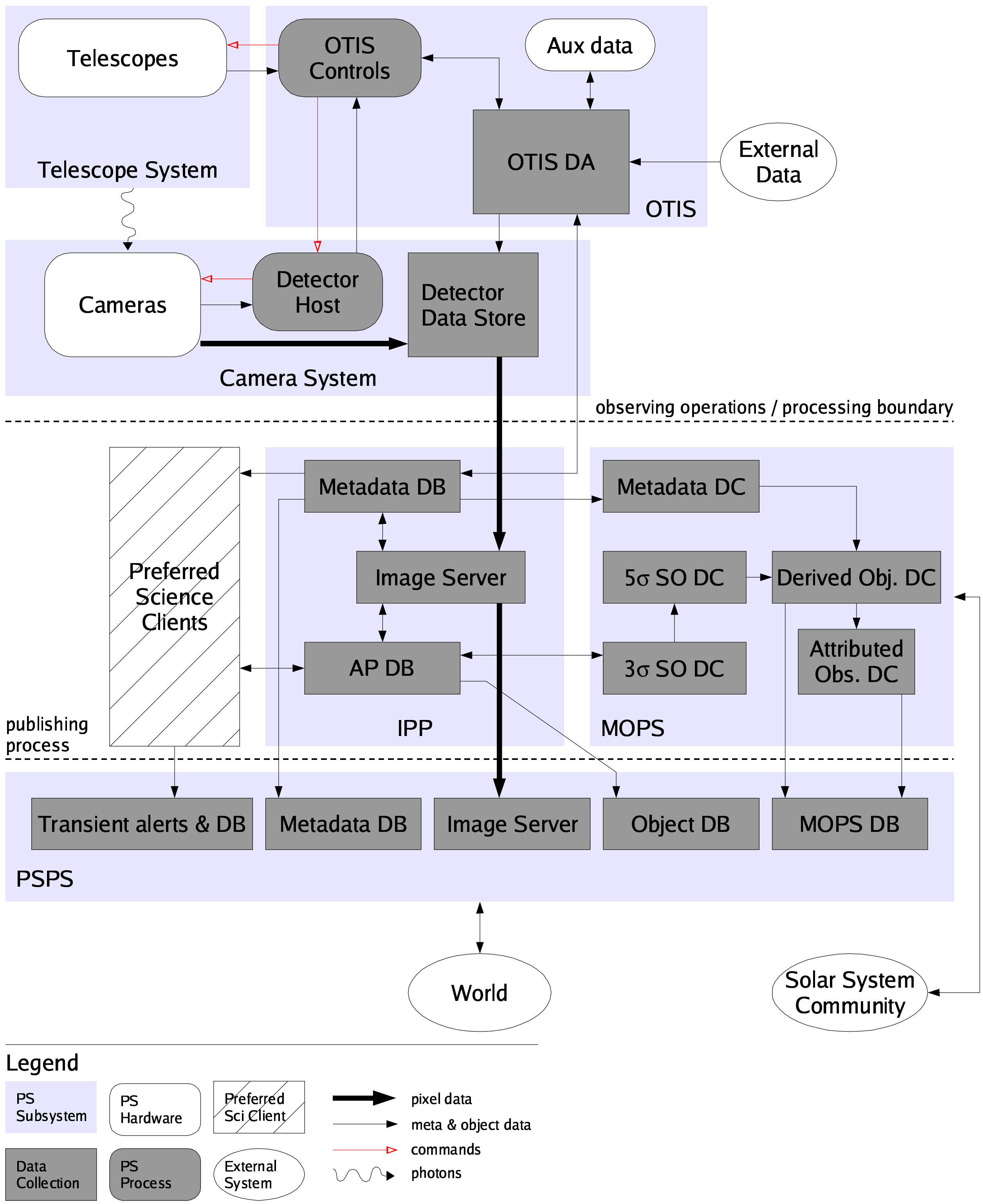

Figure 3: Pan-STARRS Dataflow

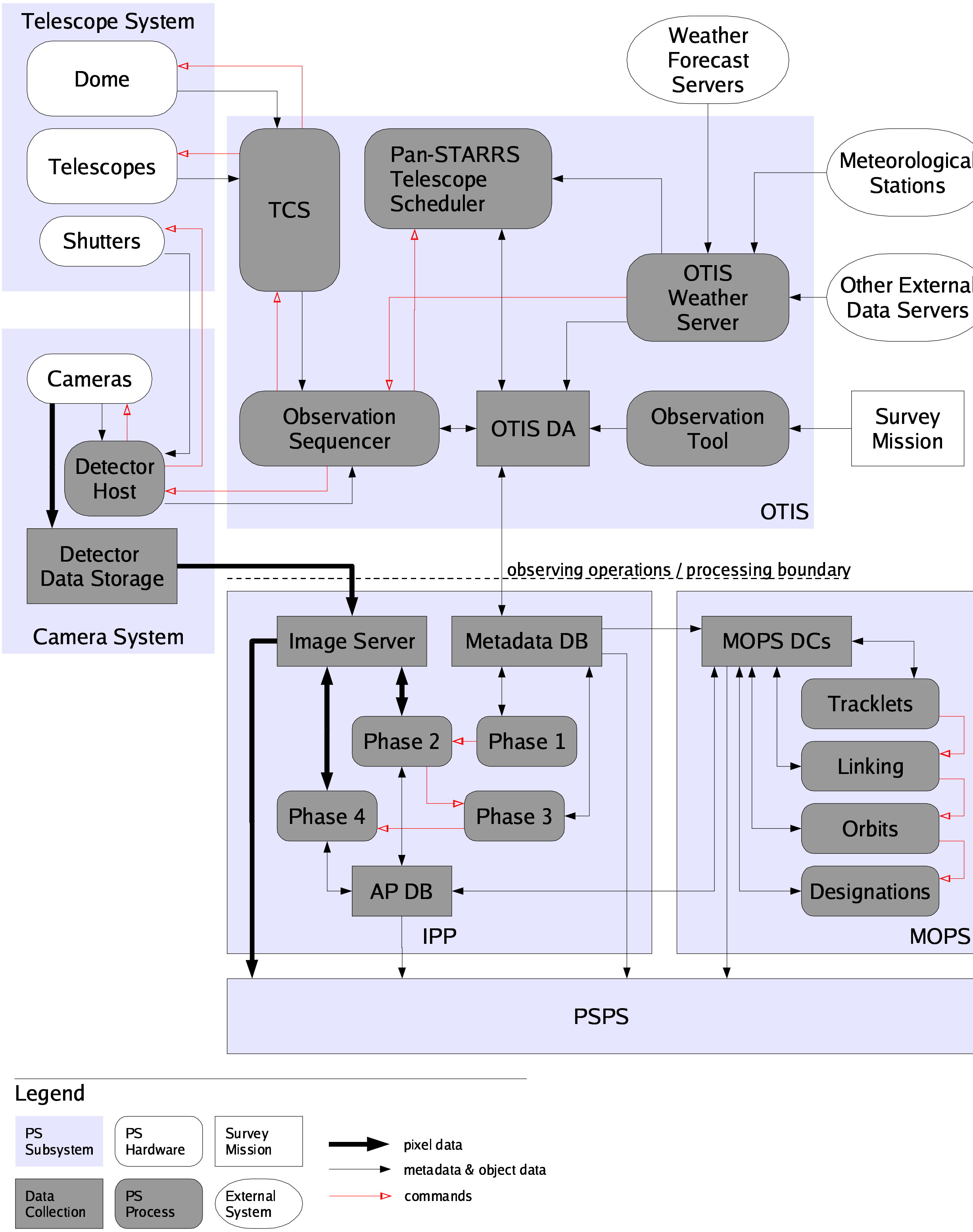

Figure 4: Pan-STARRS Functional Process Flow

Table 5: OTIS & Camera Subsystems (Pan-STARRS Internal Data Products)

Product Name	*Description*	*Reference*	*Entry Point*
Science Pixels	Raw science images (pixel data)		Camera
Calibration Pix	Raw calibration images (pixel data)		Camera
Image Logs	Log of the images		OTIS sequencer
Image Q/A	Assessment of the data in the images		Det Host
TCS Log	TCS Telemetry stream log		OTIS TCS
Camera Log	Detector temperature, pressure, TM		Det Host
Weather	General weather information		OTIS weather server
Seeing Monitor	Seeing measurements & related data		OTIS inst.
Guide Data	Guiding history and guide star metadata		Camera
WFS Data	Wave-front sensor & related data		Camera
Skyprobe B,V	Atmospheric transmission in B,V bands		OTIS inst.
Skyprobe A,E	Spectral line absorption and emission		OTIS inst.
NIR	Near IR wide field images of clouds		OTIS inst.
Schedule	Observing plan		OTIS scheduler
Obs Log	Observing history and comments		OTIS sequencer

for a sequence of exposures separated by short ($\sim 3^\circ$) slews, typical of programs which attempt to cover a large area of sky. Panel C shows the timing for a sequence of exposures in different filters, requiring a 30 second filter change. Panel D shows the timing for a sequence of exposures in different filters separated by a maximum-length slew. This last represents the worst-case scenario for fast exposure sequences.

4.5.4 Image Processing Timeline

Figure 6 shows the processing stages (identified in Section 8.1) for a typical Pan-STARRS image. Note that the three major stages (copy, phases 1 & 2, phases 2 & 4) are performed in series for a given exposure, but are performed in parallel to one another for a sequence of exposures. While a set of images is being copied, another set is being processed for Phase 2 and another for Phase 4. The timing, in seconds, illustrates the minimum time from initiation of an exposure to the resulting transient object detections from Phase 4.

4.5.5 Pan-STARRS Data Products Summary

Table 5 shows OTIS and CAM subsystems data products (Pan-STARRS Internal Data Products).

Table 6 shows the IPP subsystem data products (Pan-STARRS Internal Data Products).

Table 7 shows the MOPS subsystem data products (Pan-STARRS Internal Data Products).

Table 8 shows the PSPS subsystem data products (Pan-STARRS External Data Products).

As described in the higher-level scenarios above, there are several distinct stages in the system ConOps that lead to an end result of a science or engineering data product placed into an appropriate data collection or fed to a preferred science client:

1. Establishing the system is ready to collect and process images,
2. a. Obtaining a calibration image
   b. Obtaining a science image

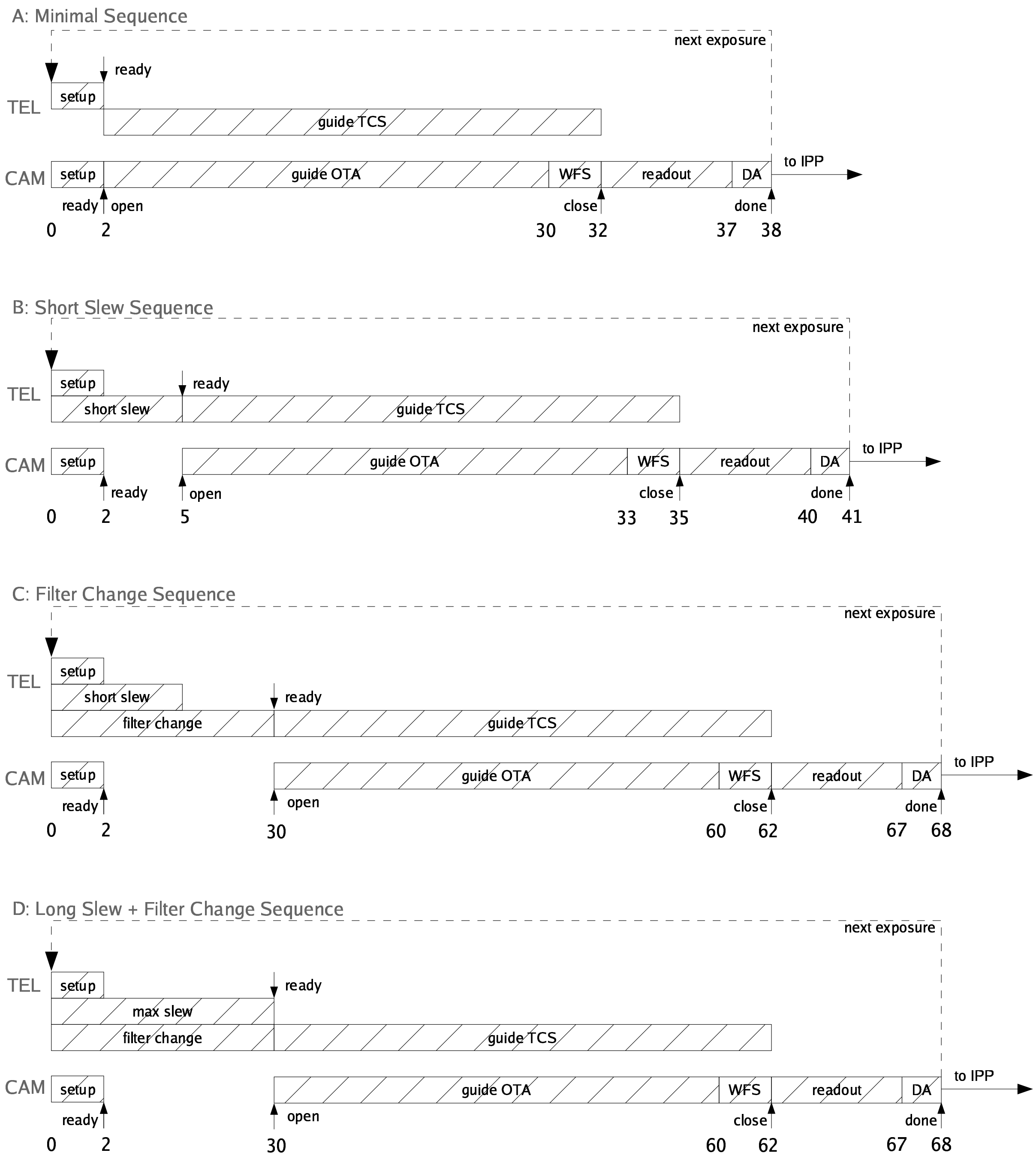

Figure 5: Pan-STARRS Exposure Timing Diagrams

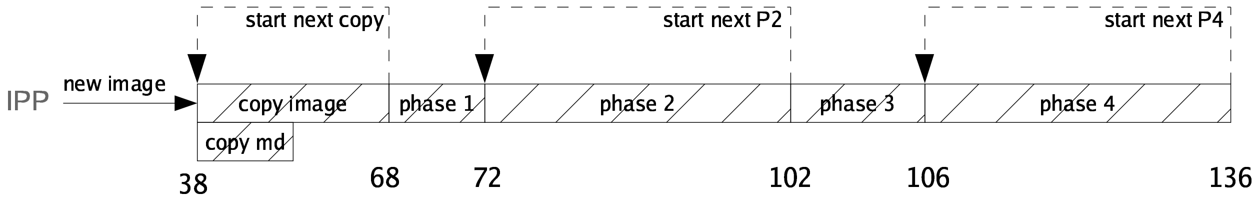

Figure 6: Pan-STARRS Processing Timing Diagram.

Table 6: IPP Subsystem (Pan-STARRS Internal Data Products)

IPP Image Server

Product Name	*Description*	*Reference*	*Entry Point*
Product Name	Description	Reference	Entry Point
Raw Images	Raw images	8.4	Camera
Cal. Images	Calibration images	8.6.2.8	IPP Calibration
P2 output images	IPP phase 2 output images	8.6.2.4	IPP Phase 2
P2 postage stamps	Postage stamps from phase 2 images	8.6.2.4	IPP Phase 2
P4Δ images	Phase 4 difference Images	8.6.2.6	IPP Phase 4
P4Σ images	Phase 4 sum Images generated from the phase 2 output	8.6.2.6	IPP Phase 4
Static sky images	Master sky summed images (current best)	8.6.2.6	IPP Phase 4

IPP AP DB

Product Name	*Description*	*Reference*	*Entry Point*
Averages	Average quantities of objects	8.6.1.2	IPP Phase 2
References	Externally provided measurements of objects	8.6.1.2	External
Filters	Description of the specific filter hardware	8.6.1.2	Telescope System
Photsys	Description of abstract photometry filter systems	8.6.1.2	External / APDB
Zpt History	Time history of the zero-point offsets for photometry systems	8.6.1.2	Phase 2
Image Metadata	Descriptive information about images in the AP database	8.6.1.2	Phase 2
Cameras	Description of Cameras known to AP DB	8.6.1.2	Camera System
Telescope	Description of telescopes known to AP DB	8.6.1.2	Telescope System
P2 out det.	Phase 2 output images detection	8.6.2.4	IPP Phase 2
P4Δ det.	Phase 4 sum images detections	8.6.2.6	IPP Phase 4
P4Σ det.	Phase 4 difference detections	8.6.2.6	IPP Phase 4
Static sky det.	Static sky image detections	8.6.2.6	IPP Phase 4

IPP Metadata DB

Product Name	*Description*	*Reference*	*Entry Point*
Raw image metadata	Descriptive information about all raw images	8.6.1.3	Camera
Pending image metadata	Information about images to be processed	8.6.1.3	IPP Phase 2
Processed image metadata	Information about processed images	8.6.1.3	IPP Phase 2
Cal. image metadata	Information about Calibration images	8.6.1.3	IPP Calibration
Static sky metadata	Information about static sky images	8.6.1.3	IPP Phase 4
Weather	Weather info (temp, humidity, pressure, etc)	8.6.1.3	OTIS weather server
Skyprobe/Etc.	Transparency, line-absorption, line-emission	8.6.1.3	OTIS inst.
Obs groups	Related images grouped for processing	8.6.1.3	OTIS scheduler
Software Config Info	Software installation and configuration information	8.6.1.3	IPP Metadata
Science parameters	Configurable parameters for various functions	8.6.1.3	IPP Metadata
System config info	Hardware configuration information	8.6.1.3	IPP Metadata
Log/Errors	Logging and error messages from IPP processing	8.6.1.3	IPP Phase 1-4
Q/A @Images	Image quality assessment information	8.6.1.3	IPP Phase 3

Table 7: MOPS Subsystems (Pan-STARRS Internal Data Products)

Product Name	*Description*	*Reference*	*Entry Point*
3σ SO	List of candidate moving-object detections	9.6.2.2	IPP Phase 4
P4Δ Image Metadata	Metadata related to P4Δ Images	9.6.2.1	IPP Phase 4
5σ SO	Filtered list of candidate moving-object detections	9.6.2.3	IPP Phase 4
Attributed Observations	Set of data collections attributed to an orbit	9.6.3.4	MOPS Attribution
Derived Objects	All measured orbital elements of a solar-system object	9.6.3.5	MOPS Identification

Table 8: Published Science Product Subsystem (External Data Products)

Product Name	*Description*	*Reference*	*Entry Point*
P2 detections	Source catalog for the individual focal plane $> 20\sigma$	10.6.2.1	IPP Phase 2
P4Σ detections	Source catalog for the major frames $> 5\sigma$	10.6.2.1	IPP Phase 4
P4Δ detections	Source catalog for the major difference frames $> 3\sigma$	10.6.2.1	IPP Phase 4
Static Sky detections	Source catalog cumulative static sky images	10.6.2.1	IPP Phase 4
P2 image metadata	Description of the images and processing history	10.6.2.3	IPP Phase 4
P4Σ image metadata	Description of the images and processing history	10.6.2.3	IPP Phase 4
P4Δ image metadata	Description of the images and processing history	10.6.2.3	IPP Phase 4
Static Sky image metadata	Description of the images and processing history	10.6.2.3	IPP Phase 4
P2 postage stamps	Postage stamps from phase 2 images	8.6.2.4	IPP Phase 2
Static Sky Images	Cumulative sky image pixel data	10.6.2.2	IPP Phase 4
Attributed MOPS obs.	Observation of identified objects	10.6.2.5	MOPS Attribution
Measured MOPS objects	Properties deduced from the observation, orbits, abs magnitude.	10.6.2.5	MOPS Identification
Collected Metadata	Metadata from Summit and IPP	8.6.1.3, 7.1, 6.1	MOPS Identification

3. Piping the image data (including metadata) to a “final resting place” as far as the system is concerned.

The high level sequence of events resulting in obtaining a science image are given in Table 9. Finer-grained details at the subsystem level are presented in the appropriate subsystem section of this document. Beginning at the end of Stage 1 above, “System Ready”, the system must perform the tasks and functions listed in Table 9 to obtain a science image for processing into a science data product (which usually will require multiple images).

Table 9: Sequence of Tasks and Functions to Produce a Science Image

1	System Ready
2	the Pan-STARRS Telescope Scheduler (PTS or Sceduler) selects an observing file for system execution
3	the PTS sends the file identifier to the Sequencer
4	the Sequencer retrieves the selected observing file from the OTIS DB and creates the appropriate command sequence queue
5	the Sequencer sends commands/data to (a) the TCS and (b) the Camera Detector Host
5.1	the TCS subsequently
5.1.1	slews the Telescope
5.1.2	moves the enclusre dome
5.1.3	commands a filter change, if required
5.1.4	sets the focus, collimation, and alighnment of the secondary
5.1.5	commands the instrument rotator (and ADC, if one is present)
5.1.6	sends a "Ready" acknowledgment to the Sequencer
5.2	the Camera Detector Host, using the exposure parameters sent by the Sequencer (e.g., stars to be used for Wavefront Sensing and whether the camera mode is stare or OT)
5.2.1	sets the correspondences between guide star, OTA cell, and expected coordinates
5.2.2	sets an acquisition exposure flag
5.2.3	configures the camera
5.2.4	sends a "ready" acknowledgment to the Sequencer
6	the Sequencer, upon receipt of ready status flags from the TCS and the Camera Detector Host, sends an "OK to take exposure" signal to the Camera Detector Host
7	the Camera Detector Host sends an "Open Shutter Command" to the shutter
8	once the shutter is opened for the prescribed time (nominally 30 seconds), the Camera subsystem operates in such a manner as to provide OT guiding (if required), and communicates metadata to the Detector Host and TCS
9	a clock in the Detector Host acts as the exposure timer and when the exposure time is reached, the Detectot Host sends a "Close Shutter" command to the shutter
10	once the shutter is closed, the shutter sends a "Shutter is Closed" acknowledgment to the Detector Host
11	Detector Host initiates data readout (to Detector Data Store) and some "housekeeping image processing" (with results being communicated to the OTIS DB)
11.1	"Data Readout Initiated" signal to the Sequencer
11.2	image is analyzed for image quality
11.3	wavefront sensor (WFS) data is analyzed
11.4	Camera is "cleared"
11.5	"Camera Ready" signal sent to Sequencer
12	Either when "Shutter is Closed" signal is received or when "Camera Ready" sugnal is received by Sequencer (TBD), the Sequencer initiates the next set of TCS commands according to its queue of commands derived from the observation file
13	the IPP queries the OTIS DB and/or the Detector Data Store (TBD) for image availability information
14	when IPP decides a new image needs to be transferred to the IPP "mirror" stores, a copy process is begun that transfers data from the OTIS DB to the IPP Metadata DB and the Detector Data Store to the IPP Image Server
15	Upon completion of the copying process, a notification to the IPP processing sequencer that an image is ready for processing
16	the IPP processes the image according to the sequential scheme outlined in Section 9 (Phases 1 through 4)
17	upon completion of the single image processing ... (whatever is supposed to happen then happens).

4.6 Observatory System Operating Environment

The operational environment of the Pan-STARRS observatory may include:

1. Periods of inaccessibility by humans,
2. High Altitude (> 9,000 ft),
3. Humidity Range $1\% \leq H \leq 100\%$,
4. Temperature Range $-10C < T < +15C$,
5. Wind speed range $0 < v < 160$ MPH,
6. Ice and snow,
7. Possible power interuption,
8. Lightning,
9. Presence of Radio Frequency Interference (RFI).

4.7 Derived Operational Requirements

The operational requirements derived from the system-level ConOps developed in this section include:

4.7.1 The system shall monitor and control the telescope, instruments, and observatory.

4.7.2 All summit operations computers must maintain time synchronization to better than **10 (TBR)** milliseconds.

4.7.3 Observatory subsystems shall be protected from lightning and electrostatic discharge.

4.7.4 The Observatory System shall be constructed to protect all subsystems from worst case weather conditions.

4.7.5 Observatory subsystems shall be protected from performance-degrading levels of RFI. **(TBD)**

4.7.6 The system shall have the capability of staging the initialization and powering up of all summit systems from *OFF* to *READY* state in **30 minutes (TBR)** without human intervention.

4.7.7 The system shall be capable of remotely changing Observing Modes (Summit Interactive, Remote Interactive, Autonomous, Robotic).

4.7.8 The system shall be capable of safely stowing the telescope and enclosure upon onset of inclement weather within 10 minutes after receiving a *STOW* command.

4.7.9 The system shall be capable of notifying designated personnel off-site in the event of a system emergency.

4.7.10 The system shall operate with an observing efficiency of $\geq 65\%$ **(TBR)** averaged over a 1 year period.

4.7.11 The system shall be capable of dynamically rescheduling observations to $\geq 95\%$ **(TBR)** completeness in the w filter for any pair of observations separated by one TTI for any survey mode.

4.7.12 The system shall be capable of dynamically rescheduling observations to $\geq 85\%$ **(TBR)** completeness in the g, r, i, z, y filters for any pair of observations separated by one TTI for any survey mode.

4.7.13 The system shall be capable of dynamically rescheduling observations to $\geq 95\%$ **(TBR)** completeness to meet cadence requirements for any survey mode.

4.7.14 The system shall be capable of dynamically rescheduling observations to $\geq 95\%$ **(TBR)** completeness to meet duration requirements for any survey mode.

4.7.15 The system shall be capable of dynamically rescheduling observations to $\geq 95\%$ **(TBR)** completeness to meet visitation requirements for any survey mode.

4.7.16 The system shall be capable of dynamically rescheduling observations to$\geq 95\%$ **(TBR)** completeness to meet the survey depth (limiting magnitudes) requirements for any survey mode.

4.7.17 The system shall be capable of dynamically rescheduling observations to$\geq 95\%$ **(TBR)** completeness for any survey mode/filter bandpass with maximum lunar illumination constraints.

4.7.18 The system shall be capable of acquiring and processing images at a sustained rate of 1 image every 40 seconds over a 10 hour time period.

4.7.19 The system shall be capable of archiving up to **3 petabytes (TBR)** of raw science data.

4.7.20 The system shall possess a computer security system to protect potentially vulnerable subsystems from malicious external actions.

4.7.21 The system shall allow remote superuser access to subsystem computers.

4.8 Requirements Trace Matrix

Derived Operational Requirements		Top-level System Requirements	
Number	**Caption**	**Number**	**Caption**
4.7.1	Monitor system/subsystem status	3.2.2.15	Robotic capability
4.7.2	Observatory time synchronization	3.2.2.6	Relative astrometry
4.7.3	Lightning/electrostatic discharge protection	allocated	
4.7.4	Worst case weather protection	allocated	
4.7.5	RFI protection	3.2.2.4	5σ detection
4.7.6	Initialization time for Off to Ready	3.2.2.15	Robotic capability
4.7.7	Remote capability to change observatory modes	3.2.2.15	Robotic capability
4.7.8	Safe stowing of telescope and enclosure	allocated	
4.7.9	Emergency notification	3.2.2.15	Robotic capability
4.7.10	System observing efficiency	3.2.2.15	Robotic capability
4.7.11	Dynamic rescheduling for TTI in w filter	3.2.2.15	Robotic capability
4.7.12	Dynamic rescheduling for TTI in g, r, i, z, y filters	3.2.2.1	Scheduling to meet timing requirements
4.7.13	Dynamic rescheduling for cadence	3.2.2.1	Scheduling to meet timing requirements
4.7.14	Dynamic rescheduling for duration	3.2.2.1	Scheduling to meet timing requirements
4.7.15	Dynamic rescheduling for visitation	3.2.2.1	Scheduling to meet timing requirements
4.7.16	Dynamic rescheduling for survey depth	3.2.2.1	Scheduling to meet timing requirements
4.7.17	Dynamic rescheduling for lunar illumination	3.2.2.1	Scheduling to meet timing requirements
4.7.18	Image throughput	3.2.2.2	Sky coverage in 7 days
		3.2.2.17	Sweet spot coverage plus transient detection
4.7.19	Data volume for all raw science data products	3.2.2.18	Data archiving and end-user access
4.7.20	Firewall against unwanted/unauthorized intrusions	allocated	
4.7.21	Remote superuser access to observatory system computers	3.2.2.15	Robotic capability

5 Telescope Conceptual Definition

5.1 Subsystem Overview

In this section the Pan-STARRS concept of the telescope, the telescope enclosure, and the support space is described. The support space is assumed to be in close juxtaposition to the telescope enclosure.

The basic Pan-STARRS telescope concept is that of multiple small telescopes working in tandem to achieve an aggregate étendue that is far greater than currently available with modern telescopes. The étendue of an optical system is the fundamental measure of its total throughput and is defined as $\epsilon = A\Omega$ where A is the effective area of the input pupil and Ω is the system field of view. For small fields of view it is more cost effective and operationally more efficient to build a single large telescope than a suite of smaller ones that work in tandem. This has driven the historical efforts to build larger and larger aperture telescopes. But the requirement of a wide-field along with a large aperture changes things considerably. Large fields of view (with half-angles, $\theta_{\rm max} \geq 1.5°$) have recently been demonstrated on 2 m class telescopes of fairly conventional design. The cost and risks of building such telescopes are therefore fairly well known. But the combination of wide field of view with large aperture ($D \geq 4$ m) has not yet been built and requires significant technological developments. For the Pan-STARRS concept to be viable, the costs of the individual telescopes must be kept small. For this reason the Pan-STARRS concept is to utilize a low risk, conventional design for the telescope.

In the past the agility of large telescopes has not been a driver in their design because they generally "stare" at a single point in the sky for long periods of time. However, to make effective use of a large étendue, a telescope must also be agile enough to point rapidly in order to allow large sky coverage in a short amount of time. This is mechanically easier to accomplish with small telescopes and becomes another motivation for the Pan-STARRS concept.

At the conceptual design level, two options are available for distributing and mounting the mirror cells: in independent telescope support structures or on a common mount. A formal process factoring in technical and other considerations will lead to the choice of mounting scheme. However, the requirements presented here are independent of whether the Pan-STARRS telescopes will be attached to independent or common mounts.

The terms "dome" and "enclosure" are used to synonymously refer to the immediate telescope housing. The support space is not necessarily an independent structure separate from the dome itself. In some scenarios, the support space could be housed in the dome. However, support functions are not required to be in the telescope dome.

The enclosure concept for the Pan-STARRS telescopes is a conventional dome where the telescope remains inside the dome during operation. This configuration helps to minimize the total footprint of the telescope facility, which is considered to be a highly desirable feature. The initial concept is to enclose each telescope in its own separate enclosure. The technical trades being conducted on the common and individual mounting options could favor a single large enclosure which houses the entire array of telescopes, but this is likely to be a more expensive option.

5.2 Top Level Requirements

We list here the fundamental requirements on the telescope, its enclosure, and the support space. Note that we do not include here requirements which are dependent on the environment or weather conditions expected at the observatory. An example of one such requirement would be the wind and snow loads which the enclosure must protect against. Environmental requirements will be generated in the telescope System/Subsystem Specification (SSS). The reasoning behind many of these top level requirements is given in the following section.

3.2.2.8 The system shall use *g,r,i,z,y* filters.

3.2.2.9 The system shall possess a broadband filter approximately equal to a $g + r + i$ filter.

3.2.2.14 The telescope system must be fully operational up to zenith angles of 70°.

3.2.2.15 The system shall be capable of operating robotically.

5.2.1 The telescope aperture shall be between 1.5 and 2.3 m in diameter.

5.2.2 The number of telescopes in the Pan-STARRS array shall be ≥ 3.

5.2.3 The half-angle of the telescope field angle shall be ≥ 1.5 deg.

5.2.4 The telescope focal length shall be $\geq 8.0\,m$.

5.2.5 The telescope shall be capable of delivering a PSF $\leq 0.43''$ at a zenith angle of 70°in the bandpasses: *g,r,i,z,y,w*.

5.2.6 The telescope shall be capable of delivering a PSF $\leq 0.31''$ at a zenith angle of 10°in the bandpasses: *g,r,i,z,y,w*.

5.2.7 The telescopes shall utilize altitude-over-azimuth mount(s).

5.2.8 The telescope focal plane shall be fully baffled against stray light.

5.2.9 The telescope shall be capable of slewing **1.5 (TBR)** degrees and settling within **5 (TBR)** seconds.

5.2.10 The filter mechanism shall be capable of switching between any of 6 filters within **30 (TBR)** seconds without degrading the systems photometric performance.

5.3 Discussion of Top Level Requirements

5.3.1 The Telescope Aperture

The system étendue, denoted by ϵ, has been identified in Section 3.4 as a fundamental figure of merit for the operation of the Pan-STARRS telescopes. Requirement (3.5.1) specifies a system étendue of $\gtrsim 40\,\mathrm{m}^2\,\mathrm{deg}^2$. Values of ϵ this large are unprecedented for modern telescopes. To achieve this goal with a single telescope will require ground-breaking technological developments. The Pan-STARRS concept is to avoid those developments by using a multitude of conventional small aperture telescopes. Thus, in the Pan-STARRS concept to achieve an étendue of $\gtrsim 40\,\mathrm{m}^2\,\mathrm{deg}^2$, a cost effective combination of telescope aperture, number of telescopes, and telescope field of view must be chosen.

A comparison of the cost per unit étendue of existing and proposed telescopes has been done which shows that in this respect small aperture telescopes compare quite favorably with large aperture telescopes even when the large aperture telescopes have been designed specifically with étendue in mind (POI: The Panoramic Optical Imager, Section 3 & Appendix A). Therefore, from a Pan-STARRS concept perspective, the main question to ask is not “how big should he telescopes be?”, but, rather, “how small?”

The desire to make the best use of an observing site with excellent seeing places a lower limit to the aperture size that will be considered. Maintaining a seeing-limited Point Spread Function (PSF) is very important to all science programs that rely on point source detections. In particular, this is needed to address the Science Goals Statement(SGS) requirement (4.2.1) to detect 90% of the PHOs within 10 degrees of the ecliptic plane. With a site which provides natural seeing of $0.6''$ FWHM, diffraction limits the choice of aperture sizes to diameters greater than 1 m.

The requirement to detect objects down to an R magnitude of 24 with a signal-to-noise of 5, the requirement to avoid trailing losses by keeping exposure times to less than 30 seconds, and the assumption that these measurements will be done in seeing conditions of FWHM 0.6 arcseconds set fundamental limits to the aperture size required. If one assumes a sky brightness of 20.8 magnitudes per square arcsecond, the w filter bandpass (448 nm), 85% filter transmission, 2% reflection losses from all 6 of the corrector lens surfaces, 88% mirror reflectivity, telescope obscuration of 36%, and an average detector QE of 70% across the w filter bandpass, then the collecting area required to achieve a signal-to-noise ratio of 5 in a 30 second exposure on a magnitude 24 object is 12.72 m^2 (PSDC-300-005-00). This collecting area corresponds to a single 4.02 m telescope, or an array of 4 2.01 m telescopes.

However, the effective collecting area required to achieve a particular signal-to-noise on objects of a given magnitude is proportional to $F_{\mathrm{sky}} A_{\mathrm{sky}}$ where F_{sky} is the flux of background light from the sky and A_{sky} is the area on the detector over which one must integrate to collect the whole flux from a single point source. If the seeing deteriorates, then A_{sky} increases, and the collecting area required for the given source, exposure time, and signal-to-noise also increases. If the sky brightness increases, the required collecting area also increases. The sky brightness quoted above corresponds to conditions of 50% lunar phase. So, if one wishes to observe under less than median seeing and under lunar phases above 50%, then the effective area must be chosen to be larger than 12.72 m^2. If one is willing to observe only during dark time, then the magnitude of the sky brightness will increase by 0.6 magnitudes, which corresponds to a decrease in the sky flux by a factor of 0.57. For an array of 4 telescopes, this results in a requirement of 1.52 m apertures for each telescope.

Calculations like these result in the effective range of telescope apertures which will be considered. Assuming only three telescopes observing under relatively bright conditions results in an upper limit of 2.3 m to the aperture size. Assuming four telescopes under very dark conditions results in a lower limit of 1.5 m to the aperture size.

Detector costs and a desire to minimize the total footprint of the array of telescopes also drive a desire to consider larger apertures. As the aperture size decreases, the fill factor of the array will go down, which means that the required footprint will go up. Note that for wide field telescopes the option of considering high fill-factor telescope forms like a segmented mirror design is not an attractive alternative because the baffle structure and its supports would significantly interfere with the field of view (FOV) of adjacent mirror segments. The number of telescopes required for a given étendue is proportional to D^{-2}, the inverse square of the telescope aperture. Therefore, the cost of detectors significantly decreases by choosing larger telescope apertures.

The system level requirement to utilize the fast guiding capabilities of the OTA arrays favors a choice of aperture size less than 2 m. Under good seeing conditions ($0.6''$ or less) there is very little to be gained from fast guiding for aperture sizes greater than 2 m. Under poor seeing conditions ($1''$ or worse) the optimal gains are seen with telescope apertures close to 1.6 m (POI: The Panoramic Optical Imager, Figure 10, pg. 39). Measured seeing distributions show that the seeing will be better than 1 arcsecond approximately 80% of the time (PSDC-200-009-00).

There is no consideration which defines the choice of aperture size more accurately than about 30%. Within the range of apertures given above the choice is somewhat arbitrary. The choice of an initial aperture size of 1.8 m is a little below the middle of the range given above. This value has been influenced slightly by the optical designs. Image quality is of course easier to maintain with smaller apertures. As the optical designs evolve small changes in the aperture size may be the result of further compromises between image quality and throughput.

In summary, the current choice of aperture size represents a compromise between throughput, allotments for poor seeing conditions, making optimal use of the seeing when it is good, and optimizing the array of telescopes for minimal footprint and detector costs. Clearly, as with any compromise, different choices can be made depending on the weighting one assigns to each of these factors. Effectively, this initial choice of the system aperture assumes that through optical design one can optimize the system for an acceptable combination of PSF and $\theta_{\max}$, the maximum half-angle of the telescope FOV. But, there is much less control over the fundamental limitations placed on the system by the atmosphere. It is therefore sensible to start by optimizing the telescope size to the atmosphere.

5.3.2 The Number of Telescopes

This requirement flows down from the requirement on the system étendue, and from the desire to be able to effectively eliminate false point source detections on the array. Elimination of false point source detections is critical for meeting the SGS requirement (4.2.1) to detect 90% of PHOs within 10 degrees of the ecliptic plane.

Since it is not reasonable to expect to meet the required étendue with a single 2 m class telescope, we are required to split the total throughput between multiple systems. The current optical design studies indicate that it is possible to have telescopes with a field angle, $\theta_{\max}$, of 1.5 degrees, which is equivalent to a 3 degree field of view and to $\Omega = 7\,\mathrm{deg}^2$. With this choice of FOV, a total aggregate effective collecting area between 5.7 and $7.1\,\mathrm{m}^2$ is implied by the SGS étendue requirement. To convert this effective collecting area into an aperture requirement, the effects of obscuration must be included. Assuming 36% obscuration, each 1.8 m telescope will contribute $1.6\,\mathrm{m}^2$ and a minimum of 4 telescopes would be required for the array. This shows that the initial choice of apertures is consistent with the required étendue, but does not give the reason for the minimum number of telescopes.

By combining the signal from multiple cameras one can effectively eliminate false point source detections which might be caused from either random noise spikes in a single camera or cosmic ray hits. The redundancy that 3 telescopes offer is considered to be the minimum required for effective elimination of false detections. This redundancy also allows a greater freedom to relax the “dead pixel” requirements on the cameras.

The calculations of the étendue for the initial choice of telescope apertures illustrates an obvious and important trade between number of telescopes in the array and aperture size. If the number of telescopes in the array were to decrease from 4 to 3, then the aperture size of each telescope would have to be increased to 2 m in order to maintain the required étendue. Given possible footprint constraints, this may be an effective alternative, but it comes at the price of losing the ability to operate the array effectively when a single telescope is down for repairs.

5.3.3 The Telescope Field of View

This is equivalent to a total field of view (FOV) of 7 deg^2 in each exposure. This requirement flows down from the SGS requirement of achieving a total étendue of $\gtrsim 40\,\mathrm{m}^2\,\mathrm{deg}^2$ and the derived telescope. If the apertures were to be increased, this requirement can be relaxed in direct proportion.

Choosing a field angle has impacts on the amount of obscuration in the system and on the baffling requirements for the telescope. Reducing the FOV reduces both the baffling requirements and the obscuration in the system. While in principal requirements for these items can be traded off against the FOV, design work shows that it is very unlikely that changes in these features of the telescope can have effects significant enough to warrant changes in the FOV specification.

5.3.4 The Telescope Focal Length

The expected size of pixels in the camera, the expected mean seeing for the site, and a desire to maximize the system FOV are the prime drivers which fix the telescope focal length. The effect of charge diffusion in the CCD pixels is also a consideration. The choice of telescope focal length fixes the image plate scale. An 8.0 m focal length is equivalent to a plate scale of 38.8 μm arcsec^{-1}.

The design specification for the site seeing that we are working with is a median seeing of 0.6 arcseconds. Charge diffusion in the Pan-STARRS camera pixels is expected to be $\sigma_{\mathrm{diffusion}} \sim 5\mu$m and the camera pixel sizes will be between 10 and 12 μm(PSDC-200-009-00).

When the pixel size is small ($\leq 15\mu m$) and the CCD substrate is thick ($\geq 40\mu m$) charge diffusion starts to become a limiting factor in the detector optical transfer function. Fixing the telescope plate scale so that the charge diffusion has minimal impact on the atmospheric PSF gives a lower limit to the telescope focal length, but this is a soft limit. Assuming $0.6''$ seeing and $\sigma_{\text{diffusion}} = 5\mu m$, a focal length greater than 8.2 m limits the image degradation from charge diffusion to less than 10% of that given by seeing. But, by allowing 20% image degradation, the limit on the focal length drops to 4.9 m (POI: The Panoramic Optical Imager, Appendix B).

It is appropriate to base the choice of system focal length on the trade off between a desire to over sample the best atmospheric seeing and the desire to sample as wide a field of view as possible because the system étendue increases with the square of the plate scale as long as the detector dimensions remain fixed. The clear trade off here is between increased field of view and the degradations on the system photometry and astrometry as the sampling of the PSF is reduced. There will also be some effects on efforts to model the system PSF as the plate scale is reduced, but this represents a specialty need which is not shared by most of the science goals for Pan-STARRS.

Simulations of the effects of under-sampling the atmospheric PSF have been conducted (PSDC-200-002-00). These indicate that for $0.6''$ seeing, pixel sizes less than $0.35''$ have little or no impact on the required photometry and astrometry while pixels as large as $0.7''$ will have significant effects. This is the driving reason for the top-level system requirement to have at least a factor of two over-sampling of the telescope PSF.

The image size budget given in Section 3 requires the telescope to have a minimum PSF of $0.27''$ at zenith. Convolving this with the expected seeing of $0.6''$ gives an expected PSF of $0.66''$ on the detector. The over-sampling requirement and an assumed pixel size of $12\,\mu$m therefore means that we must have a plate scale $\geq 36.4\,\mu$m arcsec^{-1}. The lower limit to the plate scale corresponds to the Nyquist criterion. The desire to maximize the telescope FOV drives the design to the smallest plate scales possible. Allowing for a 7% error in the telescope focal length results in a design plate scale of $38.8\,\mu$m arcsec^{-1} and a telescope focal length of 8.0 m. Note that with this choice of focal length, if the camera pixel size changes to $10\,\mu$m, we still satisfy our sampling requirement. Clearly, given our conservative allowance for errors in the plate scale, errors of 5% in the focal length specification will be acceptable.

It is well known that efforts to model the PSF will suffer when the over-sampling is only by a factor of 2. For purposes of image reconstructions or PSF modeling typical over sampling of 3-4 is needed. However, for Pan-STARRS we are combining the data from multiple cameras which sample the same field with slight differences in their FOV. Critical PSF modeling will never be done on images from a single camera and the combination of 4 shifted images mitigates the problems that might arise from only over-sampling by a factor of 2.

Items which are strongly affected by this decision are the required size of the telescope structure, the corresponding size of the telescope enclosure, and the difficulty of the optical design. For a fixed aperture and detector size, the shorter the focal length, the more complex and costly is the optical design, and the greater the field of view. Longer focal lengths result in larger telescope support structures, larger enclosure specifications, and smaller fields of view.

5.3.5 The Telescope PSF

This requirement specifies a total telescope image budget and includes contributions from the following effects:

- optical design aberrations (including chromatic aberrations)
- optical surface manufacturing errors
- collimation errors
- defocus errors

Table 10: The Pan-STARRS Filters

Filter	Half Maximum Transmission Wavelengths (nm)		Bandwidth
	Blue Side Cutoff	Red Side Cutoff	(nm)
g	402	552	150
r	552	691	139
i	691	818	127
z	818	922	104
y	948	1060	112
w	402	818	416

- support flexure errors
- tracking errors
- local seeing (i.e. mirror and dome seeing)

This requirement flows down from the allocation of image budget errors given in Section 3.4.1 of this document. We leave further details of the telescope image budget breakdown to the Telescope SSS. Table 2 of Section 3.4.1 shows that the requirement for the telescope near zenith is 0.26 arcseconds. This is consistent with our expectation that the mirrors will be tested and polished in their mirror cells while in a zenith orientation. We therefore expect to have better performance of the telescope optics near zenith.

Requirements 3.2.2.8 and 3.2.2.9 require that the telescope be capable of taking images in the filters *g, r, i, z, y*, and a solar system filter which we denote here as "w". This requirement is interpreted to mean that there should be no degradation of the image PSF over that given in Section 3.4.1 in all of the bandpasses listed in Table 10 and that the throughput of the telescope should stay above that specified in Section 3.4.

The choice of these bandpasses allows the Pan-STARRS measurements to be more easily compared with earlier measurements because the Sloan survey has already developed the appropriate filter transformations. The 'new' filters in this survey are the y and w filters. The y filter has been chosen to enhance the detection of high red-shift objects. The w filter has been chosen as the broad-band filter for the faint asteroid searches. The bandwidth of the w filter has been chosen to optimize the detection of faint point sources where the observations are dominated by the sky noise (PSDC-200-003-00). The blue cut-off of this filter minimizes the effects of scattered moonlight while the red cut-off minimizes the contributions from night sky lines which dominate the night sky emission beyond 800 nm. The bandwidths of these filters are defined in Table 10.

We leave the details of the filter specifications to the Telescope SSS.

5.3.6 The Telescope Mount

The choice of an altitude-over-azimuth mount for the telescope is a subsystem allocation based on current estimates of the costs of the telescope mount. Trade studies are underway to evaluate the costs of different mounting schemes. If these studies reveal significant advantages to a different type of mount, then this requirement will be revised.

5.3.7 The Telescope Baffling

This requirement flows down from the requirements 3.2.1.5 and 3.2.2.4 to achieve 10% accuracy in the photometric red shifts of Super Novae, the requirements 3.2.1.3 and 3.2.2.16 to support the creation of static sky maps, and the desire to maximize the efficiency of point source detections.

The term ‘fully baffled’ refers to the condition where there is no place in the useable focal plane where ‘primary’ scattering surfaces are directly visible. A primary scattering surface is one that is exposed to stray light which has not been previously scattered from some other surface.

The main impact of this requirement is on the telescope throughput. This requirement increases the telescope obscuration.

5.3.8 The Telescope Slew Rate

The telescope must be capable of efficient field-to-field pointing. This requirement flows down from the observing cadence dictated by the moving object surveys.

This specification affects the required maximum accelerations and velocities which the telescope must meet. To meet the current specifications the telescope must be capable of accelerations of $0.4\,\mathrm{deg\,sec}^{-2}$ and maximum velocities of $1\,\mathrm{deg\,sec}^{-1}$ In turn, this specification has impacts on the required stiffness of the telescope support structures.

5.3.9 The Filter Mechanism

The speed of the filter mechanism is driven primarily by the details of the observational cadence which must be done in order to satisfy the needs of the moving object surveys of NEOs and PHOs. Note that since it is not required by these surveys to swap filters between each exposure, the time to swap filters is not dictated by the need to minimize setup time between individual exposures. In addition, in the current optical design, the filters are quite far from focus. This relaxes the re-positioning requirements which are needed to maintain photometric performance.

5.4 Subsystem Top Level Views

Subsystems for the enclosure are shown in Figure 7. Most of the subsystems shown in Figure 7 are self-explanatory, but a few require clarification. The telescope calibration system is required for both wavelength and throughput measurements of the optics and camera. This system includes any specialized lamps, screens, and mechanisms for placing the output from these items in the telescope FOV. The mirror and instrument handling facilities include any specialized hatches, doors, rails or cranes which are required to move the telescope optics in and out of the enclosure. It is assumed here that many of these items will also be used for the installation and removal of the telescope instrumentation. The environment monitors include any temperature sensors, air flow meters, precipitation meters, humidity meters, pressure meters, dust meters, and enclosure cameras which are considered necessary for the tracking of conditions inside the dome. This subsystem does not include sensors which are specific to the telescope itself. A separate subsystem is designated for that function. Clearly it may be possible to combine these two subsystems. We are not ruling out that possibility by the designation of separate subsystems here. The “Building Consumables” subsystem includes facility power, air and water supplies which may be necessary for the operation of the telescope and support space.

The red lines in Figure 7 show control interfaces. The arrows denote the direction of information flow between the subsystems. The control lines shown with open arrows are defined in other sections of this document. Blue lines denote major mechanical interfaces. Circles denote computing facilities and ellipses denote major subsystems. Open circles and

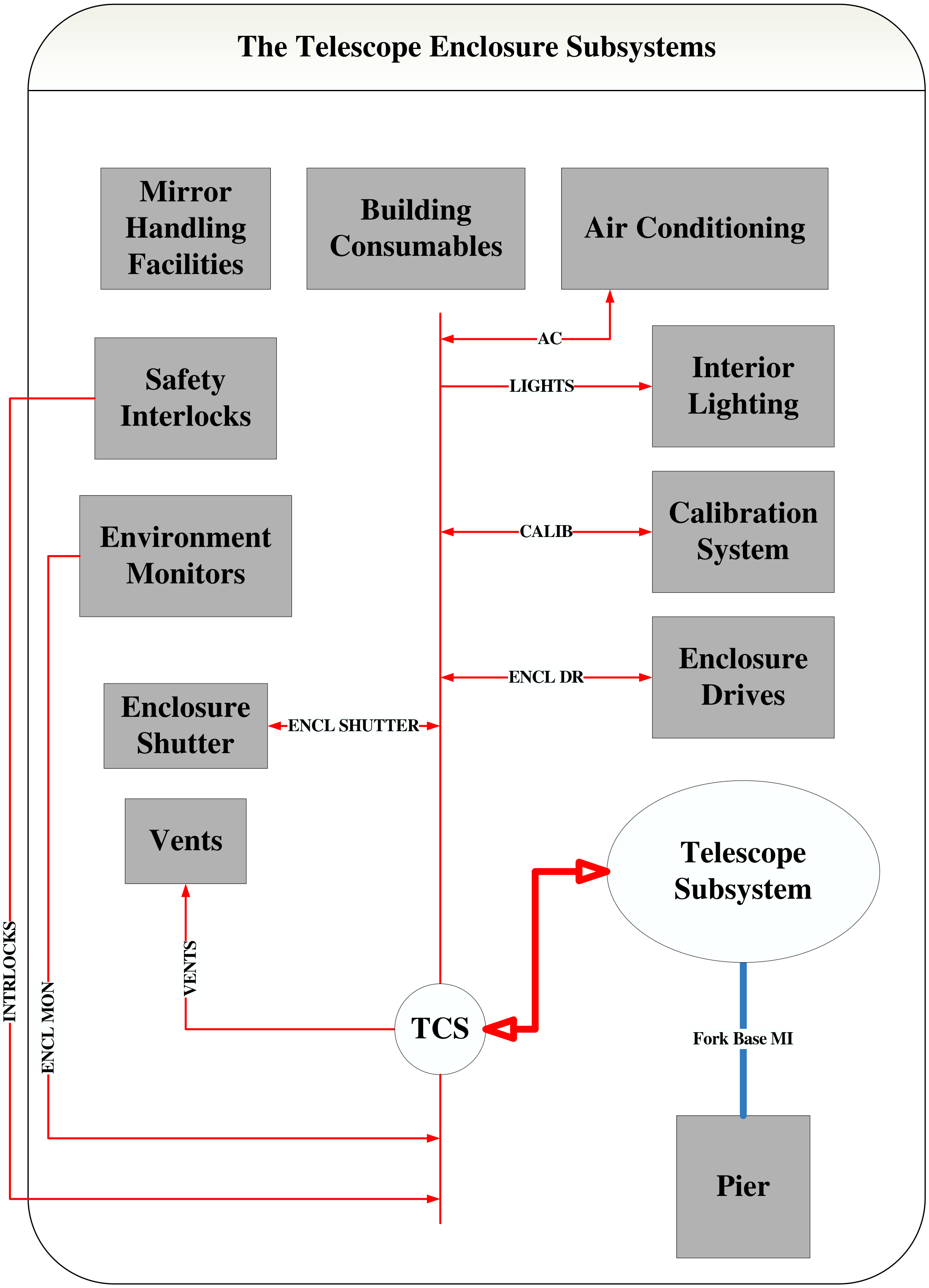

Figure 7: Enclosure Block Diagram.

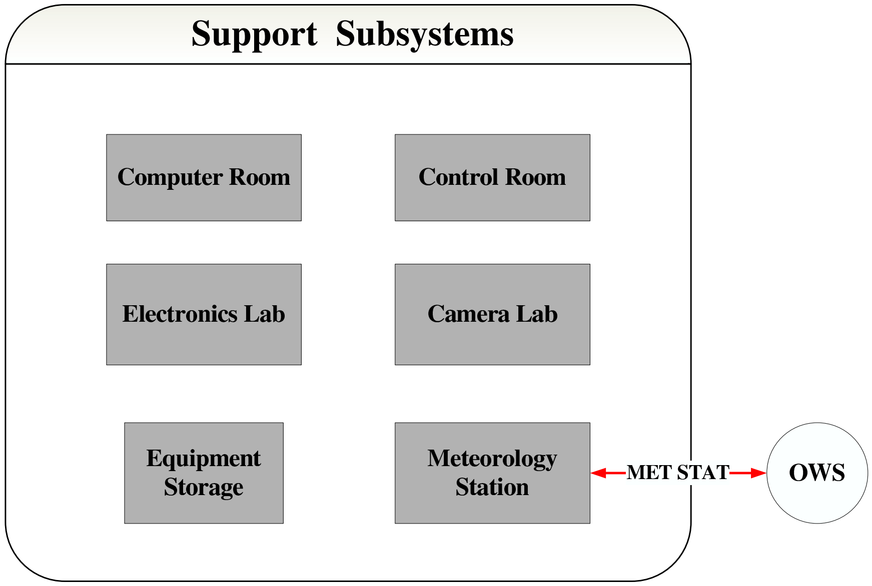

Figure 8: The Support Space Block Diagram.

ellipses denote computing facilities which are described elsewhere in this document. The Telescope Control System (TCS) is the main computing facility for control of both the enclosure and the telescope. The details of the TCS functionality is discussed in Section 7.1 of this document and will not be discussed here. There is no intent in this figure to imply the physical location of the TCS. It is possible that it will reside in the support space computer room (Figure 8). The telescope control interfaces will be discussed below in conjunction with Figure 9. The enclosure control interfaces shown as the red lines in Figure 7 are listed in Table 12 of Section 5.8 and discussed there in greater detail. The complexity of the telescope requires it to be treated as a subsystem independent of the enclosure. Most of the specifications for the enclosure and its subsystems are left to the Telescope System/Subsystem Specification (SSS).

The support subsystems shown in Figure 8 are nearly self explanatory. The Metrology Station shown in this figure provides the observatory with information on the external weather conditions. It is likely that this station will be physically separate from the rest of the support subsystems. This station is controlled by the OTIS Weather Server (OWS), which is discussed in Section 7.1.

Each telescope consists of several distinct subsystems. Figure 9 is a block diagram which defines those subsystems. M1 and M2 denote the primary and secondary mirrors, respectively. L1 and L2 denote the refractive corrector lenses. Note that there exists a third corrector element (L3), which forms the window to the camera dewar. As an integral part of the camera, this interface is discussed in Section 6.1 of this document. B1 through B3 denote the telescope baffles. The Cassegrain Core (CC) is a structure which fits within and behind the central hole in the primary mirror. The CC is fixed with respect to the M1 mirror cell, while the camera rotates around the optical axis. The main function of the CC is to support the camera, filter mechanism, shutter, and corrector optics. These blocks are shown within the CC and in darker grey to emphasize this grouping.

The major mechanical interfaces in the telescope are shown by the blue lines in Figure 9. The control interfaces are shown by the red lines with arrows denoting the direction of information flow. Once again, open blocks and control interfaces with open arrows are defined elsewhere in this document and the labels for the mechanical and control interfaces shown in Figure 9 are defined in Table 14 and Table 13 of Section 5.8. The Detector Host Computer (DHC) is responsible for handling the main interactions with the camera. Since the shutter timing is critical to the operation of the camera, this interface is controlled through the DHC rather than through the TCS itself. The DHC communicates with the TCS by way

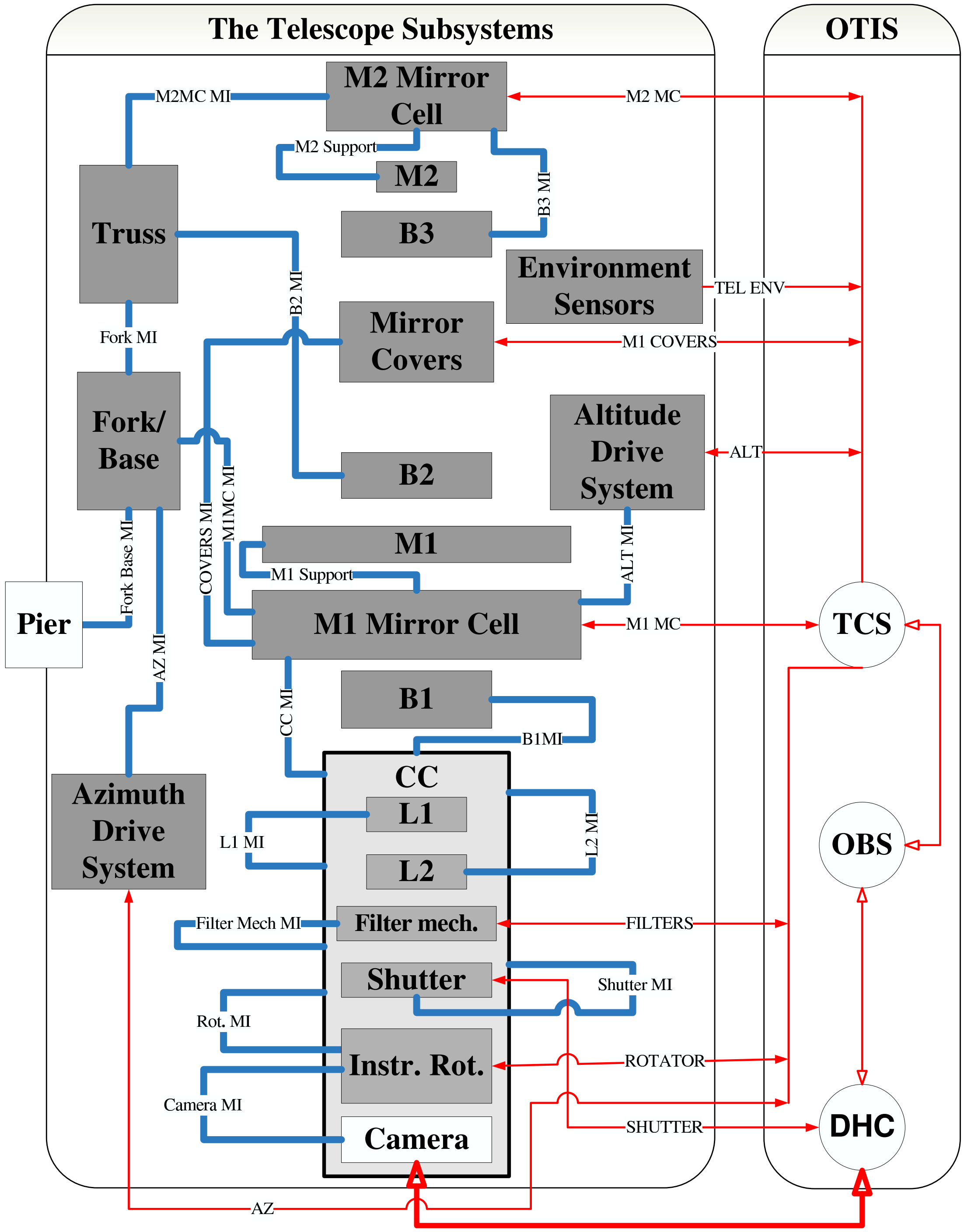

Figure 9: Telescope Subsystem Block Diagram.

of the Observation Sequencer (OBS). As indicated by the open arrows, these interfaces are discussed elsewhere and will not be discussed here. The TCS, OBS, and the DHC are discussed in detail in Section 7.1.

For independent mounts, each telescope would have identical subsystem blocks which feed control signals into the TCS and the DHC. If the trade studies indicate that it is advantageous to proceed with a common mount design, then the subsystem blocks shown in Figure 3 would remain and a subsystem called ‘Common Cell’ would be added. This subsystem refers to the base cell which the individual primary mirror cells would be mounted to. Under these circumstances the altitude and azimuth drives would be a single subsystem which has a mechanical interface to the Common Cell.

5.5 Operational Subsystem Description

The operational states of the telescope include the following:

5.5.1 Observing - The telescope is up and running taking data on the sky. The enclosure and mirror covers are open.

5.5.2 Calibrating - The telescope is static, but in a specific location, and the calibration mechanism is deployed. The mirror covers are open, but the enclosure is not.

5.5.3 Hibernating - The telescope is up and running, but the mirror covers are closed and the enclosure is closed. This mode needs to be automatically triggered by bad weather conditions.

5.5.4 Protected - The telescope is shut down in a minimum power consumption state with the enclosure closed. The mirror covers are closed. Computers in the support space have been safely shut down. This state needs to be automatically triggered by power outages.

5.5.5 Servicing - The telescope is quasi-static, moved only as required to allow removal of optics, mechanisms, or the camera. It is possible that telescope can only be moved manually in this mode. The enclosure is in a state which allows mirrors and instruments to be removed and worked on. Over-rides to the safety interlocks may be required in this mode.

5.5.6 Off - The power to the telescope, enclosure, and camera is off.

5.5.7 Failure - The telescope, enclosure, or camera has experienced some substantial failure. Immediate servicing is required. Maintenance personnel must be automatically notified that the system has entered this mode.

5.6 Conceptual Design

5.6.1 Optical Design

The telescope optical layout will be a Cassegrain configuration with a 3 element corrector. Design studies were undertaken to investigate alternative wide-field designs which might offer appropriate combinations of PSF and θ_{max}, the telescope field of view half-angle, for 2 m class telescopes. (PSDC-300-001-00, Preliminary Design for the Pan-STARRS Telescope Optics). The Cassegrain-corrector design was chosen based on the fact that the mounting and support structures for such a telescope were well known and tested designs and the size of this type of telescope was cost-effective. In addition, by selecting a design similar to one proven to work with the Sloan survey, the risk of manufacturing the optics is minimized since they become very similar to what vendors already have experience making.

The conceptual optical design layout for the telescope is shown in Figure 10. The sizes, separations, and characteristics of each optical elements shown in this figure are given in Table 11. A third corrector element was required to achieve

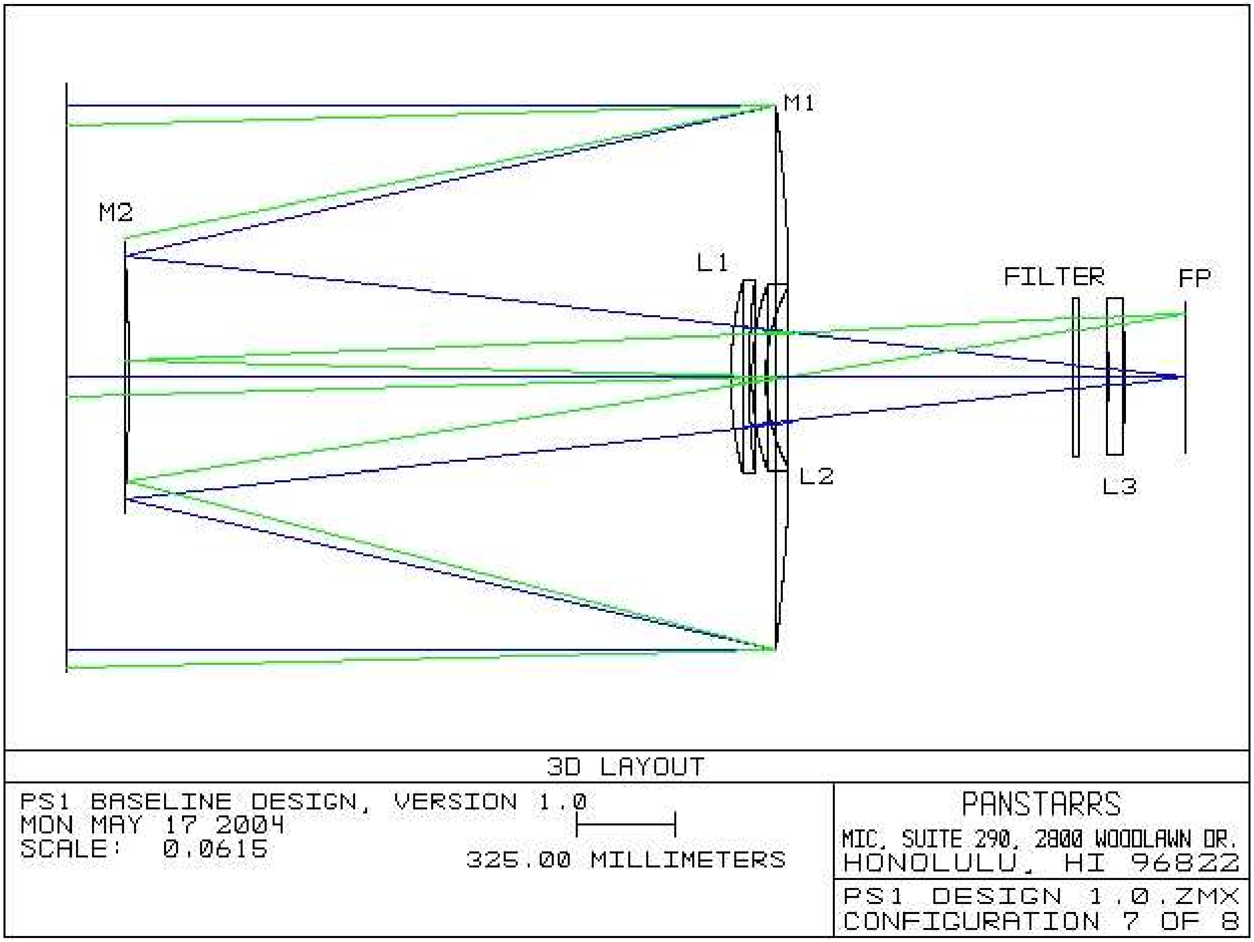

Figure 10: Pan-STARRS Conceptual Optical Design Layout

Table 11: Mechanical Properties of the Pan-STARRS Conceptual Design Optical Elements

Element	**Clear Aperture (mm)**	**Material**	**Thickness (mm)**	**Surface Characteristics**	
				A	**B**
M1	1800	ULE	100	Concave asphere	-
M2	900	ULE	TBD	Concave asphere	-
L1	621	Fused Si	60	Convex asphere	Convex asphere
L2	601	Fused Si	45	Convex asphere	Convex asphere
FILTER	464	Fused Si	20	Flat	Flat
L3	451	Fused Si	55	Concave asphere	Concave asphere
FP	420.4	CCD	-	Flat	-

imaging performance that matches the expected site characteristics. The third corrector (L3) is used for the camera dewar window. Its thickness is required to support atmospheric pressure. The camera shutter fits between the filters and L3, but is not shown on the layout. The 'Cassegrain Core' consists of the corrector lenses, the shutter and filter mechanisms, the instrument rotator, the camera, and all of the support structure for these items. The initial concept for the optical design utilizes 3 aspheric surfaces: M1, M2, and the first surface of L3. Trade studies are being conducted to optimize the current design to meet the requirements given in Table 2 and to investigate the cost and performance benefits of a reduction to the back focal distance, reductions in the aspheric coefficients to L3, and the addition of an Atmospheric Dispersion Corrector (ADC).

5.7 Derived Requirements

5.7.1 All active telescope and enclosure hardware shall be commanded by OTIS through the TCS.

5.7.2 All telescope and enclosure subsystems shall be monitored and logged by OTIS through the TCS.

5.7.3 The Filter Mechanism shall be capable of operation during telescope slews.

5.7.4 The telescope shall utilize an instrument rotator.

5.7.5 The instrument rotator shall be capable of operating between **10 (TBR)** and 70°zenith angles with a range sufficient to support **300 (TBR)** second exposures.

5.7.6 **The instrument rotator shall be capable of providing an arbitrary position angle on the sky. (TBR)**

5.7.7 **The Filter Mechanism shall rotate with the camera on the image rotator. (TBR)**

5.7.8 **The Camera Shutter shall rotate with the camera on the image rotator. (TBR)**

5.7.9 The Filter Mechanism shall be capable of operation at any orientation.

5.7.10 The Camera Shutter shall be capable of operation at any orientation.

5.7.11 The status of all subsystems on the telescope shall be fully monitored and logged.

5.7.12 The telescope mirrors shall have scattering of **5% (TBR)** or less at a reference wavelength of 402 nm.

5.8 Internal Interfaces

A listing and description of the mechanical and control interfaces found in the telescope and telescope enclosure subsystems is given here in Table 12 through Table 13. The placement of these interfaces is shown in the subsystem block diagrams given in Section 5.4 (Figure 7 through Figure 9).

The following list describes the characteristics of each enclosure and support control system interface:

- **AC.** The TCS will be required to have control of the enclosure air conditioning. It will need feedback from the building on its current set-points and temperature. This is a low bandwidth interface.
- **LIGHTS.** The TCS will be required to have control of all lights in the dome. This is a low bandwidth interface without feedback requirements.

Table 12: Enclosure and Support Control Interfaces

Interface Label	Data/Commands		Data Flow
	Source	Destination	
AC	TCS	Building Air Cond.	Bi-directional
LIGHTS	TCS	Building Lights	Uni-directional
CALIB	TCS	Calibration Facility	Bi-directional
ENCL DR	TCS	Enclosure Drives	Bi-directional
ENCL SHUTTER	TCS	Enclosure Shutter Drives	Bi-directional
VENTS	TCS	Enclosure Vents	Bi-directional
INTERLOCKS	Safety Interlocks	TCS	Uni-directional
ENCL MON	Environmental Monitors	TCS	Uni-directional
MET STAT	External Environmental Sensors	OWS	Uni-directional

- **CALIB.** The TCS will be required to have control of all calibration lamps. No feedback will be needed from the calibration lamps (we can get this from the enclosure cameras). The TCS will also be required to control any mechanisms which are needed to place the calibration sources in the camera FOV. Feedback will be required for this. Simple limit switch feedback is likely to be all that is required here. This is a low bandwidth interface.
- **ENCL DR.** The TCS will be required to control the dome rotation mechanism. In addition, we will require monitors on the motor currents. The bandwidth requirements for this interface is moderate, full encoder feedback will be required.
- **ENCL SHUTTER.** The TCS will be required to control the enclosure shutter mechanism. The bandwidth requirement is moderate. Full encoder feedback will not be required. Simple limit switch feedback is adequate, but we will require monitoring of the motor currents.
- **VENTS.** The TCS will be required to control the enclosure vent mechanisms. The bandwidth requirement is low. Simple limit switch feedback is adequate.
- **INTERLOCKS.** The TCS will be required to have full information on the status of any safety interlocks in the system. Likely places for this to exist are with the dome rotation, shutter, and calibration mechanism. The bandwidth requirement is low.
- **ENCL MON.** The TCS will be required to have constant feedback (on approximately 1 Hz timescale) of all temperature, pressure, humidity, airflow, or dust sensors in the enclosure. Note that we include in this category the need for cameras in the enclosure. Its unclear that we need the TCS to handle the video data from these cameras, but this might be required for communication to a remote control room. In this case, we need a relatively high bandwidth interface, otherwise aggregate bandwidth is moderate for this interface.
- **MET STAT.** The OWS will be required to have constant feedback from environmental monitors external to the enclosure. Many of these sensors may be identical with those used for the enclosure monitors. Aggregate bandwidth for this interface is low.

The following list describes the characteristics of each telescope control system interface:

- **ALT.** The TCS will be required to have control of the altitude drive motors and the encoder feedback from this axis. In addition, the TCS will be required to be able to monitor and log motor currents at a rate of approximately 50 Hz. This is a moderate bandwidth interface.

Table 13: Telescope Control Interfaces

Interface Label	Data/Commands		Data Flow
	Source	Destination	
ALT	TCS	Altitude Drive System	Bi-directional
AZ	TCS	Azimuth Drive System	Bi-directional
M1MC	TCS	Primary Mirror Cell	Bi-directional
M1 COVERS	TCS	Primary Mirror Cell Covers	Bi-directional
M2MC	TCS	Secondary Mirror Cell	Bi-directional
ROTATOR	TCS	Instrument Rotator	Bi-directional
FILTERS	TCS	Filter Mechanism	Bi-directional
CAM SHUTTER	DHC	Camera Shutter Mechanism	Bi-directional
TELENV	Telescope Environment Sensors	TCS	Uni-directional

- **AZ.** The TCS will be required to have control of the azimuth drive motors and the encoder feedback from this axis. In addition, the TCS will be required to be able to monitor and log motor currents at a rate of approximately 50 Hz. This is a moderate bandwidth interface.
- **M1MC.** The TCS will be required to have control of all positioning mechanisms housed in the M1 mirror cell. This includes all motors used to position the primary mirror. At a minimum, this will be a 3-axis system with encoder and limit switch feedback. If a ‘warping’ mechanism is used to control astigmatism in the mirror, there could be as many as 20 control mechanisms. This is a moderate bandwidth interface.
- **M1 COVERS.** The TCS will be required to have control of all mirror covers housed in the M1 mirror cell. Feedback from this system will be minimal. Simple limit-switch indicators are likely to be used. This is a low bandwidth interface.
- **M2MC.** The TCS will be required to have control of all positioning mechanisms housed in the M2 mirror cell. This includes all motors used to position the secondary mirror. At a minimum, this will be a 5-axis system with encoder and limit switch feedback. This is a moderate bandwidth interface.
- **ROTATOR.** The TCS will be required to have control of the instrument rotator. This will be a 1-axis system with encoder and limit switch feedback. In addition, the TCS will be required to be able to monitor and log motor currents at a rate of approximately 50 Hz. This is a moderate bandwidth interface.
- **FILTERS.** The TCS will be required to have control of the filter mechanism. This will be a 6-axis system with encoder and limit switch feedback. This is a moderate bandwidth interface.
- **CAM SHUTTER.** The DHC will be required to have control of the camera shutter. This will be a 1-axis system with encoder and limit switch feedback. This is a low bandwidth interface.
- **TEL ENV.** The TCS will be required to read information from all environmental sensors on the telescope. This includes all temperature or airflow sensors on the truss, mirror cells, and optics.

Table 14: Telescope Mechanical Interfaces

Interface Label	**Mating Parts**	
	A	**B**
M1 Support	Primary Mirror	M1 Mirror Cell
M1MC MI	M1 Mirror Cell	Telescope Fork or Base
AZ MI	Azimuth Drive System	Telescope Fork or Base
ALT MI	Altitude Drive System	M1 Mirror Cell
COVERS MI	Primary Mirror Covers	M1 Mirror Cell
M2 Support	Secondary Mirror	M2 Mirror Cell
M2MC MI	M2 Mirror Cell	Telescope Truss
B3 MI	Baffle 3	M2 Mirror Cell
Fork MI	Telescope Fork	Truss
Fork Base MI	Telescope Fork or Base	Telescope Pier
B2 MI	Baffle 2	Truss
CC MI	Cassegrain Core	M1 Mirror Cell
L1 MI	L1 Corrector Lens	Cassegrain Core
L2 MI	L2 Corrector Lens	Cassegrain Core
Filter Mech. MI	Filter Mechanism	Cassegrain Core
Shutter MI	Shutter Mechanism	Cassegrain Core
Rot. MI	Instrument Rotator	Cassegrain Core
Camera MI	Camera	Cassegrain Core
B1 MI	Baffle 1	Cassegrain Core

5.9 Requirements Trace Matrix

Subsystem Requirements		System/Subsystem Requirements	
Number	**Caption**	**Number**	**Caption**
5.2.1	Aperture between 1.5 and 2.3 m	3.5.1	system Étendue shall be $\gtrsim$ 40 m^2 deg^2
5.2.1	Aperture between 1.5 and 2.3 m	3.2.2.4	Point source detection at R = 24
5.2.2	Number of telescopes ≥ 3	3.5.1	System ´etendue shall be $\gtrsim$ 40 m^2 deg^2
5.2.2	Number of telescopes ≥ 3	3.2.2.13	False alarm rate (FAR) of $< 1\%$
5.2.3	Field angle half-angle ≥ 1.5 deg	3.5.1	System ´etendue shall be $\gtrsim$ 40 m^2 deg^2
5.2.4	Focal length $\geq 8.0\,m$	3.5.6	Over-sampling of PSF ≥ 2
5.2.5	Telescope PSF $\leq 0.43''$ FWHM at 70°	3.5.2	Image size degradation $<$ 27% of median natural seeing
5.2.5	Telescope PSF $\leq 0.43''$ FWHM at 70°	3.5.3	Δ shall be greater than $2.5 \times 10^8\ \mathrm{m}^2\mathrm{deg}^2$
5.2.6	Telescope PSF $\leq 0.31''$ FWHM at 10°	3.5.2	Image size degradation $<$ 27% of median natural seeing
5.2.6	Telescope PSF $\leq 0.31''$ FWHM at 10°	3.5.3	Δ shall be greater than $2.5 \times 10^8\ \mathrm{m}^2\mathrm{deg}^2$
5.2.7	Telescope to utilize an alt.-az. mount	(Allocated)	
5.2.8	Focal plane shall be fully baffled against stray light	3.2.2.5	Absolute photometric precision of 0.01 magnitude
5.2.8	Focal plane shall be fully baffled against stray light	3.5.12	Image foregrounds residual less than 1%
5.2.9	Slewing **1.5 (TBR)** degrees, settling within **5 (TBR)** seconds	3.5.4	Σ shall be greater than $2.0 \times 10^8\ \mathrm{m}^2\mathrm{deg}^2$
5.2.10	Switching between any of 6 filters within **30 (TBR)** seconds	4.7.11	Dynamically rescheduling observations separated by one TTI in *w* filter
5.2.10	Switching between any of 6 filters within **30 (TBR)** seconds	4.7.12	Dynamically rescheduling observations separated by one TTI in *g,r,i,z,y* filters

Derived Subsystem Requirements		Top-level Subsystem Requirements	
Number	**Caption**	**Number**	**Caption**
5.7.1	Telescope and enclosure commanded by OTIS	3.2.2.15	Telescope shall be remotely operable
5.7.2	Telescope and enclosure subsystems monitored and logged by OTIS	5.2.5	Telescope shall deliver PSF $< 0.43''$ FWHM
5.7.2	Telescope and enclosure subsystems monitored and logged by OTIS	5.2.6	Telescope shall deliver PSF $< 0.31''$ FWHM
5.7.3	Filter Mech. to operate during telescope slews	5.2.10	Switching between any of 6 filters within **30 (TBR)** seconds
5.7.4	Telescope to have an instrument rotator	5.2.7	Telescope to have an alt.-az. mount
5.7.5	Inst. rot. operates from 10 to 70°	3.2.2.14	System operational up to zenith angles of 70°
5.7.6	Inst. rot. shall be capable arbitrary position angle	3.2.2.5	Absolute photometric precision of 0.01 magnitude
5.7.7	Filter Mech. shall rotate with camera	3.2.2.5	Absolute photometric precision of 0.01 magnitude
5.7.8	Camera Shutter shall rotate with camera	3.2.2.5	Absolute photometric precision of 0.01 magnitude
5.7.9	Filter Mech. operates at any orientation	5.7.4	Telescope to have a rotator
5.7.10	Camera Shutter operates at any orientation	5.7.4	Telescope to have a rotator
5.7.11	Status of all subsystems shall be fully monitored and logged	4.7.1	System shall verify, maintain, and track the performance
5.7.12	Mirror scattering of **5% (TBR)** or less	3.5.2	Image size degradation $<$ 27% of median natural seeing

6 Camera Conceptual Definition

6.1 Subsystem Overview

The Camera subsystem (CAM) is responsible for intercepting the electromagnetic radiation (collect photons) being focused by the telescope on the focal plane and accurately reproducing and recording this pattern of energy flux density (averaged over the integration time specified by the observation sequencer). The Pan-STARRS design strategy is to exploit recent advances in CCD and CCD array technology to produce an astronomical camera that advances the state-of-the-art. This approach then has the consequence of reducing risk in the design and construction of the Telescope subsystem. The technical challenges posed by the camera design are managed by explicitly integrating risk mitigation strategies into the system schedule and budget.

6.2 Top Level Requirements

As mentioned in Section 3.3, there is close coupling between the requirements specification and design of the Telescope and Camera subsystems. In particular, the requirements for the camera depend on the focal length L and primary diameter D. Based on choices adopted for the telescope conceptual design, these are taken to be $L = 8$m, which yields as plate scale of 38.8μm/arcsec, and $D = 1.8m$ (i.e. an $f/4.4$ design).

3.5.9 The flatness of the camera focal plane array shall be such that it would not touch at any point either of two coplanar planes separated by $40\,\mu$m.[1]

6.2.1 The camera shall mount mechanically to the telescope structure at the rear of the Cassegrain Core.

6.2.2 As measured by the width of the PSF, the "detector resolution" (i.e., the image degradation leading to an increase in the image size of a point source) shall have a variance of less than $40\,\mu\mathrm{m}^2$ for a point source at zenith.[2]

6.2.3 The minimum achievable readout time shall be no greater than 5 seconds.[3]

6.2.4 The active detector area of a single camera focal plane must cover at least a disk of diameter $42\,\mathrm{cm}$.[4]

6.2.5 As defined in Section 3.4, the focal plane array filling factor including both geometrical factors and non-operational pixels shall exceed 80%. (TBR)

6.2.6 The pixel "size", characterized by the length of a pixel side that defines the area presented to incoming photons, shall be no greater than $16\,\mu$m.[5] (TBR)

6.2.7 In the absence of radio frequency interference (RFI), the read noise shall be no greater than $6e^-$ (RMS).[6]

6.2.8 The camera system shall provide a minimum of 14 bits of dynamic range.[7] (TBR)

6.2.9 The detector QE must be $\geq 40\%$ over the wavelength range of the *g* filter. (TBR)

6.2.10 The detector QE must be $\geq 60\%$ over the wavelength range of the *r* filter. (TBR)

6.2.11 The detector QE must be $\geq 75\%$ over the wavelength range of the *i* filter. (TBR)

6.2.12 The detector QE must be $\geq 40\%$ over the wavelength range of the *z* filter. (TBR)

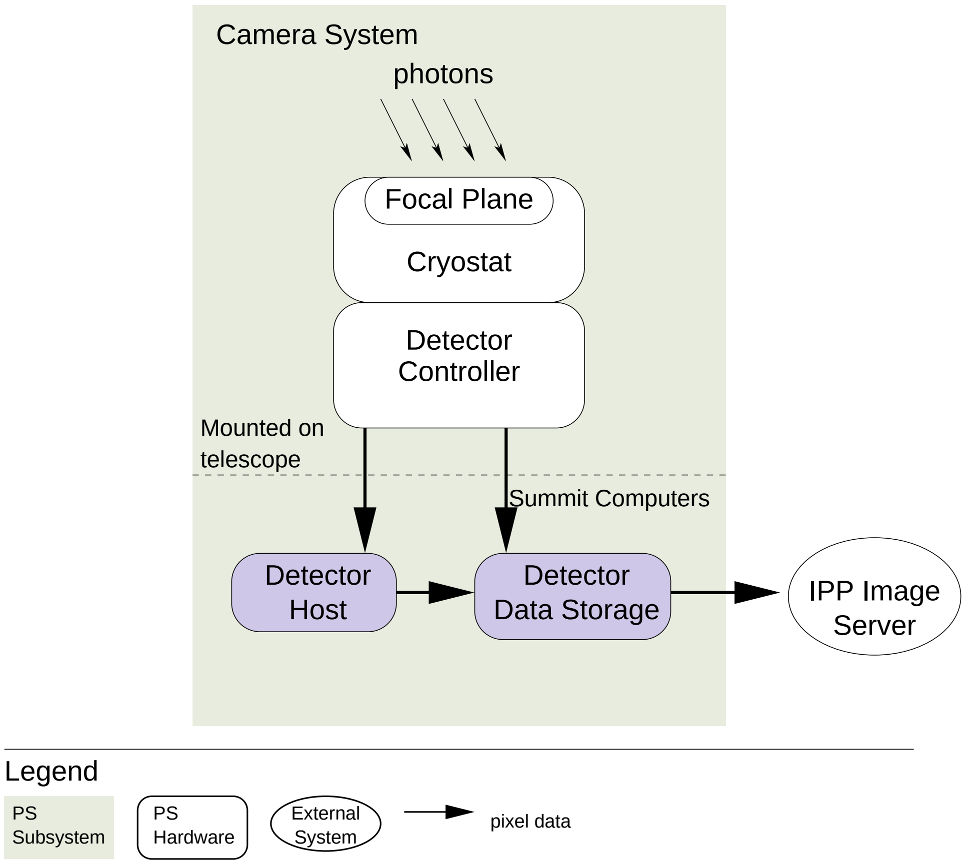

Figure 11: Camera Subsystem

6.2.13 The detector QE must be $\geq 10\%$ from the short wavelength edge to at least $1\,\mu\mathrm{m}$ on the long wavelength end of the *y* filter.[8] (TBR)

6.2.14 The raw detector QE non-uniformity shall be less than 30% rms for flatfield images in all Pan-STARRS bandpasses.

6.2.15 The detector QE non-uniformity shall be less than 2% rms on sky images when flattened by the Pan-STARRS dome flat calibration system and after OH line fringe subtraction.[9]

6.2.16 The camera subsystem shall provide images that are linear to 1% over the full dynamic range.[10] (TBR)

6.3 Subsystem Top Level Description

In general terms, the camera subsystem consists of the following:

1. A focal plane array of CCDs that accumulate an image of photo-electrons in a 2-D array of potential wells with the capability to transfer the resulting charge packets sequentially to the CCD amplifiers (resulting in a set of analog video streams); it is anticipated that it will also be possible to rapidly shift the charge pattern during the exposure in order to compensate for high-frequency telescope jitter and to partially compensate for image motions induced by the atmospheric boundary layer,

2. A cryostat to provide the thermal environment required for efficient detector operation, and to house the focal plane and control logic,

3. A “CCD signal chain,” including detector controller to provide analog voltages for the operation of the CCD, and readout of the device with Analog-to-Digital Converters (ADC) which convert analog video signals to digitized data streams (rasterized images),

4. A “Detector Host” to assist in assembling full images, and coordinate any actions of which the individual detector controllers are not capable,

5. A detector data storage system to buffer the resulting rasterized images pending retrieval by the image processing pipeline (IPP),

Note that the shutter itself could be included in either the Telescope or Camera subsystems. In the Pan-STARRS conceptual design, the shutter is considered part of the Telescope subsystem with shutter control being managed by the Camera subsystem Detector Host.

The conceptual design that has been developed to meet the requirements for the focal plane array (FPA) is an 8-by-8 array of monolithic devices each of side approximately 5 cm. Unlike conventional devices, however, each of these will consist of an 8-by-8 array of smaller detector cells of approximately 500 (600) pixels on a side for 12 (10) micron pixels. For image processing reasons, all pixels with a device lie on a common grid.

Note that a major design driver for this “array of arrays” concept is yield. Conventional devices of this size have very low yields owing to the high frequency of shorts. With the present design these shorts will only affect a small fraction of the cells. These can be isolated, rendering most devices usable. High yield is required to deliver focal planes of the required area at acceptable cost. This design also ameliorates the effects of blooming from bright stars and traps, as these will only affect a single cell. An alternative, of course, would be to make a focal plane with several thousand small independent devices. However, that would have smaller fill fraction and would present a serious challenge for metrology to create a focal plane that meets the Pan-STARRS flatness requirement.

In this design, there is a switching network that makes it possible to clock the charge in the imaging region of any one cell in a column while leaving the other cells in a quiescent state collecting charge. The output of the amplifier for the active cell can also be selected. This design feature makes it possible to rapidly read out (a sub-array from) a single cell that contains a guide star.

At the end of the exposure, the columns of each array can be read out in parallel. As each column contains $\sim$ 2M pixels this allows read out of the entire array within the 2s read time goal using $\sim$ 1Mpix/s read rates. Read noise within the required level has been demonstrated at these speeds.

Another feature of the conceptual design is to use “Orthogonal Transfer” (OT) devices. These devices allow charge to be shifted in both vertical and horizontal direction within the imaging region. Together with the independent control of the cells within a column, this makes it possible to perform fast on-chip guiding, as has been demonstrated with the OPTIC camera on the UH88″ (see PSDC-700-003).

Finally, the camera subsystem may be required to accommodate wavefront sensors that provide pre- and post-focus images of stars. These will be used by the telescope subsystem for control of collimation, alignment and focus. The camera subsystem may also be required to accommodate pin-hole cameras that can sense scattering of light from the telescope support structure. The inclusion of these auxiliary sensors into the Camera subsystem, if required, will be specified in the Camera SSS.

6.4 Operational Considerations

6.4.1 Operational States and Modes

6.4.1.1 States

The GPC operational states are

1. Idle/Safe,
2. Setup (cooling, interfacing, possible calibration),
3. Ready,
4. Test,
5. Active/Busy,
6. Safe,
7. Shutdown.

6.4.1.2 Modes

The GPC operational modes are

1. Stare,
2. OT,
3. Calibrate.

The simplest operation mode of the focal plane is ‘stare mode’. In this mode the detector is erased prior to opening of the shutter (possibly at the end of the previous exposure) and the parallel clock lines held fixed. The shutter is then opened for the desired exposure time, closed, and then the charge pattern is read out in the standard manner (i.e. the charge pattern is clocked vertically, line by line, into the horizontal (serial) register, which is then clocked rapidly, transferring the charge to the on-chip amplifier. Some part of the focal plane containing relatively bright stars will be read out rapidly to provide the low frequency guide signal to the telescope control system.

An alternative, and more complicated mode of operation, is ‘orthogonal transfer’ (OT) mode. The goal of OT mode is to compensate for both high frequency telescope motions (or common mode motions from dome seeing) that cannot be guided out mechanically and also to provide partial compensation for boundary layer seeing (which will produce motions that are not completely coherent across the focal plane). In this mode, a large number (usually on the order of hundreds) of guide stars will be continuously monitored. A low-frequency common-mode guide signal will be extracted and fed to the telescope control system as in stare mode. In addition, a high temporal frequency (bandwidth on the order of tens of Hz), spatially varying guide signal will be computed in the detector host by spatial averaging. This signal will be fed back to the CCD controller and used to perform on-chip ‘fast guiding’ of the detector regions not being used for guide star sensing. A fringe frame constructed from reduced data that has been convolved with a guiding kernel is used for calibrating the camera OT mode.

6.4.2 Operational Scenarios

The command and data sequence envisioned for the GPC and Camera subsystem is shown in Figure 12 as an "observing loop sequence".

6.5 Conceptual Design

In this Section, the Camera Subsystem components listed in Section 6.3 are described in more detail.

6.5.1 Detectors

This section describes the conceptual design of the OTA devices to be tested with the first MIT Lincoln Laboratory mask set. Also included in this section are the guidelines for the biasing and clocking of the devices.

Figure 13 illustrates the device as consisting of a two-dimensional square array of individually controllable Orthogonal Transfer CCDs (OTCCDs), that are referred to here as "cells". The OTA comprises an 8×8 array of cells, each cell comprising roughly 500×500 pixels. Figure 13 also shows the convention for row and column numbering of the cells.

The currently adopted layout of the OTCCD pixels is shown in Figure 14. This has been tested in a 512×512 pixel frame-transfer imager known as a CCID-24, and represents a design evolution over earlier developmental layouts (used in CCID-28). The convention used to label the phases is also indicated in Figure 14.

Figure 15 illustrates the basic cell architecture. The four parallel clock lines to each cell are under the control of a logic cell next to each pixel array, and this enables control and clocking of the pixels of each cell independently of all other cells. This logic cell also gates the output amplifier for each cell. However, the serial clocks and the three gates (RG, OG, SW) associated with the readout circuit are applied in parallel to all OTA cells. As a result, the serial clocking cannot be selectively applied to some cells and not others.

Figure 16 shows details of the pixel array and serial register of each cell. Because the pixel array will be shifted in all directions during the science-image acquisition an overflow drain, or "scupper", is provided along the top and sides to prevent pile-up of charge. This drain is biased sufficiently high (typically +15 V) so that it acts as a charge sink and absorbs charge transferred past the boundaries of the array. Charge pileup can occur along the serial register edge of the array, and for this reason it may be desirable to clock this register continuously.

The serial registers are three phase with the last clocked gate being the summing well (SW) for binning. When the binning feature is not used, the serial phase-3 clock voltage can be applied to this gate. The serial register can be clocked bi-directionally, and during reverse clocking the charge will be sunk into the scupper diode at the right end. This allows clearing of the register by clocking in either direction. However, it must be pointed out that the design of phase-1 and –2 serial gates has been optimized for best transfer in the forward direction, that is, from phases 1 to 2 to 3. Transferring from phase 2 to 3 to 1 involves longer paths for the electrons, as can be seen from the L-shape of the electrodes. We have not done computer simulations of the charge-transfer process for this direction, but it will clearly be a slower process than the forward transfer.

An open issue to be resolved through the design process is how well the reverse charge transfer works at the serial clock rate of 1 MHz. If incomplete charge transfer becomes a problem, it may be necessary to reduce the clock rate or provide for overclocking. Figure 17 and 15 give details of two OTA variants to be tested.

Figure 18 illustrates the output amplifier for each cell as well as the interconnections among all amplifiers within a column. The video return, RETn, is a substrate (actually, channel stop) connection next to the output amplifier, and is the ground

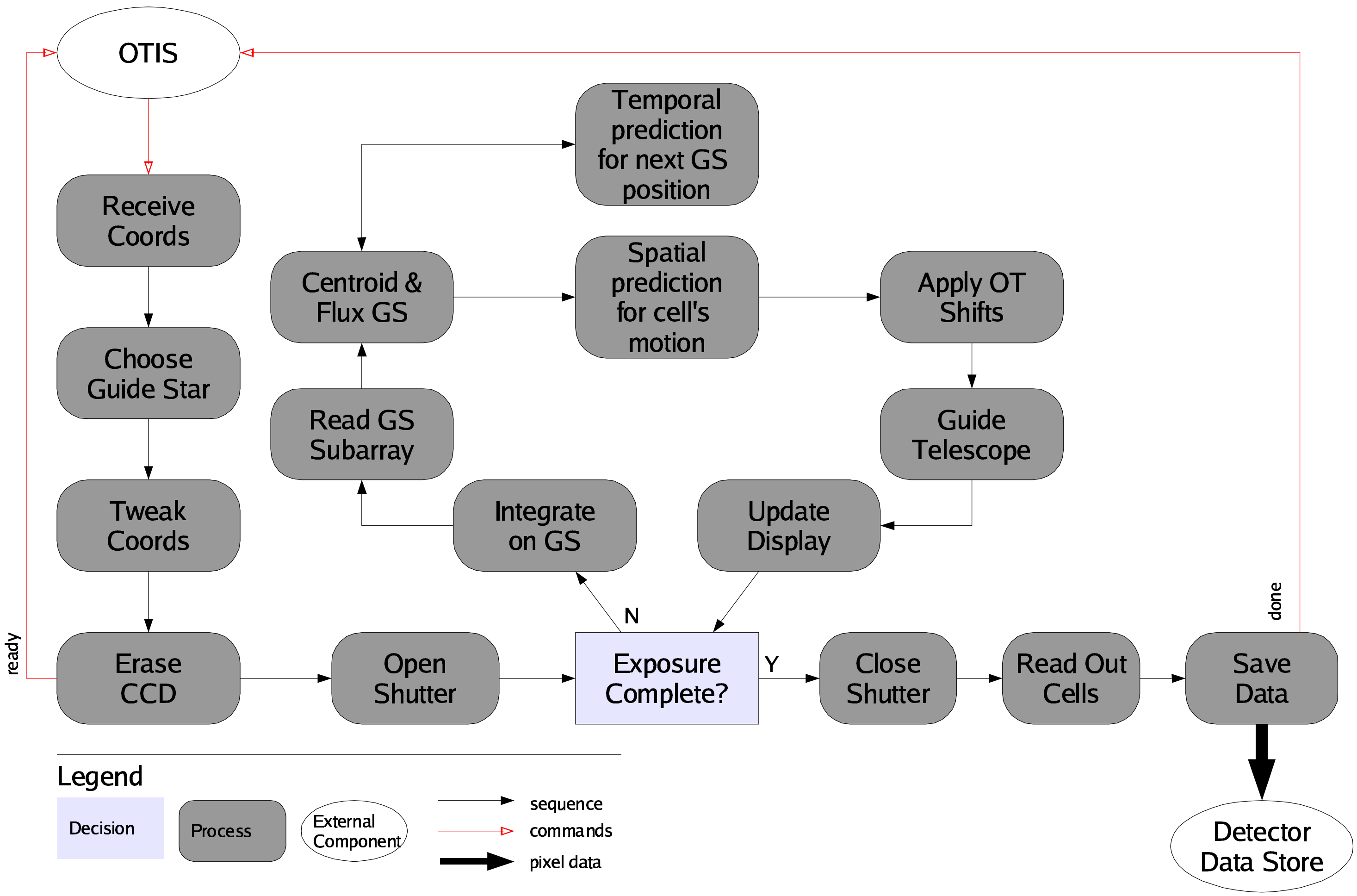

Figure 12: Camera observing loop sequence.

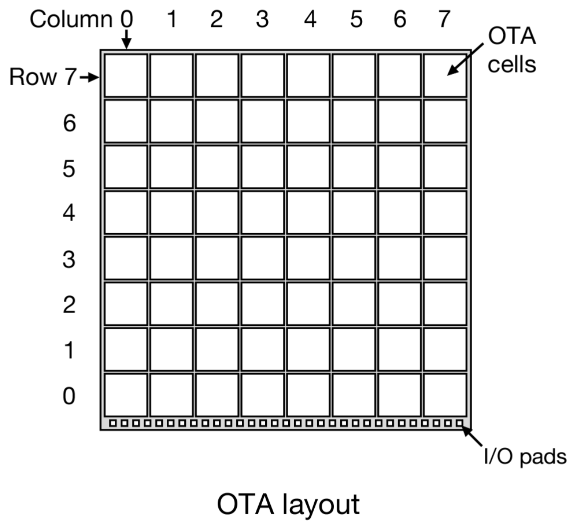

Figure 13: OTA layout overview.

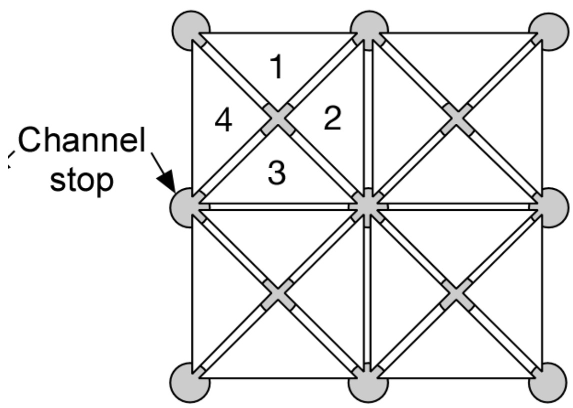

Figure 14: OTCCD layout and phase convention.

reference for the amplifier. The signal Z2 (described in more detail below) is a logic level that turns off the current through the second-stage source follower when the amplifier is not needed to read out a signal. Note that under normal circumstances only one amplifier per column would be active at any one time since all video outputs in a column share a common video output buss OUTn.

The usual practice in analog circuits is to tie the source of the first-stage current source SOn to RETn. However, previous experience has shown that in the presence of substrate bounce arising from clock coupling, the source of this transistor can inject electrons into the substrate. This injection will appear to be amplifier glow, since the injected electrons can diffuse long distances in high-quality silicon and be collected in nearby pixels. To prevent this, the source should be biased a volt or so above substrate. Also, biasing this current source allows some limited tuning of the first-stage current for optimizing operation. The second stage is intended to be operated in the source-follower mode, and therefore the output line OUTn will need to have a resistor or current source to ground or RETn.

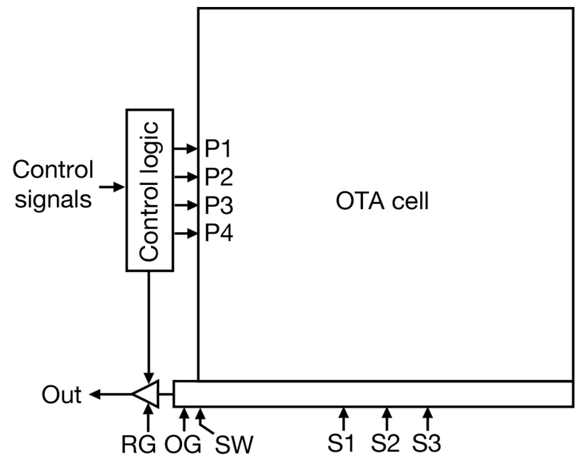

Figure 15: Illustration of basic control functions for each OTA cell.

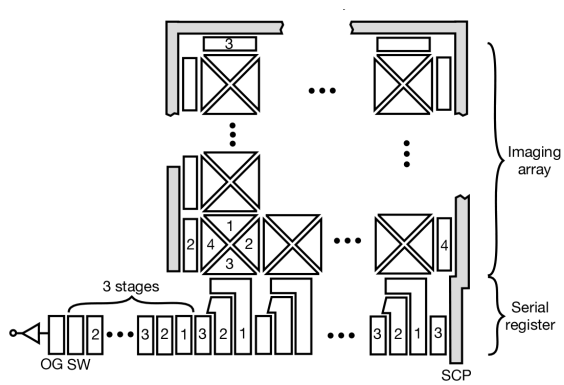

Figure 16: Details of cell gate layouts for the OTAs.

6.5.1.1 OTA Control logic

Each OTA cell has an associated control-logic block situated on the left side of the cell, as depicted in Figures 19 and 20. Figure 21 illustrates the timing needed to latch the data bits D0 and D1. The inputs consist of row (R) and column (C) select lines (active low), and three control bits (D0, D1 and D2). The output lines Z0, Z1, and Z2 to go pass transistors (switches) which function as follows:

- Z0-high connects the parallel gates to the standby levels,
- Z1-high connects the parallel gates to the active video clocks,
- Z2-high connects the cell video output to the video output (column) line,

D0 is used to disable faulty cells. If a cell is deemed bad, then D0 is set high and R and C are selected to latch D0=1 at initialization. For all functioning cells one must keep D0=0 when the cells are selected. If D0=1 has been latched, all Z outputs are set to zero, so that the parallel clocks for that cell are floating and the video output is disabled. D1 determines whether the cell is in the Standby or Active state. If D1=1 is latched by selecting R and C, then that cell will be in Standby

Table 15: OTA properties for two prototype designs.

Device	Pixel Size	Pix/Row	Pix/Col	VS	HS	TB	BB	LB	RB	DD
OTA-b	12	480	496	336.0	108.0	258.0	870.0	689.0	379.0	49,500
OTA-d	10	574	594	350.0	110.0	342.0	868.0	730.0	400.0	49,500

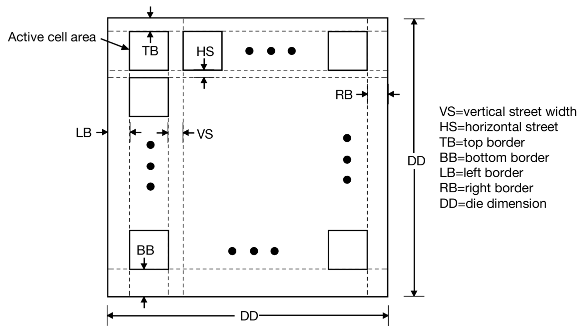

Figure 17: Definition of street widths for the OTAs.

mode. Latching D1=0 sets the cell to Active mode for either guide-star readout, science-cell tracking update or science-cell readout. D2 controls whether the video is enabled for cells in the Active state. This value is not latched so must be asserted whenever readout is performed. As mentioned, one would normally have at most only one video output active in each column. There is the potential for damage to the second stage of the output amplifiers if more than one Z2 is on at any time, so appropriate precautions should be taken to avoid this condition.

6.5.1.2 Parallel clock control

The parallel clock voltages applied to each cell are set by four active clock levels, P1A – P4A, and two standby voltages, PSH and PSL, all from off-chip circuitry. These lines are indicated in Figure 19 in red and blue. The active lines are to be driven from clocked sources and are used to shift the charge pattern in each cell, while the standby lines are dc biases that are applied to the clocks when they are holding charge but not actively being clocked. These levels are applied to the four parallel phases of each cell through eight pass transistors. In the floating state all eight pass transistors are in the off state, and the CCD gates will drop toward a bias that is near zero. (The actual biases will depend on the off-state leakage of the pass transistors and any resistive paths to substrate.) The intent is to prevent gates with serious shorts from heavily loading the six clock-level lines and also to minimize any charge injection that might bloom to neighboring cells. In the standby state (Z0=1) the PSH level is applied to phases 1 and 2 and PSL is applied to phases 3 and 4 (charge is stored under 1 and 2). When the logic cell sets Z1=1, the clock drive lines P1A – P4A are passed to the four parallel cell phases P1 – P4, and the charge can be shifted. It is important to recognize that, at the completion of a parallel-shift sequence, P1A and P2A should be high and P3A and P4A low to ensure a correct handoff to the standby levels. Conversely, these levels must also be applied to P1A – P4A at the standby-to-active transition.

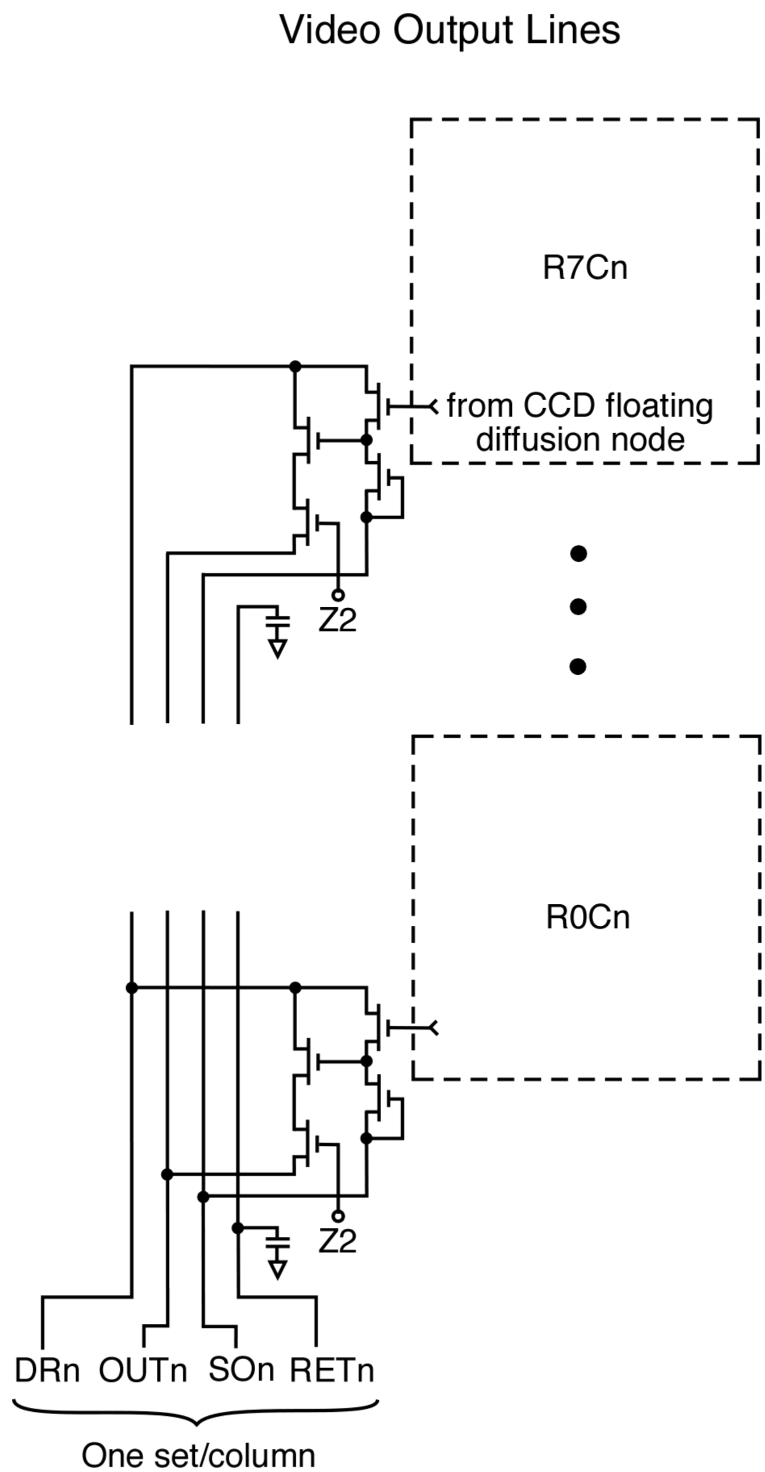

Figure 18: Readout amplifier configuration.

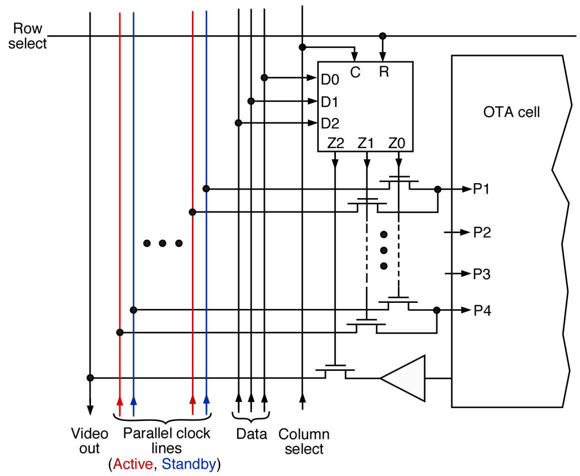

Figure 19: OTA cell addressing and control scheme.

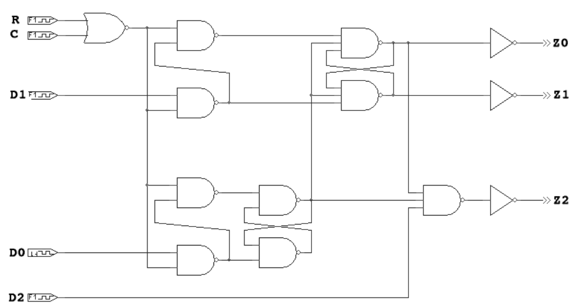

Figure 20: OTA control logic-block circuit design.

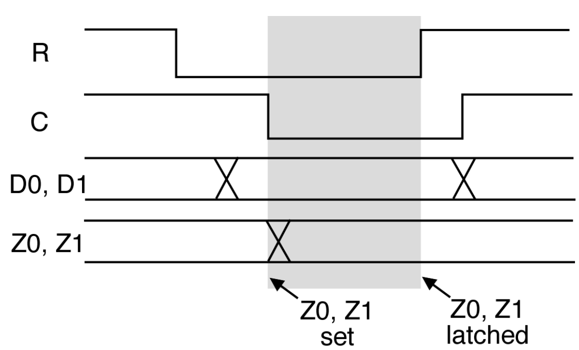

Figure 21: Timing for latching the control bits D0 and D1.

6.5.1.3 Biasing considerations

6.5.1.4 Independent substrate bias

One of the design experiments on the first OTA lot deals with a method of electrically decoupling the device substrate (SUB) from the channel stops at the chip surface (GND and RETn). This enables biasing the substrate to a negative potential in order to ensure a fully depleted condition for a back-illuminated device and to enhance the vertical component of the depletion-layer E field. One result of this approach is that the channel stops surrounding the logic are electrically independent of the output-circuit and CCD channel stops. In this design split the logic ground is GND, while the output circuit and CCD channel stops are tied to the video RET lines. (In the standard or non-substrate-bias design the device chanstops are all interconnected, so that the GND and RET connections are resistively connected on the chip via the channel stops.)

If this approach is successful, then the parallel clock voltages, as well as the logic levels and power supplies, can all be translated downward relative to the CCD and output circuit. This is very attractive because it enables inverted clocking of the OTCCD and thus reduces dark current and enables clocked anti-blooming. However, for the designer of the drive circuitry it means that provision must be made for possible level translation of the drive logic as well as the parallel clock lines. The inversion voltage, that is, the gate voltage at which the CCD surface is inverted, is about -5 V, so one should expect that the level translation might as much as -7 V or so. We may be able to know in advance of the completion of lot 1 whether this is a real possibility, because two wafers are being processed as ‘look-ahead’ wafers with only the control logic on them. A copy of the logic cell on these wafers has the design requirements to demonstrate independent biasing of the logic ground from substrate. We expect these wafers to be available some time in early March. Biasing guidelines for this case are included below.

6.5.1.5 Biasing guidelines for logic

When the SUB is not biased it can be tied to the GND and set to 0 V or the electrical ground of the electronics. The Desirable range values are intended to give a range of values that is useful for optimizing the device operation and for debugging. To avoid exceeding the absolute values it would be prudent to put some limit, perhaps in the software, to prevent such voltages from being applied. The nominal logic levels for the row and column select lines, RSELn and COLn, and the data lines D0-D2 are 5-V CMOS, e.g. logic low 0.7 V and logic high 4.3 V. These are referenced to the chip ground or GND.

The on-chip logic requires two power supplies, VDDH=12.0 V and VDDL=5.0 V. The higher voltage is needed to supply the gates that drive the pass transistors for clock and output video switching. Although VDDL is not likely to change, VDDH should be adjustable over a range of perhaps +8 to +15 V until we have experience with the logic and the clocking requirements of the device.

Normally the power supply VSS would be device ground or GND. However, there is, as in the case of the first-stage amplifier current source, the possibility of unwanted charge injection when any MOSFET source is at substrate potential. Therefore, the prudent approach for now is to actively power VSS. For the non-substrate-bias cases, this might be a range from 0 to +1.

6.5.1.6 Biasing guidelines for clock levels

The parallel clock voltages, both active (P1A, P2A, P3A, P4A) and standby (PSH, PSH), must pass through the NMOS logic and therefore cannot go below 0 V (unless the substrate-bias option proves successful). The serial clocks, on the other hand, are not constrained to be positive, since the serial clock pads connect directly to the gates and do not pass through any NMOS. Accordingly, it is recommend to allow them to swing below 0. This enables the output circuit to operate with reduced voltages.

6.5.1.7 Biasing guidelines for output-circuit biases

Estimated bias requirements and currents are given in PSDC-700-002-00. The dc level of the voltage on the OUT lines will be around +8 V. In the current package design this is applied to the gate of a U309 JFET, which, because of its negative pinch-off voltage, will have an output level one or two volts more positive. Thus, the dc level of the video signal from the JFET source coming off the package will be around +10 V. This line will need a resistor or current-source load to ground or possibly a negative bias, since it presumably will be operated as a source follower. The estimated DR current of 30 mA is for the on-chip FETs only.

6.5.1.8 Other biases

The SCP bias needs only a very modest current level. It would be a good idea to have a current limit of no more than 100 μA on this line because it biases a very large area on the chip, and an isolated device defect might lead, at some bias, to an abruptly large current that could destroy the device.

6.5.1.9 Substrate-bias case

The bias values that are to be changed when a substrate bias is applied are given in PSDC-700-002-00. All other biases are not affected. In this case both SUB and GND may be biased. As in the case of the SCP, the SUB and GND biases should have a current limit to prevent catastrophic failure. This is especially important for this case because the currents can increase very rapidly and abruptly. As mentioned earlier, the ground reference for the logic and pass transistors is called GND. Normally this is set to 0 V or system ground, but with a substrate bias present this terminal may be set below 0 volts. This in turn allows all the logic and parallel clock levels to be translated to levels as low as GND.

6.5.2 Additional considerations

6.5.2.1 Timing issues

The issue of settling time for the logic and clock levels can only be estimated at this point based on simulations during the design phase. The main uncertainty lies in the RC delays associated with the extensive on-chip wiring, since the capacitances can be difficult to estimate and the resistances will depend upon metal thicknesses that are chosen in the process. More precise values will be made after testing the first prototype devices. We attempted in the design to ensure that the parallel clocks could be driven at a minimum of a 100-kHz rate. This means that the overlap time for charge transfer between two phases can likely be 1/6 of 10 μs. For the logic-cell addressing and data writing we also estimate 10 μs should be sufficient for any level to settle within the on-chip circuitry. Also, when the output circuit is enabled, a period of 10 μs should be allowed before beginning a serial read to ensure that the pass transistor driven by Z2 is fully on.

6.5.2.2 Power sequencing

The sequence in which power and clock levels are applied to the device can be critical to avoiding permanent damage to the device. There are at least two definite requirements, but others may arise as the design process continues. The first requirement, which applies to Lincoln CCDs in general, is the power-up and power-down sequence for the output circuit. The first-stage MOSFET in this circuit can only safely sustain a drain-source voltage up to about 8 V before degradation or destruction of the transistor. If the full drain bias DR is applied when the gate is near ground, the source will be at a low bias and the 8-V limit may be exceeded. To avoid this, it is recommended that RD be powered up so that the gate of this FET (and thus its source) is at its normal bias level (a volt or so above RD) prior to or at least coincident with the power-up of DR. Likewise, DR should be powered down prior to or coincident with the turn off of RD. The second requirement is that for devices capable of substrate bias, all devices biases must be applied before biasing the substrate. This is because the device depletion layer (which is set by biases on the SCP and any other junctions such as those of the FETs) must be fully formed before this bias can be applied without drawing excessive current. Likewise it must be the first bias to be turned off. The currently recommended power-up sequence for the case of no substrate bias is: VSS, VDDL, VDDH, SCP, RD (no particular order), followed by DR. The power-down sequence is to be done in the reverse order. The case of active substrate bias is more complicated and requires some experimentation on our part. The SUB bias should definitely be the last bias applied, but the open question at the moment is how the GND and logic power-supply biases are sequenced. As requirements definition proceeds, the requirements mentioned in this paragraph will be included in the Camera System/Subsystem Specification (SSS).

6.5.2.3 Pad layout

The OTA I/O consists of 99 pads placed on 440-μm centers. This leaves a pad-free zone between the outside pads and the corners of the chip to enable possible attachment to the package of a light shield which covers the pads, nearby on-chip metal wiring, and wire bonds. The MOTA I/O uses 57 pads. The mapping of its pads into the OTA package will be included in the Camera System/Subsystem Design Description (SSDD). With the exception of OG1 and OG2, the pad functions are mirror symmetric about the chip center line (pad 50) in order to enable front- and back-illuminated devices to use the same package and probe cards. Pad 1 is in the lower left corner of the device when viewed as in Figure 13.

6.5.3 Detector Packaging and Focal Plane Array

6.5.3.1 Packaging

The proposed package for the CCID45 OTA is derived from the other 4-edge-buttable package designs developed by members of the Pan-STARRS team. The CCID45 package consists of a TZM/molybdenum base, three Cu/W stud/pins with Cu/W shim-pads, and a multilayer ceramic pin-grid-array (PGA). The OTA die is bonded to the top of the TZM/molybdenum base. This material was chosen because it is a good thermal expansion match to the Si CCD die and its suitability has been verified on numerous successfully-packaged and cryogenically-cycled devices. The Cu/W stud/pins retain the Cu/W shim pads, and engage three holes provided in the focalplane mounting surface. Ideally, these three holes should consist of a precision hole, a slot and an oversized-hole, thus providing an optimally-constrained, quasi-kinematic mount for each OTA. An OTA is pulled down onto the mounting surface using nuts and belleville spring washers that attach to the threaded end of each stud/pin. Limited tuning of the height of the detector surface to account for variations in detector substrate thickness and epoxy bondlines can be achieved by removing, lapping, and re-installing the shim-pads. This tuning can be carried out on each packaged OTA to insure the detector surface is at the required height with respect to the mounting shim-pads before the SCA is ever installed into a focalplane. The cooling path to the detector is through the three shim-pads. Again, this design has been extensively modeled thermally and has been proven in practice.

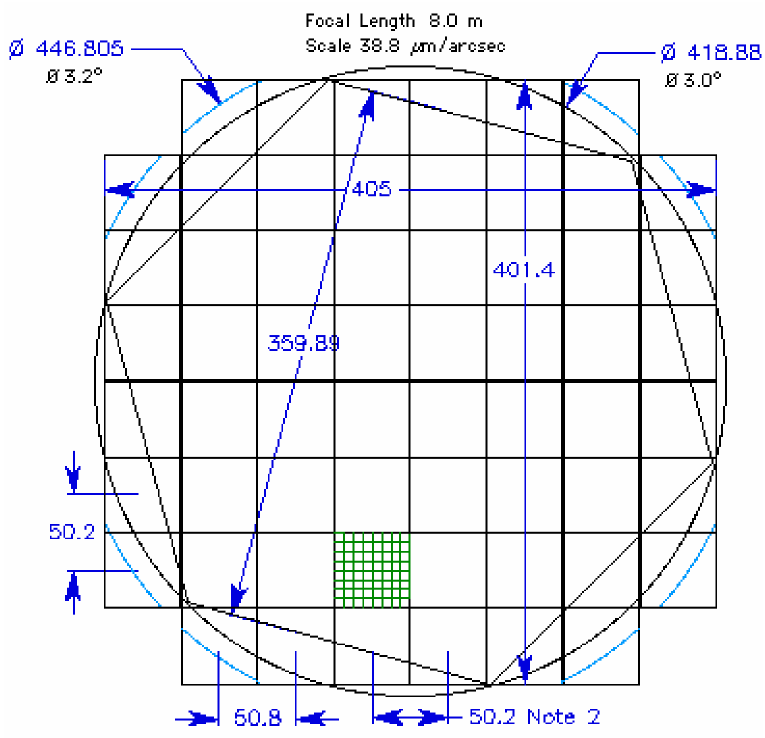

Figure 22: Focal plane mosaic layout.

Electrical connection to the OTA detector is made through the multilayer ceramic PGA. This ceramic circuit mounts in a cavity under the TZM/moly base. A small 1.5mm ledge protrudes from one edge of the package and the OTA is wirebonded to pads on the top of this ceramic ledge. Filled vias in the ceramic extend down through the ceramic ledge and connect to internal traces that route to the PGA pins on the back of the ceramic. Surface-mount filter capacitors, load resistors and JFET follower amplifiers are also mounted on the back surface of the ceramic. A flexcircuit consisting of a discrete-pin PGA socket and a high-density surface mount connector is used to connect to each SCA package.

6.5.3.2 OTA Mosaic Bar Subassembly Design Description

The proposed focal plane mosaic layout is shown in Figure 22. We have adopted a modular approach to tiling the Gigapixel Camera (GPC) focalplane with detectors. Rather than simply mounting the detectors on a common plate, we intend to build up the large GPC focalplane mosaic using discrete modules consisting of four OTAs arrayed side-by-side in a line on a 'bar.' The bars are then arrayed to form the two-dimensional mosaic focalplane. For example, 16 bars consisting of 8 rows of 2 bars mounted side-to-side will yield the desired 8×8 64 OTA focalplane

Each bar is made of TZM/molybdenum to insure a good thermal match to the OTA packages. TZM/moly is an excellent thermal conductor (comparable to aluminum), and a T-shaped cross-section is used to provide excellent mechanical stiffness and strength while minimizing the weight of the subassembly. The bars are supported by titanium rails that attach to the cryostat housing. A rigiflex PWB is suspended from each bar by mounting brackets. This PWB contains the connectors that mate to the connectors on the ends of the OTA flexcircuits.

6.5.3.3 Device installation and metrology

As described above, the height of the focal surface of each OTA is set using the shim-pads before the device is ever inserted into a bar subassembly. Using this technique on other large CCD mosaic focalplanes, we have readily achieved focal surface flatness of the individual devices of $\pm 5\mu$m and focal surface flatness of assembled focalplanes of $\pm 10\mu$m. Device metrology and bar subassembly metrology is carried out using a non-contact, long-working-distance microscope with a precise focus indicator that gives a surface height resolution of a fraction of a micron. Metrology of an assembled bar can also be carried out cold by using a long-working distance laser displacement sensor to look through a test cryostat window, so we can verify device alignment and bar and focalplane flatness at the desired operating temperature.

Installing devices into the bar subassembly is a simple and safe operation. The OTA packages are supplied with tooling holes for a handling and installation fixture. Long, tapered pins are attached to the threaded ends of two of the stud/pins and the device is simply lowered into place while holding it at its edge by the handling fixture. The tapered pins engage the precision hole and slot while the device is well above any of its neighbors; there is no possibility of crashing. The nut and spring washer is attached to the third leg, the tapered pins are removed, and then the other two nuts and spring washers are installed, thus locking down the device. Removal of a device is carried out by simply reversing the procedure. The device alignment is set by the machined-in locations of the stud/pin holes on the packages and the mounting holes on the bar.

6.5.4 Cryostat

The purpose of the Gigapixel Camera Cryostat is to house the mosaic focalplane, cool it to approximately 173K, and control that temperature to ± 1 K while maintaining the focalplane location, alignment and flatness to the required specifications.

The Gigapixel Cryostat consists of the following subsystems:

1. the focalplane mosaic structure,
2. the cryogenic cooling system,
3. the vacuum housing,
4. the temperature measurement and control subsystem,
5. the internal OTA interface PWBs and hermetic feedthroughs.

The focalplane mosaic will be constructed using a modular approach where four OTAs are mounted side-by-side on bars. The bars are then arrayed in a 2×8 arrangement to achieve the desired 8×8 OTA mosaic. The bars will be supported by a stiff titanium truss that is attached either to the inner wall of the body of the cryostat or to the back surface of the window plate. We intend to fully model the mechanical structure to insure the focalplane does not exceed any of its flatness or alignment specifications under a changing gravity load.

The focalplane will be cooled using a single-stage CTI Cryogenics 1050 closed-cycle cooler. A single 1050 cooler has more than enough capacity to cool the entire focalplane, but we will design the cryostat to use two coolers for redundancy and reliablity. We will endeavour to keep the length of the cryostat body as short as possible to minimize the weight of the instrument and to insure the camera can fit in the confined space between the telescope mirror cell and the fork. Each 4-OTA bar will be fitted with a temperature sensor and a kapton flexheater to measure and regulate the focalplane temperature.

A rigiflex PWB will be suspended vertically under each 4-OTA bar. The OTA flexcircuits mate to this PWB whose purpose is to route the OTA connections out of the cryostat to the controller electronics mounted to the sides of the cryostat. We will exploit our experience with flexcircuit-vacuum feedthroughs thus allowing us to maintain the matched trace length and preserve signal integrity from the detectors to the external electronics by avoiding the use of any intermediate hermetic connectors.

The cryostat will also be designed to the highest levels of vacuum cleanliness. All internal parts will be chemically cleaned and either nickel or gold plated. Vented fasteners will be used for all blind holes. Low outgassing materials will be used whenever possible. We expect to maintain a vacuum of 10^{-6} Toor or below during routine operation of the cryostat using activated charcoal getters mounted on the cryocoolers. We will investigate the use of the 2-stage CTI 1050 heads with the 2nd stage (operating at 20K) used exclusively for vacuum gettering.

6.5.5 Controller Electronics

The array controller will have the responsibility of receiving observing parameters and sequences, clocking driving the OTA mosaic, signal conditioning and digitizing the video output pixel values, providing data buffering and intermediate data storage of the data as well as data transport.

To accomplish the control and readout functions the 8 by 8 mosaic focal plane will be broken down into 1 by 4 OTA rigid-flex subassemblies (see figure). The rigid-flex assembly will penetrate the dewar wall and be connectorized for direct attachment to the controller.

Each of the 1 by 4 OTA rigid-flex subassemblies will be supported by a modular array controller subsystem that will coordinate and drive each OTA, preamplify and digitize the video outputs and export the data to a data aggregator.

The data acquisition portion of the subsystem controls the OTA drive, readout and processing of pixel data. Each OTA video output will have its own preamplifier and ADC (Analog to Digital Converter). The preamplifiers will provide gain, offset adjust and bandwidth limiting of the video signal. Once the pixel data is converted, noise reduction via Digital Correlated Multiple Sampling (DCMS) will be employed. The resulting data will be exported to data aggregation circuitry.

Field Programmable Gate Arrays (FPGAs) will be the basic digital control components used to provide the control communications interfaces, high speed data aggregation interfaces, CCD clock and ADC sequencing, DCMS and control of CCD bias and clock level signal generation from digital to analog converters (DACs).

The data aggregation circuitry will collect the pixel data from 4 data acquisition sources (16 OTAs), and handle the protocol overhead and high speed data transport over a fiber interface. The 1 gigabit per second Ethernet standard interface has been identified as the baseline standard for this interface.

The combined data acquisition, aggregation and transport subsystem will be replicated for each 1 by 4 OTA portion of the focal plane with each of the 1Gbps Ethernet interfaces attached to Ethernet switches. Through the switches, the Ethernet interfaces from the Detector Controllers connect to Detector Hosts which provide local data buffering and may perform further data post processing. Ethernet also provides a direct path to the summit Detector Data Store for pixel data which does not require further processing. Both of these systems are described next.

6.5.6 Detector Host

While the Detector controller is concerned mostly with pixels (clocking, sampling, and passing them on in a stream on the Ethernet) a Detector Host is concerned with whole images, and coordinating exposure sequences. Ideally, detector hosting functions are only concerned with the detector subsystem. Higher level sequencers must ensure that the Detector Host receives commands only when the telescope, filter, and other subsystems are properly configured. There are a couple of exceptions. Timing constraints on the precision of shutter events necessitate a tight coupling with the shutter subsystem. Fast guiding loops also require interaction between the detector host and the telescope guiding.

Due to the flexible and powerful design of the Detector Controllers, some "Detector Hosting" tasks could actually be performed locally by the Pan-STARRS array controllers. In general, however, a Detector Host performs coordination tasks which the controller can not or should not do. The Detector Host is tasked to coordinate:

1. commands and activities of the shutter
2. control and monitoring of the focal plane environment
3. the actions of a set of multiple detector controllers
4. the actions of other detector hosts, if a set of computers is being used for detector hosting

Tasks requiring high throughput or processing power may result in the need for 4.:

5. manage routing between the controller and detector data store
6. perform basic image processing such as bias subtraction and correction for non-linearity
7. manage guide star signals, and, in OT mode (see previous OT section), process these to generate fast-guiding signals.

In some cases routing pixel data to the detector data store may only involve instructing each controller unit where to deposit its pixel data. This is only possible if any/all Detector Host processing steps are performed on the controller itself. If they take place on a separate CPU, which is likely, then that Detector Host CPU will need to receive all data (via Ethernet, from the controller) process it, and feed it to the data storage computer (again, over Ethernet.)

6.5.7 Detector Data Store

The Detector Data Store is passive element to store per-exposure image data for the IPP. Collectively, this set of computers must have enough disk space to hold **N nights (TBD)** of observing data, enough incoming Ethernet bandwidth to receive **N MBytes/sec (TBD)** from the detector hosts, and enough outgoing bandwidth at the same time to off-load **N MBytes/sec (TBD)** from the summit.

In terms of active tasks, the only real function other than storage which is associated with the Data Store is that it must manage freeing data automatically when it is no longer used. The IPP is the main client of the Detector Data Store. However, the Data Store will support the concept of a generic client, which may register and deregister interest in subsets of data at will. Clients poll the Data Store periodically, or use information in the database as a signal that new images are available. When clients have registered interest in a data product, the data store will have created a reference copy (not taking any space, but indicating that the image has been requested but not yet collected by the client. When clients have successfully retrieved each image, they are responsible for removing the reference.

Detector Data Store auto-clean. At a periodic interval, the Detector Data Store will monitor available space and deallocate the oldest images which have no further references. In actual implementation, it is possible that the Detector Data Store will be an off-the-shelf network storage unit. In this case, the auto-clean function of the Data Store can be managed by a process running on one of the detector hosts, or the host running the observation sequencer, but it remains a task associated with managing the summit image data cache.

6.6 Summary of Derived Requirements

6.6.1 When mounted and integrated to the telescope structure at the rear of the Cassegrain Core, the camera shall fit within the allowed form factor envelope. **(TBD)**

6.6.2 As measured by the width of the PSF, the contribution of finite pixel size, σ^2_{pix}, to the detector resolution shall be less than $12\,\mu\mathrm{m}^2$.

6.6.3 As measured by the width of the PSF, The contribution of charge diffusion, σ^2_{CD}, to the detector resolution PSF shall be less than $25\,\mu\mathrm{m}^2$.

6.6.4 Guide star sampling shall occur at a rate $\geq$ 3 Hz but $\leq$ 30 Hz. **(TBR)**

6.6.5 OT shifting for fast guiding shall be possible at rates $\geq$ 10 Hz. **(TBR)**

6.6.6 The camera must be capable of fast guiding with a minimum of one star per OTA.

6.6.7 The Camera subsystem shall be capable of commanding the shutter to open and close to achieve an exposure timing accurate to $\leq$ 1 msec. **(TBR)**

6.6.8 The Camera subsystem shall be capable of reporting to OTIS the metadata associated with its shutter commands.

6.6.9 The filling factor of the camera focal plane array due to the area covered by non-operational pixels shall exceed 92%.

6.6.10 The filling factor of the camera focal plane array due to all factors except the area covered by non-operational pixels shall exceed 87%.

6.6.11 The dark current shall not exceed 1 e^- in a 60 second exposure. **(TBR)**

6.6.12 At least 1.5% of the focal plane must available to use for monitoring the motions of a small number of bright stars used as guide stars.[11]

6.6.13 The full well for a $12\,\mu$m pixel shall exceed $96,000e^-$ with the full well for smaller pixels exceeding $96,000e^-$ per $0.3''$ area on the detector.

6.6.14 The Detector Host computer shall allow both on-site and remote superuser access.

6.7 Internal Interfaces

6.8 Requirements Trace Matrix

Subsystem Requirements		System/Subsystem Requirements	
Number	**Caption**	**Number**	**Caption**
6.2.1	Camera to telescope mechanical interface	allocated	
6.2.2	Image size allocation to GPC	3.5.2	allocation within system image size budget
6.2.3	Minimum achievable readout time	4.7.18	Maximum required image throughput rate
6.2.4	Active detector area	3.5.1	required ´etendue
6.2.5	Focal plane array filling factor	3.2.2.2	Sky coverage rate
6.2.6	Maximum pixel size	3.5.6	Over-sampling shall be ≥ 2
6.2.7	Maximum read noise without RFI	3.5.4	required to meet Σ FOM
6.2.8	GPC dynamic range	4.7.20	required dynamic range in magnitudes
6.2.9	Detector QE for g filter	3.5.4	required to meet Σ FOM
6.2.10	Detector QE for r filter	3.5.4	required to meet Σ FOM
6.2.11	Detector QE for i filter	3.5.4	required to meet Σ FOM
6.2.12	Detector QE for z filter	3.5.4	required to meet Σ FOM
6.2.13	Detector QE for y filter	3.5.4	required to meet Σ FOM
6.2.14	Raw detector QE non-uniformity for flats	3.2.2.5	photometric precision of 0.01 mag
6.2.14		3.5.12	residual variance after image foregrounds removal
6.2.15	Detector QE non-uniformity on flattened sky images	3.2.2.5	photometric precision of 0.01 mag
6.2.15		3.5.12	residual variance after image foregrounds removal
6.2.16	Image linearity	3.2.2.5	photometric precision of 0.01 mag
6.2.16		3.5.12	residual variance after image foregrounds removal

Derived Subsystem Requirements		Top-level Subsystem Requirements	
Number	**Caption**	**Number**	**Caption**
6.6.1	Camera form factor	6.2.2	Camera-telescope mechanical interface
6.6.2	Contribution to image size budget from pixel size	6.2.2	Camera allocation to system image size budget
6.6.3	Contribution to image size budget from charge diffusion	6.2.2	Camera allocation to system image size budget
6.6.4	Guide star sampling rate	6.2.2	Camera allocation to system image size budget
6.6.5	OT shifting for fast guiding	6.2.2	Camera allocation to system image size budget
6.6.6	Minimum stars per OTA for guiding	6.2.2	Camera allocation to system image size budget
6.6.7	Shutter commands from camera to shutter	3.2.2.5	
6.6.8	Camera subsystem metadata passed to OTIS	3.2.2.11	System metadata needed to reconstruct PSF
6.6.9	Focal plane filling factor due to non-operational pixels	6.2.6	Camera filling factor
6.6.10	Focal plane filling factor due to gaps	6.2.6	Camera filling factor
6.6.11	Dark current contribution to read noise	6.2.8	Maximum allowed read noise
6.6.12	Focal plane area allocated for guide stars	allocated	
6.6.13	Full well for pixel sizes	6.2.9	Minimum allowable dynamic range
6.6.14	DHC remote access for superusers	4.7.21	Subsystem computers allow superuser remote access

Notes

[1]This is driven primarily by the need to control PSF anisotropy at device boundaries that would degrade the precision of weak lensing analysis.

[2]For $0.6''$ median natural seeing and the plate scale assumed above, this corresponds to 10% allowable degradation.

[3]This is driven by the requirement of the moving object program to take 30 second exposures in order to limit trailing

losses. The read time goal is 2 seconds.

[4]This is driven by the requirement for étendue.

[5]In addition to degradation of the faint point source detection efficiency, a very large pixel size would cause large variations in the astrometric precision. The preliminary devices developed from the conceptual design for manufacture and test have pixel sizes of 10 and 12 μm.

[6]This is driven by the requirement of the moving object program to take 30s exposures which, for the $f/4.4$ design, results in approximately $360(d_{\rm pix}/12\mu{\rm m})^2$ photo-electrons per pixel from the sky. The read noise goals are $4e^-$ (RMS) at 1 MHz and $2e^-$ (RMS) at 100 kHz.

[7]This is driven by the need for high precision astrometry of bright sources.

[8]The *y* filter currently is envisioned to extend on the long wavelength side from somewhere around 1028 to 1060 nm. However, after about 1000 nm, the QE drops exponentially, and it is not realistic to specify a minimum QE in this wavelength range related to the QE over the shorter wavelength part of the passband.

[9]This needs to result in color term variations between devices of no more than 10% in all passbands, and this is driven by the requirement for 1% photometric precision. It may not be possible to achieve this in the reddest passbands.

[10]This is driven by the photometric precision requirement.

[11]These positions will be filtered to provide a low frequency ($\simeq$ 1Hz) guide signal to the telescope control. (Derived requirement flowing from task to do guide stars so don't forget to include words in the Tasks and Functions section).

7 OTIS Conceptual Definition

7.1 Observatory, Telescope, and Instrument Software (OTIS) Overview

The Observatory, Telescope, and Instrument Software (OTIS) subsytem is a collection of hardware and software intended for autonomous[12] execution of the Pan-STARRS observing program as specified by the Science Goals Statement.

The primary goals of the OTIS systems are to enable the efficient scheduling of the observing program according to ephemerides, current and anticipated seeing and transparency conditions and calibration requirements, and to track and maintain the quality of the data and the performance of the instruments, telescopes, and observatory.

7.2 Top Level Requirements

7.2.1 System Level Requirements

The requirements in this section are from the top level system requirements (Section 3) and and top level System Operations Requirements (Section 4).

3.5.10 The system shall have the capability to determine the schedulable fraction of a specified science program.

3.2.2.1 The system shall be capable of timing observations to meet Science Requirements(SGS-4.2.1, SGS-4.2.2, SGS-4.2.6).

4.7.6 The system shall have the capability of staging the initialization and powering up of all summit systems from *OFF* to *READY* state without human intervention in **30 minutes (TBR)**.

4.7.7 The system shall be capable of remotely changing Observing Modes (Summit Interactive, Remote Interactive, Autonomous, Robotic).

4.7.21 The system shall allow remote superuser access to subsystem computers.

7.2.2 Subsystem Top Level Requirements

The OTIS mission is the construction and maintence of a collection of hardware and software capable of autonomously executing the Pan-STARRS observing program as specified by the Science Goals Statement. OTIS has the following requirements:

7.2.2.1 OTIS shall be capable of operating the observatory robotically.

7.2.2.2 OTIS shall enable an observing efficiency $e = (t_{exposure}/t_{clear}) \geq 65\%$ **(TBR)** averaged over a 1 year interval.

7.2.2.3 OTIS shall ensure the observation time devoted to each survey mode averaged over one year matches the goals of the total science program.

7.2.2.4 OTIS shall dynamically re-schedule observations with $\geq$ **95% (TBR)** completeness for any survey mode with a cadence specified as a number of nights between similar exposures and an allowable window in nights: $t_{cadence} \pm \Delta t_{cadence}$ nights.

7.2.2.5 OTIS shall be able to dynamically re-schedule observations with $\geq$ **95% (TBR)** completeness for any survey mode with a duration of $t_{Duration}$ number nights of $n_{Cadences}$ to within an allowable window: $n_{Cadences} \times t_{Cadence} = t_{Duration} \pm \Delta t_{Duration}$.

7.2.2.6 OTIS shall dynamically re-schedule observations with $\geq$ **95% (TBR)** completeness for any survey mode with a pairwise cadence such that at least one chronological pair of observations in a duration have a minimum and maximum separation: $t_{Min} < t_{n+1} - t_n < t_{Max}$ where t_{Min} and t_{Max} are integer numbers of nights.

7.2.2.7 OTIS shall dynamically re-schedule observations with $\geq$ **95% (TBR)** completeness for any survey mode requiring $N_{exposures}$ per night in any filter in order to reach a given depth per vistitation (night) sensitivity.

7.2.2.8 OTIS shall dynamically re-schedule observations with $\geq$ **95% (TBR)** completeness for all survey modes in pairs of exposures separated by a Transient Time Interval (TTI).[13]

7.2.2.9 OTIS shall dynamically re-schedule observations with $\geq$ **95% (TBR)** completeness for any survey mode/filter bandpass with maximum lunar illumination requirements.

7.2.2.10 OTIS shall be able to schedule a science program with m different kinds of survey modes, where $m \leq 7$.

7.2.2.11 OTIS shall ensure that all exposures required to be background limited ($\mathrm{Noise}_{\mathrm{sky}}$ **5 (TBR)** $\times\mathrm{Noise}_{\mathrm{read}}$) have sufficient integration time to meet this requirement.

7.2.2.12 OTIS shall re-schedule until sucessful completion calibration (dome and sky) observations sufficient to maintain an absolute photometric precision in the zeropoints of < 0.01 magnitudes rms across 3π steradians.

7.2.2.13 OTIS shall re-schedule until sucessful completion calibration (dome and sky) observations sufficient to maintain an absolute photometric precision in the zeropoints of < 0.01 magnitudes rms over the 10 year duration of the project.

7.2.2.14 OTIS computers must maintain time synchronization to better than **10 (TBR)** milliseconds.

7.2.2.15 OTIS shall control the telescope such that the contribution to the Image Budget from the telescope does not exceed a FWHM of 0.3″ for ($10\,\mathrm{deg} \leq \mathrm{zenith\ \ angle} \leq 70\,\mathrm{deg}$) in all filters.

7.2.2.16 OTIS shall re-schedule until sucessful completion enginneering time as required to verify, maintain, and track the performance of the telescope, instruments, and observatory.

7.2.2.17 OTIS shall verify, maintain, and track the mechanical and optical performance of the telescope, instruments, and observatory.

7.2.2.18 OTIS shall possess a computer security system to protect potentially vulnerable subsystems from malicious external actions.

7.3 OTIS Top Level Description

7.3.1 OTIS Subsystems

OTIS is conceived of as a modular set of independent subsystems as described below.

7.3.1.1 **OTIS Observation Tool (OOT).** The OTIS Observation Tool (OOT) is a stand-alone program capable of interactive or autonomous creation of an *Observe File*. The OOT takes either commissioning, engineering, or science mission goals to construct an *Observe File* for a given exposure or set of exposures, whether they be calibration, engineering, or science exposures. An *Observe File* contains a complete description of the required parameters of the exposure or set of exposures, including position, filter, exposure length, seeing reqirements, cadence requirements, sky background requirements, guide stars, and any scientifically linked Observe Files.

7.3.1.2 **Pan-STARRS Telescope Scheduler (PTS).** The Pan-STARRS Telescope Scheduler (PTS) is a program that selects, which observations are to be carried out at any given time on any given night and queues up the *Observe File* for that observeration for the Observation Sequencer (OBS). The PTS performs an optimization of the telescope schedule in terms of amount of time required to obtain science data while ensuring that all the requirements of the science programs are met. The program is expected to perform during any given night without human intervention.

7.3.1.3 **Observation Sequencer (OBS).** The Observation Sequencer (OBS) executes the *Observe File*. It sends commands to the Telescope Control System (TCS) and the Detector Host Computer (DHC) and receives acknowlegements and metadata from those systems that provide updates to the current status of the dome, telescope, and camera. The OBS passes all metadata from the TCS and DHC for logging to the OTIS Data Archive. OBS accepts emergency alerts from the Weather Server or human interface to abort an observation, stow the telescope, and close the dome.

7.3.1.4 **Telescope Control System (TCS).** The TCS controls all Dome and Telescope hardware and subsystems, (except the GPC and its shutter). It collects all of the dome and telescope metadata, and supplies it to the OBS.

7.3.1.5 **OTIS Weather Server and External Data Processor (OWS).** The OTIS Weather Server polls all the Pan-STARRS and all other available local meteorological stations for continuous monitoring of current weather status. If inclement conditions arise, the OWS sends an alert to the OBS to abort the exposure, stow the telescope and close the dome. If the weather clears, (e.g. humidity drops) then the OWS informs the OBS that it can restart observations. The the OWS also polls available forcast models. This information is processed for use by the PTS for short term scheduling. The OWS also gathers all other relevant external sources of data, e.g. DIMM instrumentation, Concam images, All-Sky IR Camera images, from internal/external sources and carries out any necessary processing for input to the PTS and the OTIS Data Archive.

7.3.1.6 **OTIS Data Archive (ODA).** The OTIS Data Archive (ODA) is a data archive system that stores all telescope, dome, instrument, and environmental metadata relevant to the operation of Pan-STARRS. It will provide tools for standard analyses of the performance of all aspects of the Instruments, Telescopes, and Observatory.

7.3.2 OTIS Overview Diagram

The block diagram in Figure 23 illustrates how these subsystems are organized and how commands and metadata flow between them and external systems.

7.3.3 OTIS Data Products

The OTIS Data products consist of all metadata from the telescope, camera, and Weather Server, including an archive of all status changes and time-stamped commands and faults. All OTIS Data products are archived for a minimum of the lifetime of the project in the OTIS Data Archive. A subset of OTIS Data Products, specifically the metadata necessary for proper interpretation of the data, is passed on to the IPP and the MOPS, eventually published as metadata in the PSPS.

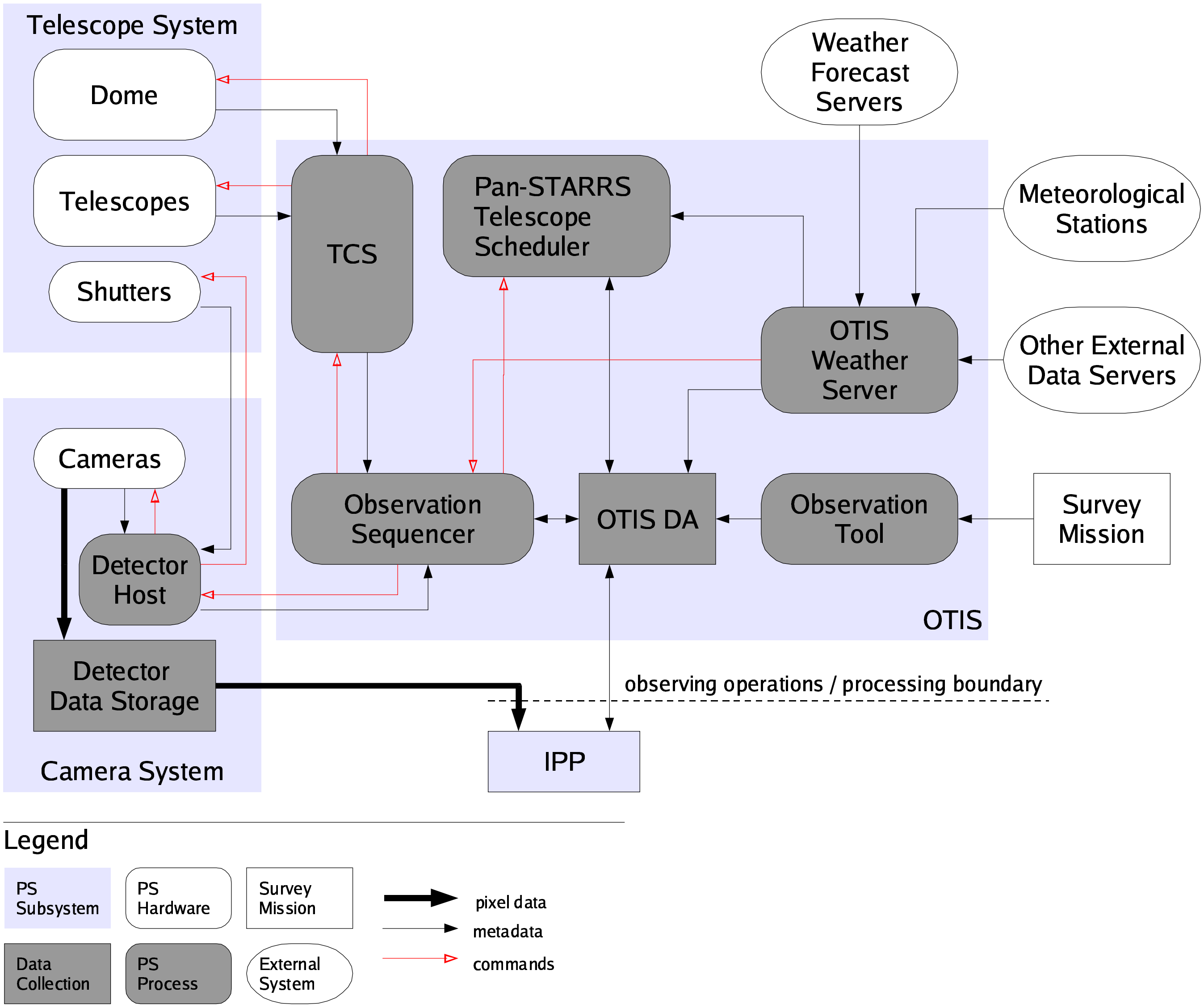

Figure 23: OTIS Operations and Dataflow

7.4 OTIS Tasks and Functions

7.4.1 OTIS Observation Tool (OOT) Tasks and Functions

The function of the Observation Tool is to create *Observe Files*. An *Observe File* contains a complete description of the required parameters to take an exposure or set of exposures. *Observe Files* are stored in the OTIS Data Archive.

7.4.2 Pan-STARRS Telescope Scheduler (PTS) Tasks and Functions

The task of the PTS is to schedule all science and calibration exposures required by the Science Goals and send them to the queue for execution by the OBS for execution.

Due to the fundamental nature of the scheduling problem, finding the schedule with the 'maximium' efficiency may not be practical, or even unique. However the task of the PTS includes performing an optimization of the schedule to find a schedule with a high observing efficiency, where the observing efficiency is defined as $e = t_{exposure}/t_{clear}$ where $t_{exposure}$ is the total exposure time on science targets and t_{clear} is the total clear time available, i.e. nighttime with acceptible transparency conditions.

The development of the algorithm or algorithms to do this is expected to be incremental and evolutionary.

With the above preamble in mind, the tasks of the PTS include:

7.4.2.1 The PTS will have an iterative optimization scheme to improve the observing efficiency of a science program.

7.4.2.2 The PTS will be capable of scheduling observations in *Right Ascension and Declination* (α, δ).

7.4.2.3 The PTS will be capable of scheduling observations in *Helio-Ecliptic Coordinates* (θ, β) which rotate with respect to *Ecliptic Coordinates* (λ, β), where the axis of rotation is along the ecliptic pole, and the rotation is such that the Sun is always at zero Helio-Ecliptic longitude θ and latitude β: $(\theta_\odot \equiv 0, \beta_\odot \equiv 0)$.

7.4.2.4 The PTS will computes position, airmass and visibility of target fields in the sky at any given time for both moving and non-moving objects.

7.4.2.5 The PTS calculates the RA and Dec position of the *Sweet Spots* for each lunation.

7.4.2.6 The PTS will determine the small-scale dithering pattern. [14]

7.4.2.7 The PTS will maintain epherides of the Sun, Moon, and other bright solar sytem objects.

7.4.2.8 The PTS will account for the changing sky background due to changing moon illumination and twilight.

7.4.2.9 The PTS maintains knowlege of diffuse emission in the Galactic plane (e.g. WMAP region).[15]

7.4.2.10 The PTS will account for the current configuration of the telescope. required action.

7.4.2.11 The PTS will produce a timeline giving each required action.

7.4.2.12 The PTS will produce an ordered list of the Observe Files that make up the schedule.

7.4.3 Observation Sequencer (OBS) Tasks and Functions

The tasks of the Observation Sequencer (OBS) include:

7.4.3.1 The OBS will be responsible for changing Operational Modes of OTIS (Summit Interactive, Remote Interactive, Autonomous, Robotic).

7.4.3.2 The OBS will be capable of commanding all commandable summit hardware (including telescope and dome through the TCS).

7.4.3.3 The OBS will be capable of prioritizing processes.

7.4.3.4 Receive alerts from the Weather Server; upon onset of clear weather, open the dome and prepare for observing.

7.4.3.5 Execute an *Observe File* as scheduled by the PTS.

7.4.3.6 Receive real time telescope offset commands from the Detector Host computer and send them to the TCS.

7.4.3.7 Receive corrections for focus, alignment, and collimation from the Detector Host computer and send them to the TCS.

7.4.3.8 Receive primary mirror support corrections and send them on to the TCS.

7.4.3.9 Receive alerts from the Weather Server; upon the expectation of inclement weather, execute a shutdown sequence to stop observing, stow the telescope, and close the dome.

7.4.3.10 Continuously evaluates the *Queue* and decides when to insert changes in the wind screen (dome slit elevation).

7.4.3.11 Log all commands sent to the TCS and Detector Host Computer with the OTIS Data Archive.

7.4.3.12 Log all metadata and fault messages gathered from the TCS and Detector Host to the OTIS Data Archive.

7.4.3.13 Re-act to all fault messages by predesigned prescription.

7.4.4 Telescope Control System (TCS) Tasks and Functions

The tasks of the TCS include:

7.4.4.1 Command, control, and accept metadata from all Dome and Telescope hardware, sensors, and exposure related subsystems (except GPC and shutter).

7.4.4.2 Accept real time guiding offsets from OBS which receives them from the Detector Host Computer.

7.4.4.3 Accept real time alignment and collimation adjustments from OBS which receives them from the Detector Host Computer.

7.4.4.4 Calculate and apply pointing, tracking, focus, collimation, alignment, primary mirror support and rotator models as functions of azimuth and environmental data.

7.4.4.5 Command and control of the *Calibration Unit* (dome flat illumination system).

7.4.4.6 Pass all exposure and environmental related metadata to the OBS.

7.4.4.7 Pass all fault messages to the OBS.

7.4.4.8 Provide a system wide *GPS* Clock Time Server for telescope functions and time stamps of all commands, metadata, and faults.

7.4.4.9 The TCS will provide API's to the engineering interface capable of issuing low level device specific commands to all telescope and enclosure hardware.

7.4.4.10 The TCS will produce secondary mirror models with resolution sufficient to produce focus to the tolerences given in the Image Budget.

7.4.4.11 The TCS will produce secondary mirror models with resolution sufficient to produce alignment to the tolerences given in the Image Budget.

7.4.4.12 The TCS will produce secondary mirror models with resolution sufficient to produce collimation to the tolerences given in the Image Budget.

7.4.5 Weather Server and External Data Processor(OWS) Tasks and Functions

The tasks of the Weather Server and External Data Processor (OWS) include:

7.4.5.1 Polling all available nearby meteorological stations, including Pan-STARRS' own local met station, for continuous monitoring of current weather conditions.

7.4.5.2 Perform any processing of weather data, (e.g., calculating appropriate time averages for exposures.)

7.4.5.3 Immediately, upon determination of impending inclement weather, send alert to the OBS.

7.4.5.4 Upon determination of satisfactory weather conditions for observing, send notification to the OBS.

7.4.5.5 Polling available long and short term forecast models from the web and process the results of these models into probablites for use by the PTS.

7.4.5.6 Collects and processes data from all other external sources of data, e.g. DIMM instrumentation, Concam images, All Sky IR GPC images, transparency montiors, etc.

7.4.5.7 All weather data is logged and sent to the OTIS Data Archive.

7.4.5.8 All forcast results are logged and sent to the OTIS Data Archive.

7.4.6 OTIS Data Archive (ODA) Tasks and Functions

The function of the OTIS Data Archive (ODA) is to archive all telescope, dome, instrument, and environmental metadata relavent to the operation of Pan-STARRS. *Metadata* in this context represents all data which is not included in the pixel data itself. Metadata of several different classes is stored, including processed metadata:

- Observe Files from OOT.
- Time-stamped short and long term schedules from the PTS.
- Continuous metadata (e.g., external humidity, ccd camera temperature).

- Metadata by exposure number. (e.g. start time, stop time, average metadata calculated from continuous metadata).

The OTIS Data Archive also provides a set of standard tools and user interfaces with the following tasks:

- Current Status Tool which displays heirarchically the current Status of the instrument, telescope, and observatory.
- Forecast Status Tool which displays predicted conditions.
- Night Log Tool which produces a summary of each nights observations.
- Fault Log Tool which produces a summary of faults on a nightly basis.
- Exposure Accounting Tool which tracks the sucessful completion of *Observe Files* and tracks the status of each survey goal.
- Scheduling Efficiency Tool which evaluates the efficiency of the PTS an an analysis thereof.
- Forecast Effectiveness Tool which evaluates the accuracy and precision of forecast variables as inputs to the PTS.
- The ODA will be capable of priortizing processes.

7.5 OTIS Operational Scenarios

7.5.1 OTIS Operational Modes

There are four major Operational Modes for OTIS:

7.5.1.1 **Summit Interactive.** Night time operations with humans in the loop at summit.

7.5.1.2 **Remote Interactive.** Night time operations with humans in the loop remotely, but no one at summit.

7.5.1.3 **Autonomous.** No human intervention necessary for 3 consecutive days out of 7 days. Summit daytime support (4 consecutive days per week) includes supporting dome calibration observations as well as standard maintaince.

7.5.1.4 **Robotic.** No human intervention necessary. Summit daytime support of maintaince only and such support required no more than 4 consecutive days per week.

7.5.2 OTIS Observing Modes

There are five major observing modes for OTIS:

7.5.2.1 **Dome Calibration.** (Dome closed, Telescope pointing, but GPC active).

7.5.2.2 **Sky Calibration.** (Sky Flats)

7.5.2.3 **Special Calibration. (Telescope Aperture stopped down for bright Astrometric and Photometric Standards) (TBR)**

7.5.2.4 **Science Observation.**

7.5.2.5 **Engineering/Maintaince/Commissioning.**

7.5.3 OTIS States

OTIS has the following States:

7.5.3.1 **Off -** No power.

7.5.3.2 **Initialize -** Bring up properly when power is present.

7.5.3.3 **Ready -** All systems powered up and ready.

7.5.3.4 **Observing -** The telescope is up and running taking data on the sky. The enclosure and mirror covers are open.

7.5.3.5 **Calibrating -** The telescope is static, but in a specific location, and the calibration mechanism is deployed. The mirror covers are open, but the enclosure is not.

7.5.3.6 **Hibernating -** The telescope is up and running, but the mirror covers are closed and the enclosure is closed. This mode needs to be automatically triggered by bad weather conditions.

7.5.3.7 **Safe -** The telescope is shut down in a minimum power consumption state with the enclosure closed. The mirror covers are closed. Computers in the support space have been safely shut down. This mode needs to be automatically triggered by power outages.

7.5.3.8 **Servicing -** The telescope is quasi-static, moved only as required to allow removal of optics, mechanisms, or the camera. It is possible that telescope can only be moved manually in this mode. The enclosure is in a state which allows mirrors and instruments to be removed and worked on. Over-rides to the safety interlocks may be required in this mode, in which case a *Lock-out/Tag-out* system will be employed.

7.5.3.9 **Fault -** (FUBAR)

7.5.3.10 **Shutdown -** (Take system down to a safe and recoverable OFF state.)

See also Telescope States in section 5.

7.5.4 OTIS Operations

OTIS will dynamically schedule and obtain science and calibration exposures by commanding the Telescope, Enclosure and GPC as discussed above. To accomplish this efficiently, concurrent actions must be commandable, e.g. slew the telescope while changing the filter. Therefore we outline the concept of operations that OTIS will carry out is as follows, where each set of actions is concurrent.

- OTIS: OBSERVING
- OBS: Initialize

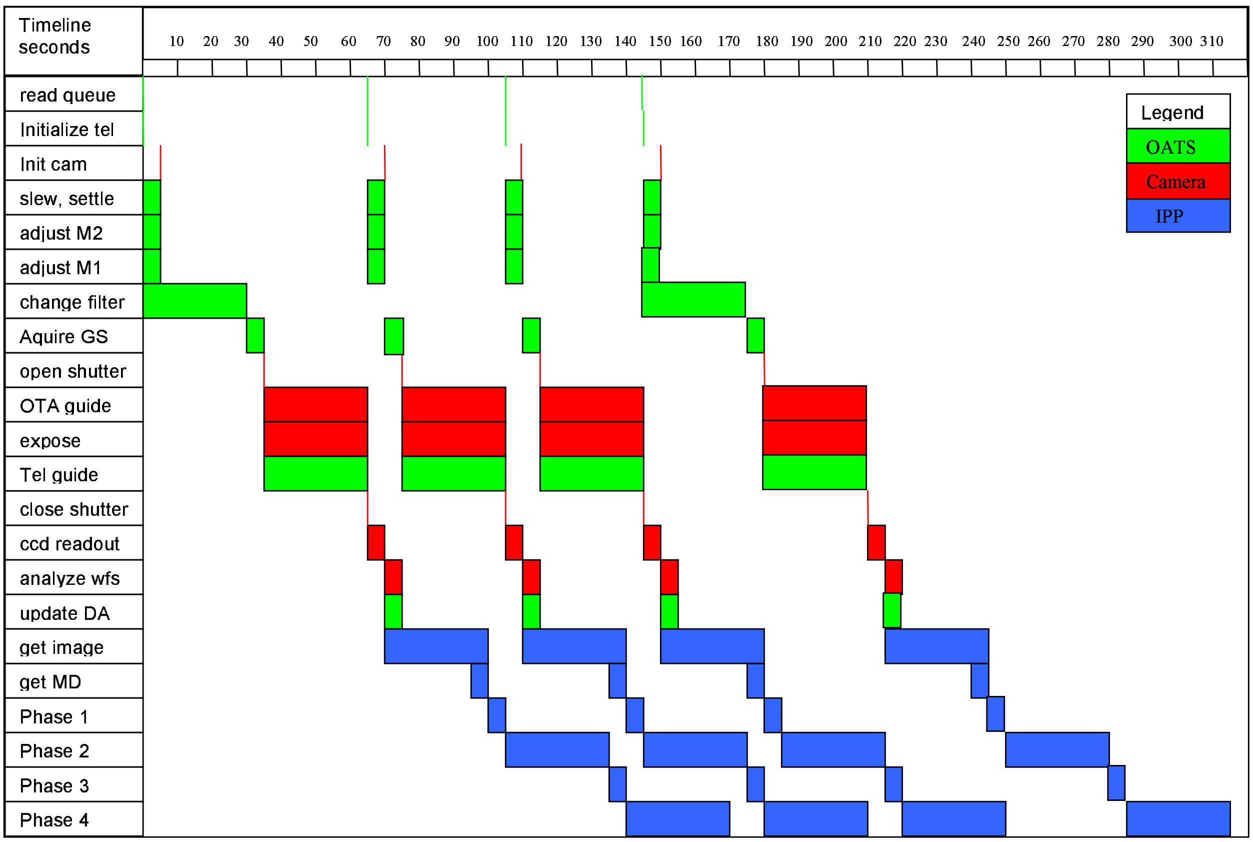

Figure 24: PanSTARRS Data acquistion and processing timeline

  - Telescope
  - Enclosure
- TCS
  - Slew
  - Adjust M1 for predicted position according to TCS model.
  - Adjust M2 for predicted position according to TCS model.
  - Change filter if necessary.
- TCS, OBS, DHC
  - Settle telescope
  - Initialize GPC (by way of DHC)
- TCS, OBS, DHC (if pointing model worse than **1 (TBR)** arcsec r.m.s.)
  - Short Exposure to Aquire Guide Star (Sequentially Open Shutter, Close Shutter, Read Guide OTA, Compute Telescope Offset, Offset Telescope, Initalize GPC).
- TCS, OBS, DHC (if pointing model better than **1 (TBR)** arcsec r.m.s., or if Guide Star has been acquired.)
  - Sequentially Open Shutter, Guide (TCS guide of common mode shifts, OTA guide of uncorrelated shifts) Close Shutter, Read out CCD.
- DHC, ODA
  - Analyze wave front sensor data, compute M2 adjustments.
  - Update OTIS Data Archive and DHC with metadata
- DHC, IPP
  - IPP get metadata from DHC
  - IPP get image data from Summit Data Collection.
- IPP Phase 1
- IPP Phase 2
- IPP Phase 3
- IPP Phase 4

While the data is being transported and processed, the telescope has moved on to the next field and begun taking the next exposure. See Figure 24 for a timeline with four sequential exposures and two filter changes.

7.6 OTIS Conceptual Design

7.6.1 OTIS System Architecture

The architecture of the OTIS system will be a *reflective meta-system*. The features of this include:

(i) The software can discover at initialization the functionality that exists within the system. This provides flexible software development that can be used across multiple or evolving hardware systems independently of the functionality within each subsystem. Clients can be written that will adapt, at initialization, to whatever functionality is discovered.

(ii) The architecture inherently supports run-time binding, in which new software and hardware can be added to the system without the system knowing anything in advance about the content of those components.

(iii) The architecture supports extension of the system software without requiring the original developers. Extension capabilities include user interfaces, hardware control, and functional behavior.

The tasks and functions of the OTIS subsystems as layed out above and shown in Figure 25 can be characterized by the architecture heirarchy as follows:

7.6.1.1 Application Layer

The *Application Layer* contains all of the upper-level functionality of the system including user interfaces, engineering interfaces for the camera, telescope, and enclosure, systems tools for the telescope, scripting engines (e.g. PTS and OOT) and external web resources, e.g., the weather server.

7.6.1.2 Device Abstraction Layer

Servers in the *Device Abstraction Layer* encapsulate hardware and/or software devices within the OTIS (and GPC) system. DML commands are recieved from clients and appropriate commands are issued to the underlying hardware. Devices implement stardard client/server interfaces. A basic *subscriber/publisher* design pattern is envisioned.

7.6.1.3 Hardware Abstraction Layer

Servers in the *Hardware Interface Abstraction Layer* encapsulate hardware interfaces that support multiple logical devices, e.g., generic digtial I/O, serial networks, and buses (such as Controller Area Network or CAN).

7.6.1.4 Subsystem Layer

These are the other Subsystems that are commanded by OTIS as *Abstraction Layers*, i.e. the Telescope Subsystem and the Camera Subsystem, and their associated hardware.

7.6.1.5 Control System Infrastructure Layer

Servers in the *Control System Infrastructure Layer* provide the underlying backbone of the necessary control systems for the telescope, enclosure, and other hardware systems. It provides such services as specific device logging, event-driven

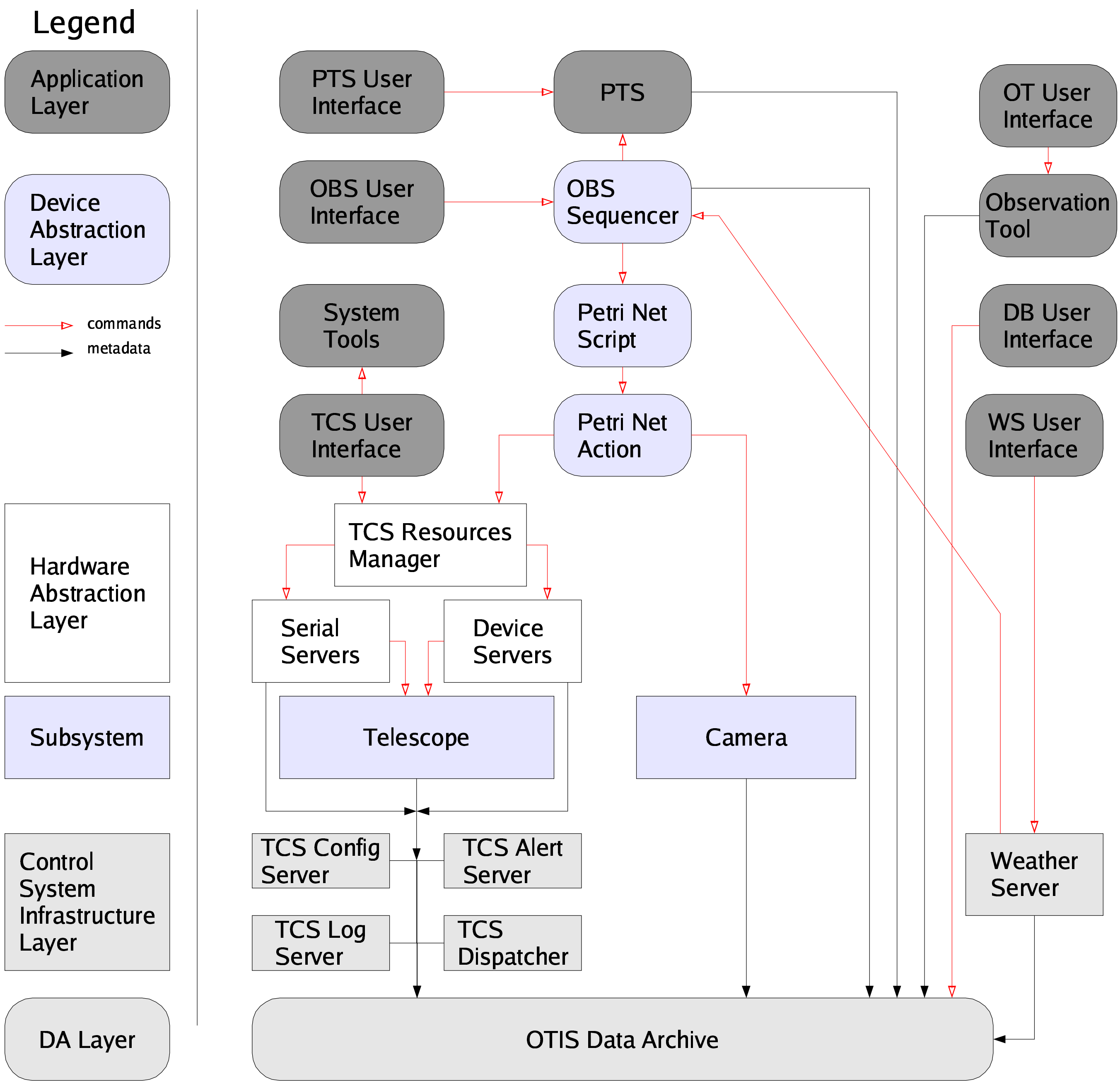

Figure 25: OTIS Architecture.
The OTIS system of Figure 1 is broken down into a heirarchy of (i) an Application Layer, (ii) a Device Abstraction Layer, (iii) a Hardware Abstraction Layer, (iv) a Control System Infrastructure Layer, and (v) a Data Archive Layer.

alerts, and system configuration.

7.6.1.6 Metadata Archive Layer

All commands, events, changes in configuration, and metadata are passed to the OTIS Data Archive for permanent archival storage.

7.6.2 OTIS Observation Tool (OOT) Conceptual Design

The OTIS Observation Tool (OOT) is a stand alone *Application Layer* program capable of interactive or autonomous creation of an *Observe File*. The OOT takes either commissioning, engineering, or science mission goals to construct an Observe File for a given exposure or set of exposures, whether they be calibration, engineering, or science exposures. An *Observe File* contains a complete description of the required parameters of the exposure or set of exposures, including position, filter, exposure length, seeing reqirements, cadence requirements, sky background requirements, guide stars, and any scientifically linked Observe Files.

OOT modules include:

- 7.6.2.1 Boresight Generator. This takes the reference mission field requirements and turns them into a set of boresight positions on the sky in Right Ascension and Declination (J2000).
- 7.6.2.2 Catalog Server. For each field-of-view, all possible guide stars are retrieved from the catalog server. Guide stars that fall between gaps are flaged and noted.
- 7.6.2.3 Digital Sky Server. For each boresight, an image of the sky as it appears in the focal plane is generated from the DSS.
- 7.6.2.4 Focal Plane Overlay. An overlay of the GPC mosiaic is generated to fit on the extracted DSS image.
- 7.6.2.5 OTA and Cell Image statistics. For the position of each OTA and cell within that OTA image statistics are generated from DSS images to determine presence of diffuse emission. If a problem is detected, boresight is flagged for interactive examination.
- 7.6.2.6 Guide Star Selector (GSS). From the list generated by the Catalog server, the GSS applies an algorithm to choose a set of guide stars and alternates.
- 7.6.2.7 Wavefront Sensor Star Selector (OWSSS). From the list generated by the Catalog server, the OWSSS applies an algorithm to choose a set of stars and alternates suitable for wavefront sensing.
- 7.6.2.8 Calibration sequence generator. This constructs a standard sequence of calibration exposures.
- 7.6.2.9 User Interface. The User interface will have a variety of tools to display the focal plane overlay, and interactively edit the position and choice of Guide Stars, and Wavefront Sensor Stars etc.

7.6.3 Pan-STARRS Telescope Scheduler (PTS) Conceptual Design

The Pan-STARRS Telescope Scheduler (PTS) is an *Application Layer* program that decides, in advance and in real time, by means of the various inputs decribed below, which observations are to be carried out on any given night and sends a time ordered list of Observe Files to the OBS queue. It continually runs, accessing updated forcasts and current conditions and re-schedules accordingly, providing an updated queue to the OBS. The PTS will be capable of performing without human intervention. The PTS must also perform an optimization of the telescope schedule in terms of amount of time required to obtain science data while ensuring that all the requirements of the science programs are met. Specific derived requirements for the PTS are given in the derived requirements section below. Here we outline the concept and design issues for the PTS.

7.6.3.1 PTS Overview

A telescope scheduler arranges telescope tasks in an efficient manner such that all important constraints are satisfied. These constraints include but are not limited to weather, seeing, calibration, hardware restrictions, and science priorities. Many large ground and space-based astronomical facilities schedule their observing using automated software because the problem phase space is far too large for a human operator to consider all the constraints.

The Science Advisory Committee has identified five modes of operation (or survey types) for Pan-STARRS as outlined in the SGS: (i) Solar System Mode, (ii)3π Mode, (iii) Medium-Deep Mode, (iv) Ultra-Deep Mode, and (v) Auxiliary Mode.

For each science goal, every filter will be assigned a Unit Exposure Time (UET) equal to the minimum time necessary to be background limited and/or satisfy trailing loss requirements. Note that since the background is variable accross the sky, the UET is not a fixed quantity. Except photometric and astrometric standard fields, most exposures in a filter in every survey mode will be obtained with the UET. To build deeper exposures subsequent UETs will be co-added. The time between the first two UETs in a filter on the same night will be chosen to identify and separate transient moving and stationary objects (the TTI). Subsequent UETs in this filter can be taken immediately following the second. This procedure will allow all survey modes to participate in Transient Object Detection of both stationary (supernovae, GRB, etc) and moving objects.

7.6.3.2 PTS Inputs

The inputs of the PTS will be different for each survey mode. Only the Medium-Deep Survey (MDS) and Ultra-Deep Survey (UDS) will have identified fields over the sky. The 3π aims at observing the whole sky accessible from the site to a required final depth, so that its input is likely to take the form of an exposure map of the whole sky. The SS survey input will likely be in the form of a co-rotating map of image locations with respect to opposition in order to find PHOs in the sweet spots.

These diverse inputs will have to be understood by the PTS. The PTS must: (i) accept as input an exposure or co-rotating map and the previous history of observations; (ii) understand various system coordinates used for inputs, e.g. equatorial or ecliptic or galactic or azimuthal or orbital elements (e.g. be able to compute the positions of the *Sweet Spots*); (iii) be able to derive Unit Exposure Times (UET); (iv) take into account the requirements of science programs, e.g., prioritization, cadence, duration, and point source sensitivity in a single visit.

7.6.3.3 PTS Optimization

Due to the fundamental nature of the scheduling problem, finding the schedule with the 'maximium' efficiency may not be practical, or even unique. However the task of the PTS includes performing an optimization of the schedule to find a schedule with a high efficiency.

Four major loops of optimizing the schedule are evident: (i) Very long term scheduling of the science program given a start date, and weather statistics (1 to 10 years). (ii) Long term scheduling of the science program given a reasonable long term weather forecast (7 days) and progress to date. (iii) Short term scheduling of science program given a short term forcast model (48 hours). (iv) Immediate re-scheduling using current conditions.

The development of the algorithms to do this is expected to be incremental and evolutionary. Two possible approaches include optimize using traveling salesman type algorithms, or optimizing using a look-ahead-at-every-move chess playing type algorithm. Testing with real weather data streams will be necessary to determine the most efficent algorithm or combination of algorithms.

7.6.3.4 PTS User Interface

The PTS must provide a user interface for human operators to graphically visualize the schedule and assess the performance of the PTS. For example, percentage of completion of various scientific programs with time, graphical view of the timeline, sky coverage, exposure map, etc..

7.6.4 Observation Sequencer (OBS) Conceptual Design

The Observation Sequencer is the task manager of OTIS. The OBS is a task manager that commands all hardware, including the camera, telescope, and observatory as *abstract devices*. as illustrated in the *device abstraction layer* of Figure 25 The OBS maintains the *Queue* of observations as scheduled by PTS, executes them, checks that each observation has executed properly, and proceeds to the next. When necessary it closes the observatory upon warning of inclement weather from the OWS, and then re-opens upon the onset of clear weather. OBS logs all commands, reponses, faults, and metadata to the OTIS Data Archive.

The OBS launches and monitors *Tasks*. Each task is a *Petri Net* that can launch a sequence of *Actions* which can be either sequential or and/or concurrent.

7.6.4.1 Concurrent Command Capability

The OBS must be capable of executing concurrent commands, e.g. slewing the telescope while changing the filter and secondary mirror position. In order to execute concurrent commands and obtain acknowlegment that all concurrent commands have successfully completed before executing a subsequent command, some formal structure to track concurrent commands and resolve faults and conflicts is required. This capablility is generically called a Petri Net, it does not impose a specific technique for this task management, but it does symbolically represent the requirement for issuing concurrent commands with conflict resolution. Since this capability is required at the conceptual design level, we know we will need Petri Nets or their operational equivalent in order to accomplish the Task management required by the OBS. A Petri Net is a form of script that is useful for describing concurrent, interacting processes. Figure 26 shows a representative Petri Net that symbolically represents the concurrent command capability required to move to a new target.

The rectangles in the Petri Net diagram in Figure 26 represent *actions* and the circles represent *signals*. *Actions* contain the actual functionality that can be executed by the Net. This functionality is a stand-alone executable module that is independent of any physical location.

In the much simplified example in Figure 26, the Net operates as follows: (i) Net begins at the ‘Start’ signal, (ii) Net executes action ‘initalize sequence for going to a new target’ (iii) when, and only when, that action has sucessfully completed, then (iv) the net simultaneously executes at least three actions: (a) Slew telescope and dome, (b) change filter

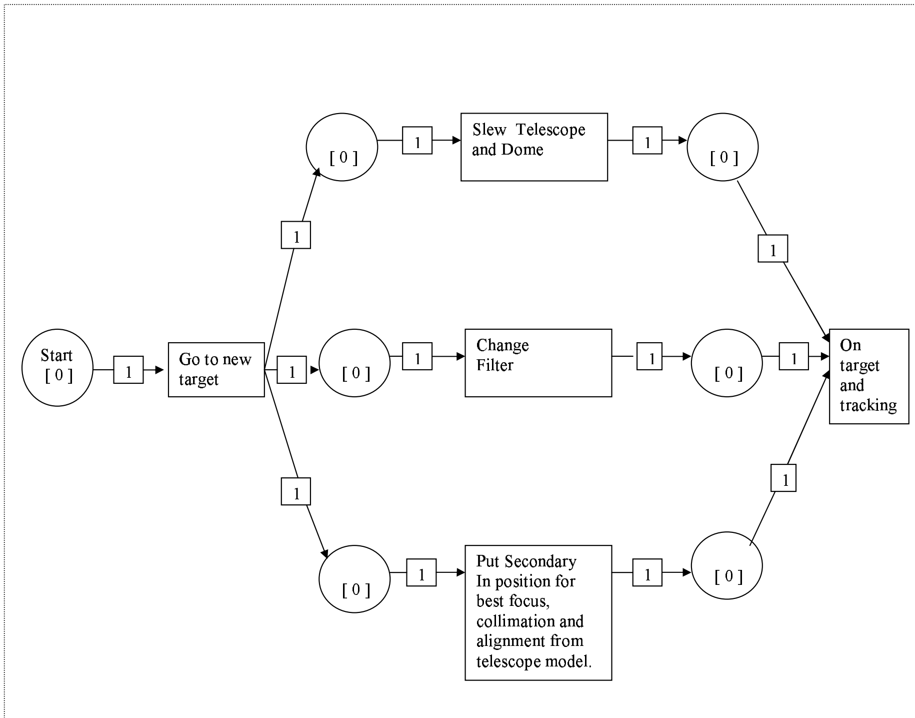

Figure 26: Petri Net Example

as required, (c) position secondary mirror to that expected for given conditions (temperature) and elevation angle. (v) Only when all of these have succesfully completed is the telescope ready for the next exposure.

Petri Nets allow developers to break a complex task (take an exposure) down into a sequence of small atomic actions and then specify, via the Petri Net script, how those actions interact with one another. The software within each of the actions is then simpler, and the overall behavior of the net can be modified at any later stage with out changing the software. Each action can actually be a Petri Net itself, with multiple parallel actions.

Whenever an action fails, there is then a predetermined procedure as to what to do and how to recover.

For most functions a basic *subscriber/publisher* design pattern is envisioned for communicating the signals. Whether this is fast enough for telescope guiding will be a design issue that may require for example, a dedicated and protected LAN for communications between the OBS, the TCS, and the DHC.

7.6.4.2 OBS User Interface

With the OBS User Interface, Petri Nets can be scripted textually or graphically. The OBS User Interface will graphically display Petri Nets undergoing execution.

The OBS User Interface will also enable direct editing of the Queue by an Operator/Observer.

7.6.5 Telescope Control System (TCS) Conceptual Design

The TCS has functionality at both the *Hardware Abstraction Layer* and the *Control System Infrastructure Layer*, and it accepts *actions* from the OBS at the Device Abstraction Layer. The TCS will be a *reflective meta-system*, meaning that at run-time the software is able to discover the functionality that exists within the system and adapt itself accordingly.

7.6.5.1 Device Meta Language (DML)

To facilitate the communication with telescope hardware some sort of meta-language will be required for communication between the TCS and the hardware serial server or device driver. We will refer to this as a *Device Meta Language* or DML. It is through this DML that we achieve the *Hardware Abstraction Layer* of the OTIS architecture.

DML is a C-like ASCII language that expresses *data structures* to a similar level of complexity as the C language. For serial servers or device drivers with idiosyncratic commands, a wrapper will be written around it so that all devices appear to communicate via a standard DML. All communication between devices and their clients will thus consists of DML structures transmitted across the appropriate transport protocol (e.g. TCP/IP, see Interface Section Below).

7.6.5.2 TCS Resource Manager

The TCS Resource Manger is the brain of the TCS and a device server that manages shared access to telescope and enclosure servers and resolves control conflicts. It accepts commands for *actions* from OBS. The TCS Resource Manager *subscribes* to all the servers and drivers under its command, and publishes the state of the telescope and observatory to the OBS.

7.6.5.3 TCS Device Servers

Device Server is the fundamental abstraction of a device in the system. In the TCS a *Device Server* usually encapsulates a hardware device e.g. dome azimuth drive servo, mirror covers etc. (See Section 5.) but may also be a software-only server. Basic types of Device Servers the TCS will require include: *(i) Dispatcher Server*, a specialized Device Server that provides a name resolution sevice to clients requesting a connection to a particular Device Server; *(ii) Log Server*, a specialized Device Server that handles logging across the distributed system; *(iii) Configuration Server*, a specialized Device Server that stores and distributes global configuration data across the distributed system; *(iv) Alert Server*, an asynchronous notification of an *event of interest* occuring somewhere in the system.

7.6.5.4 TCS Enginneering Interface

Engineering Interface is the term used to describe user interfaces that provide very low-level *engineering* access to system hardware. These interfaces are not designed to be used by high-level operators (e.g. for astronomical observations), but are intended for controlling and monitoring the hardware subsystems directly.

7.6.5.5 TCS System Tools

System Tools are stand alone applications for use in verifying, maintaining, and tracking the TCS performance, e.g., programs for the construction of models for conversion of *indicated values* to *true values* and sometimes to *apparent* *values*. These include (i) Pointing models that convert indicated altitude and azimuth to to true altitude and azimuth as a function of position and telescope structure temperature; (ii) Refraction models that convert true altitude and azimuth to to apparent RA and Dec in a given bandpass as a function of temperature, pressure and humidity; (iii) Focus, alignment, and collimation models that predict the proper position of the secondary as a funtion of elevation and temperature.

7.6.5.6 TCS User Interface

The TCS User Interface will include menu driven and command line interfaces for commanding all hardware under control of the TCS.

The TCS User Interface will also include graphical and alpha-numeric status displays of all instrument, telescope, and enclosure, hardware.

7.6.6 OTIS Weather Server and External Data Processor (OWS) Conceptual Design

The OTIS Weather Server and External Data Processor (OWS) will support both hardware device drivers (e.g. the Pan-STARRS Meteorlogical Station) as well as software-only servers, both internal and external to Pan-STARRS.

7.6.6.1 The OWS Resource Manager

The OWS will require a Resource Manager which is a device server that manages shared access to the OBS, the PTS, and the ODA, as well as external servers and resolves any control conflicts.

The OWS *subscribes* to all the relevent internal and external servers of meterological data, and it *publishes* the current and forecast weather conditions to its OTIS clients.

7.6.6.2 The OWS Device Servers

The basic types of Device Servers the OWS will require include: *(i) Dispatcher Server*, a specialized Device Server that provides a name resolution sevice to clients requesting a connection to a particular Device Server; *(ii) Log Server*, a specialized Device Server that handles logging across the distributed system; *(iii) Configuration Server*, a specialized Device Server that stores and distributes global configuration data across the distributed system; *(iv) Alert Server*, an asynchronous notification of an *event of interest* occuring somewhere in the system.

7.6.6.3 The OWS System Tools for External Data Processing

Data from both internal device drivers (e.g. IR All Sky GPC, Transparency Monitor) and external web resources sources (ConCam, DIMMS, Tau monitors, Weather Forcast Models) will in many cases require data reduction. For each such data stream there will be standalone System Tool which will process that data stream and put it in a format useful to the PTS and for storage in the ODA.

7.6.7 OTIS Data Archive (ODA) Conceptual Design

The various tasks and functions of the ODA are discussed above. These all imply that the OTIS Data Archive be capable of storing a wide variety of data types, for example: (i) time series of numerical data (temperature, humidity etc); (ii) images of various types (IR All sky camera, weather satellite images, web cam images, or more generically fits, jpeg, video), (iii) data files of various formats (XML, flat files, metadata).

The requirement that OTIS shall verify, maintain, and track the mechanical and optical performance of the telescope, instruments, and observatory suggests a relational database to organize the structure of the data archive with the realization that many objects in the database will be pointers to archival files which may themselves not necessary lend themself to specific inclusion in a relational database. The IPP also requires metadata on at least an exposure by exposure basis, and thus must be readily accesible as needed. The OTIS Data Archive will serve as the permanent archive of all ancillary data that is not included in the PSPS metadata, e.g. CCD camera temperature through out the day.

7.6.7.1 ODA System Tools

Metadata describing the environmental conditions at the telescope must also be stored and provided as needed.

The OTIS Data Archive also provides a set of standard tools and user interfaces with the following tasks:

7.6.7.1.1 Current Status Tool which displays heirarchically the current Status of the instrument, telescope, and observatory.

7.6.7.1.2 Forecast Status Tool which displays predicted conditions.

7.6.7.1.3 Night Log Tool which produces a summary of each nights observations.

7.6.7.1.4 Fault Log Tool which produces a summary of faults on a nightly basis.

7.6.7.1.5 Exposure Accounting Tool which tracks the sucessful completion of *Observe Files* and tracks the status of each survey goal.

7.6.7.1.6 Scheduling Efficiency Tool which evaluates the efficiency of the PTS an an analysis thereof.

7.6.7.1.7 Forecast Effectiveness Tool which evaluates the accuracy and precision of forecast variables as inputs to the PTS.

7.6.7.2 ODA User Interface

7.7 Summary of Derived Requirements

7.7.1 Derived System Requirements for OTIS

7.7.1.1 OTIS shall be configurable; i.e. designed with layers of abstraction such that incorporating evolving hardware subsystems and device drivers is modular and transparent to all other layers of software.

7.7.1.2 OTIS shall be capable of executing concurrent, interacting processes.

7.7.1.3 All OTIS entities must maintain time synchronization to better than **10 (TBR)** milliseconds.

7.7.1.4 All OTIS computers will support remote superuser login.

7.7.1.5 All OTIS computers will support status and error logging to the ODA using project standard message structure.

7.7.2 Derived Requirements for the OOT

7.7.2.1 The OOT shall extract representations of focal plane images from the Digital Sky Survey within **2 (TBR)** seconds.

7.7.2.2 The OOT shall construct a catalog of stellar and non-stellar objects in a given focal plane within **2 (TBR)** seconds.

7.7.3 Derived Requirements for the PTS

7.7.3.1 The PTS shall be capable of scheduling 5000 exposures a night.

7.7.3.2 PTS shall enable a surveying efficiency of $\geq 65\%$ **(TBR)** averaged over a 1 year interval.

7.7.3.3 PTS shall ensure the observation time devoted to each survey mode averaged over one year matches the goals of the total science program.

7.7.3.4 PTS shall dynamically re-schedule observations with $\geq$ **95 (TBR)** percent completeness for any survey mode with a cadence specified as a number of nights between similar exposures and an allowable window in nights: $t_{cadence} \pm \Delta t_{cadence}$ nights.

7.7.3.5 PTS shall be able to dynamically re-schedule observations with $\geq$ **95 (TBR)** percent completeness for any survey mode with a duration of $t_{Duration}$ number nights of $n_{Cadences}$ to within an allowable window: $n_{Cadences} \times t_{Cadence} = t_{Duration} \pm \Delta t_{Duration}$.

7.7.3.6 PTS shall dynamically re-schedule observations with $\geq$ **95 (TBR)** percent completeness for any survey mode with a pairwise cadence such that at least one chronological pair of observations in a duration have a minimum and maximum separation: $t_{Min} < t_{n+1} - t_n < t_{Max}$ where t_{Min} and t_{Max} are integer numbers of nights.

7.7.3.7 PTS shall dynamically re-schedule observations with $\geq$ **95 (TBR)** percent completeness for any survey mode requiring $N_{exposures}$ per night in any filter in order to reach a given depth per vistitation (night) sensitivity.

7.7.3.8 PTS shall dynamically re-schedule observations with $\geq$ **95 (TBR)** percent completeness for all survey modes in pairs of exposures separated by a Transient Time Interval (TTI).[16]

7.7.3.9 PTS shall dynamically re-schedule observations with $\geq$ **95 (TBR)** percent completeness for any survey mode/filter bandpass with maximum lunar illumination requirements.

7.7.3.10 PTS shall be able to schedule a science program with m different kinds of survey modes, where $m \leq 7$.

7.7.3.11 PTS shall ensure that all exposures required to be background limited ($\mathrm{Noise}_{\mathrm{sky}}$ **5 (TBR)** $\times \mathrm{Noise}_{\mathrm{read}}$) have sufficient integration time to meet this requirement.

7.7.3.12 PTS shall re-schedule until sucessful completion calibration (dome and sky) observations sufficient to maintain an absolute photometric precision in the zeropoints of < 0.01 magnitudes rms across 3π steradians.

7.7.3.13 PTS shall re-schedule until sucessful completion calibration (dome and sky) observations sufficient to maintain an absolute photometric precision in the zeropoints of < 0.01 magnitudes rms over the 10 year duration of the project.

7.7.3.14 The PTS long term scheduling must ensure that the final depth of the static sky image matches the requirements of the various science programs.

7.7.3.15 PTS shall produce a schedule for a minimum of the next TTI within one half of a TTI.

7.7.3.16 The PTS shall account for current seeing conditions in its short term programming to meet the requirements of the science program. [17]

7.7.3.17 The PTS shall account for current local atmospheric conditions.

7.7.3.18 The PTS shall account for current cloud coverage conditions. [18]

7.7.3.19 The PTS shall account for real time output of the transparency monitor (sky probe).

7.7.3.20 The PTS shall take into account the long term (1 week) site weather forecast.

7.7.3.21 The PTS shall take into account the near term (48 hour) site weather forecast.

7.7.3.22 The PTS shall take into account the short term (30 minute) site humidity forecast.

7.7.3.23 The PTS must take into account the required depth and astrometric accuracy of Science/Calibration programs in terms of exposure time and airmass.

7.7.3.24 The PTS shall schedule calibration and engineering images (biases, dome flats, twilight flats, etc.).

7.7.3.25 The PTS shall schedule observations of standard photometry fields.

7.7.3.26 The PTS shall account for the pointing and software limits of the telescope.

7.7.3.27 The PTS shall account for any area of the sky which is obscured by obstacles.

7.7.3.28 The PTS shall account for telescope slewing time.

7.7.3.29 The PTS shall account for telescope settling time.

7.7.3.30 The PTS shall account for change of wind screen (dome slit).

7.7.3.31 The PTS shall account for image rotation time.

7.7.3.32 The PTS shall account for ccd initialization time.

7.7.3.33 The PTS shall account for time to take guide star acquistion image if necessary.

7.7.3.34 The PTS shall account for exposure time.

7.7.3.35 The PTS shall account for CCD read time.

7.7.3.36 The PTS shall account for CCD write time.

7.7.3.37 The PTS shall account for filter/configuration change time.

7.7.3.38 The PTS shall account for the telescope and enclosure cable wrap and any required unwraping time.

7.7.3.39 The PTS shall account for the instrument rotator cable wrap and any required unwraping time.

7.7.3.40 If some operational configurations are not available (e.g. filter wheel stuck and only filter can be used), the scheduler must not command it, and shall account for the current configuration in the construction of a short term schedule.

7.7.3.41 The PTS shall provide tools for human operators to graphically visualize the schedule and assess the performance of the PTS.[19]

7.7.3.42 The PTS and its interfaces with the various input/output systems shall be testable with simulated or real time weather data streams.

7.7.3.43 The PTS shall be able to initialize and begin scheduling upon changing from Interactive Observing to Autonomous or Robotic Observing.

7.7.4 Derived Requirements for the OBS

7.7.4.1 The OBS shall be responsible for staging the initialization and powering up of all summit systems from *OFF* to *READY* state without human intervention in **30 minutes (TBR)**.

7.7.4.2 OBS shall be capable of safely stowing the telescope and enclosure upon onset of inclement weather.

7.7.4.3 OBS shall be capable of notifying designated personnel off-site in the event of a system emergency.

7.7.4.4 The OBS shall never delay telescope guiding offsets in favor of competing processes.

7.7.4.5 The OBS shall pass real time telescope guiding offsets from the DHC to TCS with a latency less than **10 (TBR)** milliseconds.

7.7.4.6 The OBS shall pass M2MC corrections from the DHC to TCS. with a latency less than **100 (TBR)** milliseconds.

7.7.5 Derived Requirements for the TCS

7.7.5.1 The TCS shall execute real time telescope guiding offsets from the OBS with a latency less than **10 (TBR)** milliseconds.

7.7.5.2 The TCS shall execute M2MC corrections from the OBS with a latency less than **100 (TBR)** milliseconds.

7.7.5.3 The TCS secondary mirror model shall achieve the tolerances necesary to produce the focus tolerances required in the Image Budget.

7.7.5.4 The TCS secondary mirror model shall achieve the tolerances necesary to produce the alignment tolerances required in the Image Budget.

7.7.5.5 The TCS secondary mirror model shall achieve the tolerances necesary to produce the colimation tolerances required in the Image Budget.

7.7.5.6 The TCS alt-az model shall achieve the tolerances necesary to produce the pointing accuracy required for guide star acquisition (rms $\leq 5''$).

Table 16: OTIS Subsystem to System Requirements Trace Matrix

Top Level Subsystem Requirements		System/Subsystem Requirements	
Number	**Caption**	**Number**	**Caption**
7.2.2.1	Robotic operations	3.2.2.15	Robotic operations
7.2.2.2	Observing efficiency	4.7.10	Observing efficiency
7.2.2.3	Match science program	3.5.10	Schedule science program
7.2.2.4	Schedule cadences	4.7.13	cadence time
7.2.2.5	Schedule duration	4.7.14	duration time
7.2.2.6	Schedule chronological pair	3.2.2.1	science time domain requirements
7.2.2.7	Schedule visitation	4.7.15	depth of visitation
7.2.2.8	Schedule TTI	4.7.12	observe in pairs of observations
7.2.2.9	Schedule sky brightness	4.7.21	sky brightness limits
7.2.2.10	Schedule ≤ 7 survey modes	allocated	
7.2.2.11	Background limited exposures	4.7.10	Observing efficiency
7.2.2.12	Spatial stability of calibration	3.2.2.5	photometric precision
7.2.2.13	Temporal stability of calibration	3.2.2.5	photometric precision
7.2.2.14	Synchronization	4.7.10	Observing efficiency
7.2.2.15	OTIS control maintains PSF	5.2.5	PSF has FWHM $\leq 0.3''$
7.2.2.16	Schedule Engineering	4.7.1	verify, maintain, track performance
7.2.2.17	verify, maintain, track performance	4.7.1	verify,maintain, track perfomance
7.2.2.18	computer security	4.7.20	computer security

7.7.6 Derived Requirements for the OWS

7.7.6.1 The OWS shall be capable of sending an alert within 10 seconds to OBS to safely stow the telescope and enclosure upon onset of inclement weather in

7.7.6.2 The OWS shall have access to external web servers.

7.7.6.3 The OWS shall reduce and analyze all available meteorological data and forecasts in less than **2 (TBR)** minutes.

7.7.7 Derived Requirements for the ODA

7.7.7.1 The ODA shall be capable of processing and logging all exposure related metadata in less than 2 seconds.

7.7.7.2 The ODA shall provide $\geq$ **1 (TBR)** Terabyte of hard disk space.

7.7.7.3 The ODA shall provide $\geq$ **1 (TBR)** Terabyte of mirror disk space.

7.7.7.4 All autonommous process shall not be delayed due to interactive or periodic querys.

7.8 Requirements Trace Matrices

7.9 OTIS Subsystem Interfaces

The OTIS subsystem as currently envisioned consists of five primary subsystems described above. These are composit hardware/software entities which are hosted at the summit observatory facility and themselves constitute the interface between the conceptual operational scenarios required to accomplish Pan-STARRS science goals and the telescope, facility,

Table 17: OTIS Derived Subsubsystem to Subsystem Requirements Trace Matrix

Derived Subsystem Requirements		Top Level Subsytem Requirements	
Number	**Caption**	**Number**	**Caption**
7.7.1.1	OTIS shall be configurable	allocated	
7.7.1.2	time synchronization	7.2.2.14	time synchronization
7.7.1.3	remote superuser login	4.7.21	remote superuser login
7.7.1.4	status and error logging	7.2.2.17	verify, maintain, track performance

Table 18: OTT Derived Subsubsystem to Subsystem Requirements Trace Matrix

Derived Subsubsystem Requirements - OOT		Top-level Subsytem Requirements	
Number	**Caption**	**Number**	**Caption**
7.7.2.1	extract DSS images	allocated	
7.7.2.2	extract Catalog objects	allocated	

and data processing systems which perform the observations. Internal and external interfaces between these modules are described in the following section.

7.9.1 Global Subsystem Interfaces

All OTIS subsystems will support certain project specified service interfaces to allow system-wide service implemetation. These will include:

7.9.1.1 Pan-STARRS Time Service: All entities will support access to the local Network Time Server using NTP over ethernet.

7.9.1.2 Supervisory Monitoring and Control:

7.9.1.2.1 All entities will support remote supervisory user access via network-connected workstation and project approved protocol.

7.9.1.2.2 All primary entities will support status and error logging to a central engineering database/data logging service (see ODA) using project standard message structure.

7.9.2 OTIS Observation Tool (OOT)

The Observation tool is a software entity intended to convert sets of mission requirements into the parameters of a specific set of observations that will accomplish the mission.

7.9.2.1 External OOT data interface: Communication with external entities will via a set of files containing the mission goal description. File keyword dictionary and contents are **(TBD)**.

7.9.2.2 OOT command/control interface: Under normal operational mode execution of the OOT process will be under system-level script control. Comand and data structures will conform to project standards. Human supervision will be performed via command line and/or Graphical User Interface (GUI) in interactive/engineering modes.

Table 19: PTS Derived Subsubsystem to Subsystem Requirements Trace Matrix

Derived Subsubsystem Requirements - PTS		Top-level Subsytem Requirements	
Number	**Caption**	**Number**	**Caption**
7.7.3.1	schedule 5000 exposures night	allocated	
7.7.3.2	observing efficiency	7.2.2.2	Observing efficiency
7.7.3.3	match science goals annually	7.2.2.3	Match science program
7.7.3.4	schedule cadence	7.2.2.4	Schedule cadences
7.7.3.5	schedule duration	7.2.2.5	Schedule duration
7.7.3.6	schedule chronological pair	7.2.2.6	Schedule chronological pair
7.7.3.7	schedule visitation	7.2.2.7	Schedule visitation
7.7.3.8	schedule TTI	7.2.2.8	Schedule TTI
7.7.3.9	schedule sky brightness	7.2.2.9	Schedule sky brightness
7.7.3.10	schedule survey modes	7.2.2.10	Schedule survey modes
7.7.3.11	sackground limited exposures	7.2.2.11	Background limited exposures
7.7.3.12	spatial stability of calibration	7.2.2.12	Spatial stability of calibration
7.7.3.13	temporal stability of calibration	7.2.2.13	Temporal stability of calibration
7.7.3.14	final depth of static sky	7.2.2.3	Match science program
7.7.3.15	schedule next TTI in min 1/2 TTI	7.2.2.2	Observing efficiency
7.7.3.16	current seeing	7.2.2.3	Match science program
		7.2.2.7	Schedule visitation
7.7.3.17	current local atmospheric conditions	7.2.2.2	Observing efficiency
7.7.3.18	current cloud cover	7.2.2.2	Observing efficiency
		7.2.2.3	Match science program
		7.2.2.4	Schedule cadences
		7.2.2.5	Schedule duration
		7.2.2.6	Schedule chronological pair
		7.2.2.7	Schedule visitation
		7.2.2.10	Schedule survey modes
		7.2.2.12	Spatial stability of calibration
		7.2.2.13	Temporal stability of calibration
7.7.3.19	transparency monitors	7.2.2.2	Observing efficiency
		7.2.2.3	Match science program
		7.2.2.4	Schedule cadences
		7.2.2.5	Schedule duration
		7.2.2.6	Schedule chronological pair
		7.2.2.7	Schedule visitation
		7.2.2.10	Schedule survey modes
		7.2.2.12	Spatial stability of calibration
		7.2.2.13	Temporal stability of calibration
7.7.3.20	1 week forcast	7.2.2.2	Observing efficiency
		7.2.2.3	Match science program
		7.2.2.4	Schedule cadences
		7.2.2.5	Schedule duration
		7.2.2.6	Schedule chronological pair
		7.2.2.7	Schedule visitation
		7.2.2.10	Schedule survey modes
		7.2.2.12	Spatial stability of calibration
		7.2.2.13	Temporal stability of calibration
7.7.3.21	48 hour forcast	7.2.2.2	Observing efficiency
		7.2.2.3	Match science program
		7.2.2.4	Schedule cadences
		7.2.2.5	Schedule duration
		7.2.2.6	Schedule chronological pair
		7.2.2.7	Schedule visitation
		7.2.2.10	Schedule survey modes
		7.2.2.12	Spatial stability of calibration
		7.2.2.13	Temporal stability of calibration

Table 20: PTS Derived Subsubsystem to Subsystem Requirements Trace Matrix - Continued

Derived Subsubsystem Requirements - PTS Continued		Top-level Subsytem Requirements	
Number	**Caption**	**Number**	**Caption**
7.7.3.22	15 minute forcast	7.2.2.2	Observing efficiency
		7.2.2.3	Match science program
		7.2.2.4	Schedule cadences
		7.2.2.5	Schedule duration
		7.2.2.6	Schedule chronological pair
		7.2.2.7	Schedule visitation
		7.2.2.10	Schedule survey modes
		7.2.2.12	Spatial stability of calibration
		7.2.2.13	Temporal stability of calibration
7.7.3.23	required depth	7.2.2.2	Observing efficiency
		7.2.2.3	Match science program
		7.2.2.4	Schedule cadences
		7.2.2.5	Schedule duration
		7.2.2.6	Schedule chronological pair
		7.2.2.7	Schedule visitation
		7.2.2.10	Schedule survey modes
		7.2.2.12	Spatial stability of calibration
		7.2.2.13	Temporal stability of calibration
7.7.3.24	schedule calibration, engineering	7.2.2.2	Observing efficiency
		7.2.2.12	Spatial stability of calibration
		7.2.2.13	Temporal stability of calibration
		7.2.2.16	Schedule Engineering
		7.2.2.17	verify, maintain, track performance
7.7.3.25	schedule standard stars	7.2.2.12	Spatial stability of calibration
		7.2.2.13	Temporal stability of calibration
7.7.3.26	account for software limits	7.2.2.2	Observing efficiency
7.7.3.27	account for obstacles	7.2.2.2	Observing efficiency
7.7.3.28	account for slew time	7.2.2.2	Observing efficiency
7.7.3.29	account for settling time	7.2.2.2	Observing efficiency
7.7.3.30	account for change of wind screen	7.2.2.2	Observing efficiency
7.7.3.31	account for image rotator time	7.2.2.2	Observing efficiency
7.7.3.32	account for ccd initialization time	7.2.2.2	Observing efficiency
7.7.3.33	account for acquisition image time if req.	7.2.2.2	Observing efficiency
7.7.3.34	account for exposure time	7.2.2.2	Observing efficiency
7.7.3.35	account for read time	7.2.2.2	Observing efficiency
7.7.3.36	account for write time	7.2.2.2	Observing efficiency
7.7.3.37	account for filter/config change time	7.2.2.2	Observing efficiency
7.7.3.38	telescope, enclosure cable-wrap time	7.2.2.2	Observing efficiency
7.7.3.39	instrument rotator cable wrap time	7.2.2.2	Observing efficiency
7.7.3.40	account for current configuration	7.2.2.2	Observing efficiency
7.7.3.41	interactive interface	allocated	
7.7.3.42	testable by simulation	allocated	
7.7.3.43	initalize upon changing to Auto or Robo	4.7.7	remotely changing Observing Modes
		7.2.2.1	Robotic operations

Table 21: OBS Derived Subsubsystem to Subsystem Requirements Trace Matrix

Derived Subsubsystem Requirements - OBS		Top-level Subsytem Requirements	
Number	**Caption**	**Number**	**Caption**
7.7.4.1	Staging initialization and power up	4.7.6	
7.7.4.2	Stowing telescope upon inclement weather	7.2.2.1	Robotic operations
7.7.4.3	Notification in emergency	7.2.2.1	Robotic operations
7.7.4.4	Never delay telescope guiding offsets	7.2.2.15	OTIS control should maintain PSF
7.7.4.5	guiding offset latency $\leq$ 10ms	7.2.2.15	OTIS control should maintain PSF
7.7.4.6	M2MC corrections latency $\leq$ 100ms	7.2.2.2	Observing efficiency

Table 22: TCS Derived Subsubsystem to Subsystem Requirements Trace Matrix

Derived Subsubsystem Requirements - TCS		Top-level Subsytem Requirements	
Number	**Caption**	**Number**	**Caption**
7.7.5.1	guiding offset latency $\leq$ 10ms	7.2.2.15	Guiding should not degrade PSF
7.7.5.2	M2MC corrections latency $\leq 100ms$	7.2.2.2	Observing efficiency
7.7.5.3	M2 focus model	7.2.2.2	Observing efficiency
		7.2.2.15	OTIS control should maintain PSF
		7.2.2.16	Schedule Engineering
		7.2.2.17	verify, maintain, track performance
7.7.5.4	M2 alignment model	7.2.2.2	Observing efficiency
		7.2.2.15	OTIS control should maintain PSF
		7.2.2.16	Schedule Engineering
		7.2.2.17	verify, maintain, track performance
7.7.5.5	M2 collimation model	7.2.2.2	Observing efficiency
		7.2.2.15	OTIS control should maintain PSF
		7.2.2.16	Schedule Engineering
		7.2.2.17	verify, maintain, track performance
7.7.5.6	Alt-Az pointing model	7.2.2.2	Observing efficiency
		7.2.2.17	verify, maintain, track performance

Table 23: OWS Derived Subsubsystem to Subsystem Requirements Trace Matrix

Derived Subsubsystem Requirements - OWS		Top-level Subsytem Requirements	
Number	**Caption**	**Number**	**Caption**
7.7.6.1	Alert to stow telescope	7.2.2.1	Robotic operations
7.7.6.2	Access to external web servers	7.2.2.1	Robotic operations
		7.2.2.1	Robotic operations
		7.2.2.2	Observing efficiency
		7.2.2.3	Match science program
		7.2.2.4	Schedule cadences
		7.2.2.5	Schedule duration
		7.2.2.6	Schedule chronological pair
		7.2.2.7	Schedule visitation
		7.2.2.8	Schedule TTI
		7.2.2.9	Schedule sky brightness
		7.2.2.10	Schedule survey modes
7.7.6.3	Reduce supporting data	7.2.2.1	Robotic operations
		7.2.2.2	Observing efficiency
		7.2.2.3	Match science program
		7.2.2.4	Schedule cadences
		7.2.2.5	Schedule duration
		7.2.2.6	Schedule chronological pair
		7.2.2.7	Schedule visitation
		7.2.2.8	Schedule TTI
		7.2.2.9	Schedule sky brightness
		7.2.2.10	Schedule survey modes

Table 24: ODA Derived Subsubsystem to Subsystem Requirements Trace Matrix

Derived Subsubsystem Requirements - ODA		Top-level Subsytem Requirements	
Number	**Caption**	**Number**	**Caption**
7.7.7.1	Process and log all metadata	7.2.2.17	verify, maintain, track performance
7.7.7.2	Provide $\geq$ 1 TByte of data storage	7.2.2.17	verify, maintain, track performance
7.7.7.3	Provide $\geq$ 1 TByte mirror	7.2.2.17	verify, maintain, track performance
7.7.7.4	Autonomous processes not delayed	7.2.2.2	Observing efficiency

7.9.2.3 Internal OOT data interface: The OOT output product that communicates with internal OTIS objects will be “Observe Files”. These will containing a complete description of all independent parameters (system settings, e.g. exposure length, filter position, telescope pointing, ADC setting) for an exposure set(s). These files will be read and parsed by the Pan-STARRS Telescope Scheduler (PTS) to determine optimal ordering of observations and by the Observation Sequencer (OBS) to set up and execute an indicidual observation.

7.9.3 Pan-STARRS Telescope Scheduler (PTS)

The PTS is a software entity intended to dynamically analyze the available set of Observe Files and select the optimal subset of observations to execute at any given time.

7.9.3.1 PTS command/control interface: Under normal operational mode execution of the PTS processes will be under system-level script control. Comand and data structures will conform to project standards. Human supervision will be performed via a command line and/or GUI interface in interactive/engineering modes.

7.9.3.2 External PTS interface: The PTS does not interface with any non-OTIS entities.

7.9.3.3 Internal PTS Data interface: The PTS will interface with three OTIS subsystems:

7.9.3.3.1 PTS - OTIS Data archive (ODA): PTS will read and write records in the ODA data store using SQL-99 standard queries and commands. Record format and content will be declared and maintained by the ODA subsytem. Data transmission will occur via project inter-system comunications standards.

7.9.3.3.2 PTS - OTIS Weather Server (OWS): During operation the PTS will periodically request data from the OWS to determine current and predicted environmental conditions.

7.9.3.3.3 PTS - Obeservation Sequencer (OBS): actions and status of PTS operation under autonomous/robotic operation will be controlled by the Observation Sequencer subsystem via a command/acknowledge interface.

7.9.4 Observation Sequencer (OBS)

The observation sequencer provides fine-grained command & control to the Pan-STARRS system.

7.9.4.1 OBS Internal Interfaces: The OBS communicates with OTIS subsystems to sequence and command system operations.

7.9.4.1.1 OBS - TCS Command/Acknowledge interface: OBS will send supervisory/setup/action commands to the TCS interface and receives command acknowledgement messages containing status data in return.

7.9.4.1.2 OBS-Detector Host Command/Acknowledge interface: OBS will send supervisory commands to the Detector Host Computer subsystem interface and receives command acknowledgement messages containing status data in return.

7.9.4.1.3 OBS - ODA interface: OBS will connect to the ODA and support data logging and record retrieval.

i. Observe File retrieval: ODA will provide reference to Observer Files (or the equivalent data records) containing complete system setup parameters for an available exposure (sequence).

ii. Observation activity logging: OBS will write status records to the ODA recording all command activity and supervisory status data. Record formats and data dictionary will be maintained by the ODA subsystem.

7.9.4.1.4 OBS-PTS Request/response interace: OBS will send commands to initiate updated scheduling to the PTS interface. PTS will respond with reference to current scheduling status information.

7.9.4.1.5 OBS - OWS weather alert interface: OBS will listen for messages broadcast by the OWS to a project-defined ethernet braodcast address containing adverse weather alert and all-clear information.

7.9.5 Telescope Control System (TCS)

The TCS provides the interface between Pan-STARRS internal subsystems and all external observatory hardware including the telescope, dome, adjustable optics, and facility sensors (except external meterological systems). It is composed of vendor-supplied hardware and driver software, and project-supplied software components that provide a high-level interface to other Pan-STARRS subsystems. TCS will provide translation between high-level action commands and low-level command structures to directly control individual devices. Command status and completion reporting will be logged to ODA as they occur.

The interface between other subsystems and the observatory support equipment will consist of access to sensor data through queries to the ODA subsystem and pre-defined requests for actions through the command/acknowledge interface.

The interfaces between TCS and the hardware of the telesceop, facility, and sensor systems will be defined and controlled as part of the TCS

7.9.5.1 TCS - OBS Command/Acknowledge interface: OBS will send supervisory/setup/action commands to the TCS interface. TCS will send acknowledgement messages containing status data in return.

7.9.5.2 TCS - Detector system: a very low-latency $\leq$ **10 millisec (TBR)** data channel will be provided to transport guiding updates between the camera and telescope drive to maintain pointing during exposures.

7.9.5.3 TCS External interfaces: TCS will provide wrappers to assist external access to the scripting and programming API low level interfaces provided by the telescope/enclosure vendor. The subsystems shown in Figure 27 will be presented via an abstracted interface consisting of a TCS-maintained device dictionary and a uniform command dictionary. Both action commands and status/data queries will be implemented.

7.9.6 OTIS Data archive (ODA)

OTIS will maintain an internal data store containing engineering data, environmental data, and system operations status records. This data store is intended to permit the exact reconstruction of conditions and system actions during operation for data quality, validationa and engineering purposes. This system is intended to operate as a passive data sink to all Pan-STARRS summit systems.

7.9.6.1 ODA Data Interface: Data and command interactions will occur using command and record messages transported via a system standard protocol. Command and record dictionaries and record formats will be declared and maintained by the ODA subsystem.

7.9.6.2 ODA Analysis Interface: Tools will be provided to perform standard queries against the database and produce reports of operational performance.

7.9.6.2.1 Local and remote access to data and reports will be supported.

7.9.6.2.2 Priority will be given to data collection at the expense of analysis performance during telescope operations.

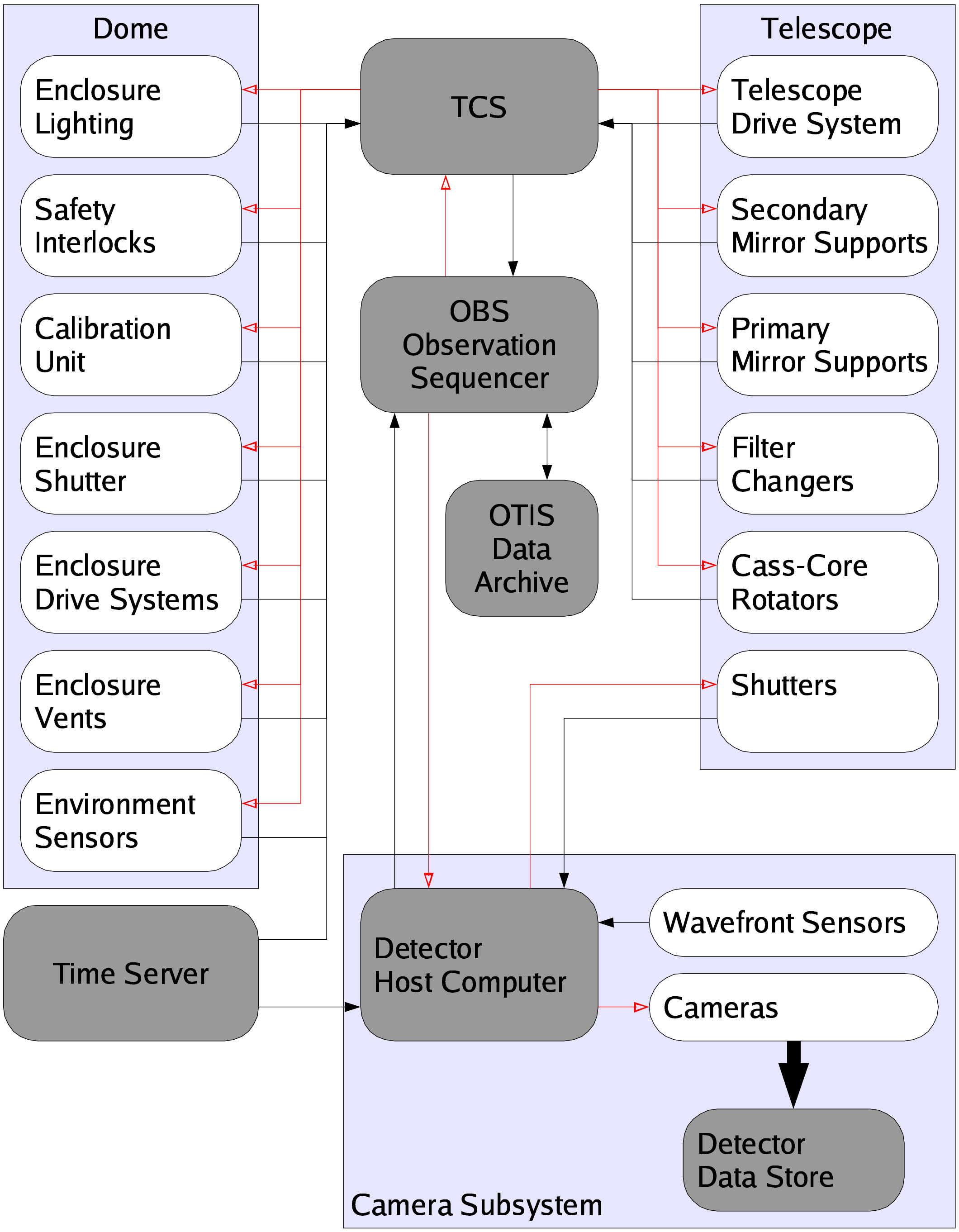

Figure 27: TCS Interfaces

7.9.6.3 ODA External interface: The ODA will provide write and query access to Pan-STARRS system entities for system state logging, operational data transfer, and engineering purposes.

7.9.6.3.1 ODA will accept logging messages containing environmental and operation/action data from the GPC/Detector system contining exposure header information.

7.9.6.3.2 ODA will support at a high priority remote queries for system operational data from the Pan-STARRS IPP subsystem.

7.9.6.3.3 ODA will accept pre-defined data objects for logging purposes from system clients outside of OTIS as the implementation of a centralized system logging facility.

7.9.7 OTIS Weather Server (OWS)

The OWS subsystem is hardware/software entity implementing an interface between Pan-STARRS systems and external sources of environmental data including weather forcast servers, meterological instrumentation systems, and other related stand-alone external environmental data systems such as seeing monitors, sky-transparency probes, all-sky cameras, etc. It will perform remote data requesting, cacheing, processing/reduction, reformating, and buffering functions to allow internal Pan-STARRS clients to obtain the "latest & best known environmental data values" from a single source/point of access.

7.9.7.1 OWS internal client interface (presented to Pan-STARRS clients):

7.9.7.1.1 The OWS will listen for requests and server data products.

7.9.7.1.2 The OWS will communicate with clients.

7.9.7.1.3 The OWS will accept requests for any subset of the currently available weather data values.

7.9.7.2 OWS-ODA interface: Periodic snapshots of OWS data will be autonomously written to the ODA subsystem using the ODA data communication interface and record structure.

7.9.7.3 OWS Weather Alert Interface: The OWS system will monitor relevant local sensor systems and asynchronously broadcast an adverse weather warning signal in the event of the onset of conditions which should modify or abort current operations. Subsystems such as the Observation Sequencer and PTS will listen for these messages and take appropriate actions to safeguard the telescope systems. OWS will also broadcast suitable messages to indicate that weather has returned to acceptable conditions.

7.9.7.3.1 Messages will be broadcast to a project-specific ethernet port will notify all systems supporting asynchronous broadcast messages.

7.9.7.3.2 Alternatively a hard-wired alarm signal will be provided as a failsafe alert.

7.9.7.4 OWS External Interfaces:

7.9.7.4.1 The OWS will request data from external servers and systems using standard protocols.

7.9.7.4.2 Other vendor-specific instrument interfaces may be handled if no other alternative is available.

7.9.8 System Time Server (PSTS)

A facility time standard will be provided to maintain and supply reference time using local standards synchronized to external sources. All Pan-STARRS computing resources and all exposure and control timing will synchronize to this reference.

7.9.8.1 PSTS Network Time Interface: The PSTS will provide standard NTP time reference services to the Pan-STARRS summit network for synchronization of all summmit computer systems.

7.9.8.2 PSTS Hardware Time Service: [If required]: the PSTS will produce a time reference output **(TBD)** for use by critical subsystems (Detector, telescope drives) which do not support NTP synchronization.

7.9.8.3 External Local time reference source connection will provide PSTS primary time reference signals [e.g. GPS receiver system and antenna].

Notes

[12]In this context ‘autonomous’ means an ablility to operate without human intervention for a period of three consecutive days out of seven.

[13]This is required to distinquish moving solar system objects from stationary transients.

[14]This is to ensure observations of each field are scheduled in manner that avoids putting bright stars on the same OTA cell on every vist.

[15] It may be desireable to interleave out-of-plane observations at constant airmass to provide a nearly contemporaneous model of the absolute sky level.

[16]This is required to distinquish moving solar system objects from stationary transients.

[17]For example, under poor seeing conditions the supernova project, which has depth per visit requirements, should be rescheduled.

[18]Using a mid-IR real time all sky camera

[19]For example, percentage of completion of various scientific programs with time, graphical view of the timeline, sky coverage, etc...

8 IPP Conceptual Definition

8.1 Subsystem Overview

The Pan-STARRS Image Processing Pipeline (IPP) performs the image processing and data analysis tasks needed to enable the scientific use of the images obtained by the Pan-STARRS telescopes. The primary goals of the IPP are to process the science images from the Pan-STARRS telescopes and make the results available to other systems within Pan-STARRS. It also is responsible for combining all of the science images in a given filter into a single representation of the non-variable component of the night sky called the "Static Sky". To achieve these goals, the IPP also performs other analysis functions to generate the calibrations needed in the science image processing and to occasionally use the derived data to generate improved astrometric and photometric reference catalogs. It also provides the infrastructure needed to store the incoming data and the resulting data products.

The IPP inherits lessons learned, and in some cases code and prototype code, from several other astronomy image analysis systems, including Imcat (Kaiser), the Sloan Digital Sky Survey (REF), the Elixir system (Magnier & Cuillandre), and Vista (Tonry). Imcat and Vista have a large number of robust image processing functions. SDSS has demonstrated a working analysis pipeline and large-scale database system for a dedicated project. The Elixir system has demonstrated an automatic image processing system and an object database system for operational usage.

The users of the IPP output are all systems internal to the Pan-STARRS project. They consist of the Transient Science Client, which will receive the detections of transient objects on short time-scales; the Moving Object Processing System (MOPS), which will receive the detections of non-stationary transient objects on day-to-week timescales; and the Published Science Products Subsystem (PSPS), which will receive all data products of interest to the outside world, and will act as the long-term archive and publishing clearinghouse.

An important operational choice for the IPP is the decision not to attempt to save all raw data. Once the IPP is running in a standard operational mode, data will be processed by the pipeline and deleted when it is no longer needed. Raw images will only be saved for a short period to allow tests and quality assurance, and potentially to allow systems which study transient phenomena to return to recent data for closer inspection. In general, during normal operations, raw science images will be deleted after $\sim$1 month.

The primary IPP hardware system on which the software operates will not be located at the summit. Instead, because of thermal, power, and space constraints, the hardware will likely be located in a facility off the mountain. A subset of processing tasks may eventually be assigned to machines at the summit if justified by the savings in data transfer time and cost.

8.2 Subsystem Top-level Requirements

The IPP has the following top-level requirements derived from the system requirements above (Section 3.2):

8.2.1 Produce reduced science images for each full camera exposure which are photometrically consistent across the field to within 1%.

8.2.2 Produce reduced science images for each full camera exposure which are photometrically calibrated to within 1%.

8.2.3 Produce reduced science images for each full camera exposure which are astrometrically calibrated to 100 milliarcseconds to an absolute reference.

8.2.4 Produce reduced science images for each full camera exposure which are astrometrically consistent to 30 milliarcseconds.

8.2.5 Produce reduced science images for each full camera exposure which have foreground emission subtracted with no more than 1% variation in the non-astronomical background.

8.2.6 Merge all g filter science images into a static sky image.

8.2.7 Merge all r filter science images into a static sky image.

8.2.8 Merge all i filter science images into a static sky image.

8.2.9 Merge all z filter science images into a static sky image.

8.2.10 Merge all y filter science images into a static sky image.

8.2.11 Merge all w filter science images into a static sky image.

8.2.12 Detect and classify objects on the individual processed science images.

8.2.13 Detect and classify objects on the stacked groups of science images.

8.2.14 Detect and classify objects on the static sky image.

8.2.15 Detect all significant transients in the individual science images relative to the static sky image.

8.2.16 Degrade the stacked image by no more than **10 milliarcseconds (TBR)**.

8.2.17 Perform the processing of science images to the level of transient detection and static sky inclusion at a rate such that exposures taken at a cadence of **40 (TBR)** seconds do not accumulate in the processing buffer.

8.2.18 Limit false alarm rate (FAR) for transient detections to **< 1% (TBR)**.

8.2.19 Publish the static sky images to the Pan-STARRS Published Science Products Subsystem (PSPS) once per 6 months.

8.2.20 Publish the detected objects to the Pan-STARRS Published Science Products Subsystem (PSPS) once per month.

8.2.21 Send the IPP metadata and received OTIS metadata to the Pan-STARRS Published Science Products Subsystem (PSPS) weekly.

8.2.22 Provide access to preferred Pan-STARRS science clients to the detected transient objects within **5 minutes (TBR)**.

8.2.23 Store the raw images for a period of **1 month (TBR)**.

8.2.24 Store the detected objects for a minimum of **1 year (TBR)**.

8.2.25 Store the metadata for the lifetime of the project.

8.3 Subsystem Top Level Description

We now discuss three aspects of the IPP and their relationships: the IPP Analysis Stages, the Architectural Components which make up the IPP, and the Hardware System which provides the basic computer resources needed by the IPP. We discuss these aspects of the IPP in general terms first, and in later sections, address the conceptual design issues for each of the three aspects of the IPP.

8.3.1 Analysis Tasks and Stages

Specific programs are required to perform the processing steps listed above. These can be divided into well-defined analysis stages, each of which operates on a particular unit of data, such as a single OTA image or a collection of astronomical objects. Analysis tasks representing the different analysis stages are performed on the IPP computer cluster. Note the distinction between the generic analysis *stage* and a specific analysis *task*. An analysis stage represents a type of analysis which is performed, such as the basic image calibration and object detection analysis. An analysis task is a particular realization of an analysis stage, e.g., the analysis of OTA number 61 from exposure 654321 to produce a specific set of output data products. The analysis stages are discussed in detail in Section 8.6.2.

8.3.2 Architectural Components

In order to achieve the required functionality, the IPP provides an infrastructure within which the Analysis Stages above are exectuted. We have divided the IPP software infrastructure into a number of clearly-defined architectural software units, listed as follows:

8.3.2.1 **Image Server:** This component is a large data store for all images used by the IPP, including the raw images from the telescope, the master calibration images, the reference static-sky images, and any temporary image data products produced by the IPP. The Image Server accepts the incoming data and stores it until it is no longer needed by other portions of the IPP. The Image Server is not restricted to imaging data: it is capable of storing any large data files which are not well-suited for inclusion in a more structured relational database and for which access needs to be widely available beyond the individual process which created the file.

8.3.2.2 **Astrometry & Photometry Database (AP DB):** This component stores and manipulates astronomical objects detected in various images, as identified above, including individual measurements of objects on the images, the summary information about those objects, and reference object data. It also provides mechanisms for users to query and manipulate the objects and detections.

8.3.2.3 **Metadata Database:** This component stores the data which is not directly related to images or astronomical objects, but which is needed to perform the IPP analyses. The metadata may include the summary weather information for each night, or details about the filters, camera, telescopes, etc.

8.3.2.4 **IPP Controller:** In order to perform the analysis stages required by the IPP, it is necessary to use distributed computing processes on a large number of computers. The IPP Controller manages the collection of analysis tasks performed on these machines.

8.3.2.5 **IPP Scheduler:** This component is a decision-making mechanism which guides the operation of the IPP. It evaluates the currently available collection of data, identifies the necessary analysis, and assigns the analysis tasks to the IPP Controller.

The relationship between these software units is shown in Figure 28. This figure also shows the interactions between the IPP and other Pan-STARRS systems. The architectural components are discussed in detail in Section 8.6.1.

8.3.3 IPP Hardware Organization

The IPP needs substantial computer resources, both in terms of computational power and in terms of data storage and network bandwidth. The IPP requires relatively large amounts of data storage space, primarily for the image data. Image data is organized in two categories. First, there is the per-OTA data – data associated with specific OTAs, including the raw images, the calibration images, and temporary processed images at various stages. Second, there is the data associated with the static sky imagery, which is in turn organized into smaller sky-cell units. In addition to image data, there are the somewhat smaller data entities of the Metadata Database and AP Database.

The computer hardware is organized into nodes which provide both data storage and computational resources. The data storage nodes are divided into three classes: those which deal with the per-OTA image data, those that provide the storage for the static sky images, and those that provide the storage for the other data systems, the Metadata Database and the AP Database. In addition, the computational tasks related to Phase 2 take place on the per-OTA storage nodes and the Phase 4 computation takes place on the static sky storage nodes.

Figure 29 shows our basic concept for the hardware organization for the IPP. This diagram shows the two types of compute nodes: OTA-level processing and storage nodes (dominated by Phase 2) and static sky processing and storage nodes (mostly Phase 4). Also shown are two switches which divide the network into OTA and Static-Sky portions. In such an organization, the interswitch communication must meet the throughput needs between these network portions. The additional data systems (Metadata Database and AP Database) are also shown.

8.3.4 Data Products

The IPP data products are listed in Table 6 and are discussed in detail in the sections below.

8.4 Subsystem Tasks and Functions

In order to achieve the top-level requirements listed above, the IPP performs the following tasks:

8.4.1 Accept raw images from OTIS.

8.4.2 Accept metadata from OTIS.

8.4.3 Produce high-quality calibration images from the raw calibration images.

8.4.4 Pre-process the science images with the high-quality master calibration images. This analysis is called “Phase 2” and the resulting images are called “Phase 2” or P2 images.

8.4.5 Perform an image-wide improvement to the astrometric and photometric calibrations and the sky background subtraction (“Phase 3”).

8.4.6 Merge multiple pre-processed science images – from multiple telescopes or from sequential, dithered exposures – into single, cleaned, stacked images. This analysis, and the next task, constitute “Phase 4”. The resulting images are called “Phase 4 Summed” or P4Σ images.

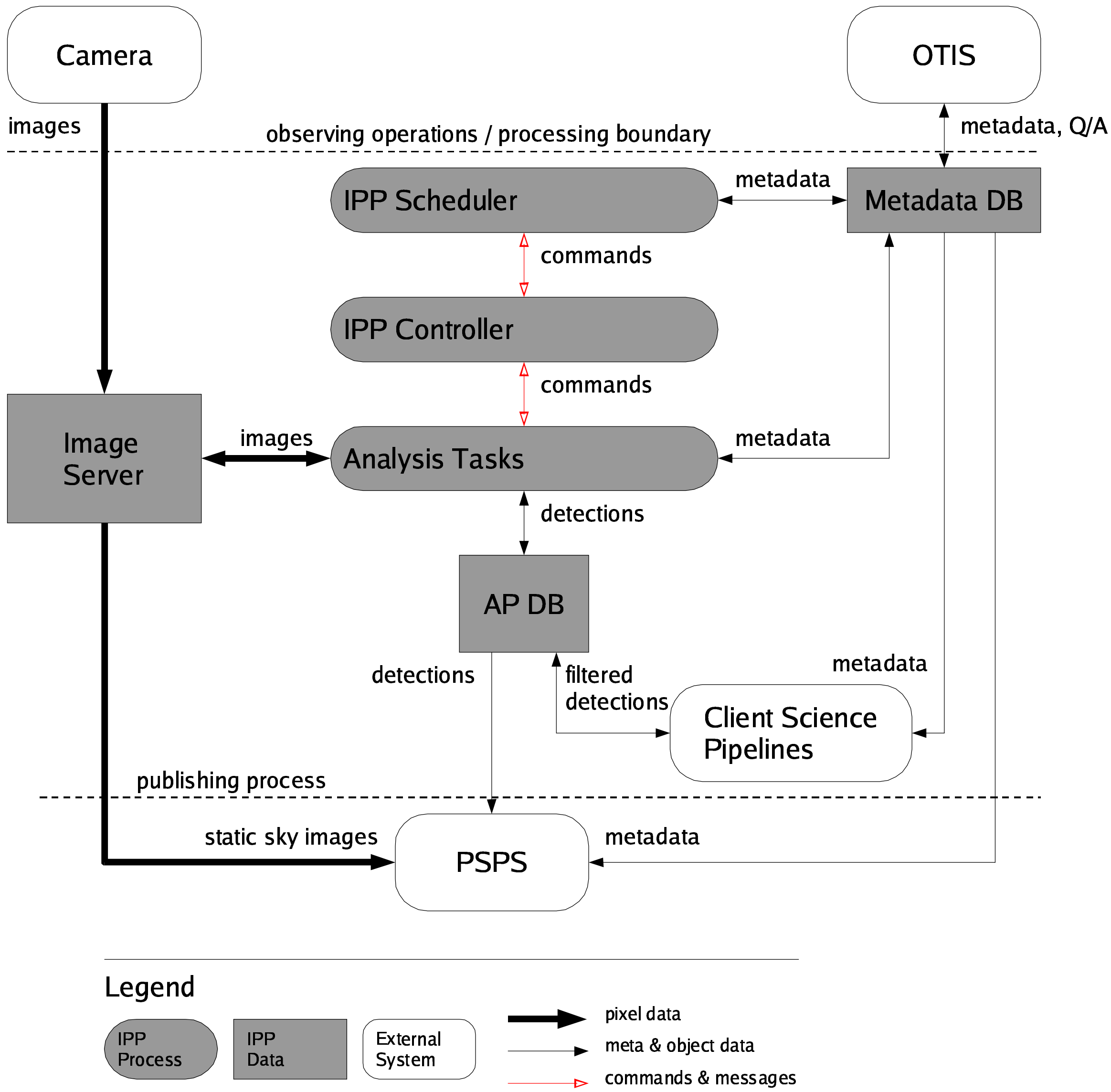

Figure 28: IPP System Overview

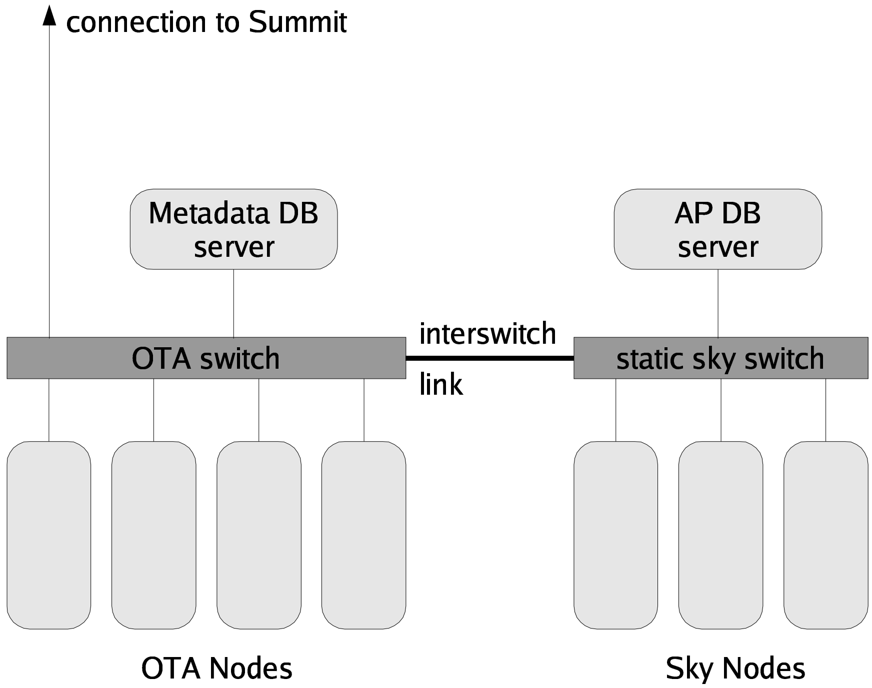

Figure 29: IPP Hardware Organization

8.4.7 Subtract a static sky image from the cleaned, stacked images to produce an image of only the transient events. The resulting images are called “Phase 4 Difference” or P4Δ images.

8.4.8 Excise the significant transients and outliers from the pre-processed science images and merge the cleaned images into the static sky image.

8.4.9 Detect objects on the four types of images: pre-processed images, the stacked image, the difference image, and the static sky image.

8.4.10 Determine astrometry of the detected objects relative to an astrometric reference.

8.4.11 Determine photometry of the detected objects relative to a photometric reference.

8.4.12 Provide the tools and data sources needed to construct a high-quality astrometric reference catalog from the extracted objects.

8.4.13 Provide the tools and data sources needed to construct a high-quality photometric reference catalog from the extracted objects.

8.4.14 Publish the static sky images to the Pan-STARRS PSPS after data validation.

8.4.15 Publish the detected objects to the Pan-STARRS PSPS after data validation.

8.4.16 Provide access to MOPS to the single-occurrence detections of transient objects on short time scales.

8.4.17 Provide access to MOPS to the metadata specific to the images in which single-occurrence detections were found.

8.4.18 Provide access to othe preferred Pan-STARRS science clients to the measurements of the detected transient objects on short time scales.

8.4.19 Store the raw images for a period of time, depending on the survey source of the data. During normal operations, raw data is stored for **1 month (TBR)**.

8.4.20 Store the detected objects for a period of time, depending on the type of detection. Transients from the P4Δ images may be excised after **6 months (TBR)**.

8.5 Operational Scenarios

In the normal operational state, the IPP continuously accepts data from the summit (to the Image Server) and schedules new analysis tasks for operation. At the start of a night, it will need to choose between performing analysis on science images and analysis on calibration images. It will also feed data to the MOPS and other preferred science clients (such as the Transient Science Client) in real time. For the MOPS, this data feed occurs at the end of each night. Other clients may require the data to be delivered more rapidly. The IPP has a top-level requirement to be capable of delivering the transients to clients which need them within 5 minutes of the image being taken.

As a continuous process, the IPP will perform detailed object analysis on the static sky images. The logical time to schedule this analysis is to process those portions of the sky which are within ~ 15 degrees of the sun (in RA), since these are regions which are guaranteed to be unobserved and unchanging for at least 2 months.

Some of the IPP computational and data resources will also be used to construct the astrometric and photometric calibration catalogs. The processing tasks involved in this effort will be assigned to the IPP cluster along with the standard, nightly processing tasks. These analysis tasks will be initiated by a human.

On a longer term timescale (possibly once a month when the system is running in an operational mode), some of the data products will be pushed to the PSPS. In some cases (static sky images, most of the metadata), this publication will involve the simple copying of the data structures to an identical system on PSPS hardware. In other cases (object detections), data will be sent to the PSPS which will be processed by the PSPS for incorporation in PSPS databases. For the static sky publication, it is again logical to send those portions of the static sky which are within ~ 15 degrees of the sun in RA.

The start-up process for the IPP as a whole may be viewed as a start-up procedure for each of the architectural systems independently. The three data storage systems (Image Server, AP Database, and Metadata Database) need to check the existence and validity of the hardware and data it manages. The IPP Controller needs to determine which computers are available before allowing processing. The IPP Scheduler will need to check that all of the other systems are sufficiently operational before attempting to make decisions and submit jobs to the IPP Controller.

8.6 Conceptual Design

8.6.1 Architectural Components

8.6.1.1 Image Server

The IPP Image Server is a large data store for all images used by the IPP. The Image Server stores all of the images needed by the IPP for the length of time they are required; total data volume is specified in detail in the separate report, 'The Pan-STARRS Image Processing Pipeline Computational Challange' (PSDC-4xx-xx); the total data volume for PS-4 is approximately 1000 TB.

The IPP Image Server stores science and calibration images as FITS files on disk Images of the Static Sky are stored as a variant of FITS, using a data representation yet to be determined to minimize the total data volume and pixel overlap and to minimize the losses from warping of the images. The optimal representation of the Static Sky is a topic for study by the IfA IPP Team. Two parameters which critically affect the total data volume requirements of the Image Server are 1) the pixel scale (arcseconds per pixel) and 2) the byte representation of the data. Current working numbers for these are $0.2''$ and 4 bytes per pixel (2 for the signal and 2 for the noise map).

The IPP Image Server distributes images across a cluster of machines. Multiple copies of each image may be requested for redundancy or for improved throughput. The image (or one of the copies) may be placed on a specified machine. The specific machine on which a particular copy of an image resides may be determined via the user interface methods.

The IPP Image Server maintains a record of all images currently available in the repository. The Image Server is only responsible for tracking the location of the images, not for tracking metadata information such as the image summary statistics or the state of the image processing for the image. These aspects are included in the Metadata Database discussed below.

The IPP Image Server interfaces with other subsystems of the IPP. It provides a mechanism by which other IPP subsystems may identify the image location (the computer on which it resides). It also provides a mechanism to serve a specified image to an IPP or Pan-STARRS subsystem on request. It also provides maintainence mechanisms for deletion, relocation, and duplication of images in the Image Server as necessary.

The IPP Image Server is not limited to image data. Any large file would be an appropriate object to store in the Image Server. Raw images from the telescope are stored as separate OTA images, with multiple Cell images per file, as well as video sequences from the guide stars in the form of MEF extensions.

8.6.1.2 AP Database

The AP (Astrometry & Photometry) Database is a mechanism to store data related to astronomical objects derived from various sources with a variety of associations. The AP Database deals with two related concepts: *objects* and *detections*. The objects are descriptions of astronomical objects while the detections are the specific measurements of those objects, typically measured from astronomical images. A collection of *detections* may be used to derive average quantities which describe a particular *object*. A third class of object information which must also be considered are those supplied by external references. These may be treated as *detections*, with the caveat that access to the raw measurements and metadata are usually unavailable; the reported measurements and errors must be accepted as they are reported.

The AP Database stores the collections of detections which were derived from specific images from any of the analysis stages. It provides a mechanism to determine and (in conjunction with the Image Server) locate the image from which a specific detection was derived. The AP Database also makes it possible to extract all detections derived from a specific image and to determine quantities such as the coordinates of the detection in pixel coordinates on the image.

The AP Database also has the capability to associate multiple detections of a specific object. Several major classes of objects will be present, each of which must be handled correctly.

First, the most distant stars, compact galaxies, and QSOs will have nearly fixed locations relative to other nearby stars, with only small deviations for individual measurements. The association between multiple detections of such objects is made on the basis of their coincident positions. The AP Database determines the average position of the object and the deviations of the individual detections from that average on the basis of the ensemble of individual detection.

Second, solar system objects do not have a fixed location. Detections of such objects are linked by their orbits, and depend on both the position and the time of the image. The AP Database does not attempt to make this link, which is the role of the MOPS system. However, it has the ability to accept identifications made externally with specified detections and to return the identifier of the moving object associated with the specific detections. These associations also include descriptive information such as the offset of the detection from the predicted location of the detection based on the orbit.

Table 25: AP Detection Classes & Object Parameters

Object Parameter	P2	P4S	P4D	SS
PSF x,y, covar, α, δ	+	+	+	+
PSF mag, $\sigma_{\rm mag}$	+	+	+	+
star/gal sep	+	+	+	+
σ_x, σ_y, θ	+	+	+	+
local sky data	+	+	+	+
Petrosian R, M, R_{50}, R_{90}	-	+	-	+
Sérsic R, M, AB, ϕ, ν	-	+	-	+
W.L. γ_1, γ_2, pol. terms	-	-	-	+
exp. spaced aps., Poisson noise, variance	-	-	-	+

This functionality is required to allow the AP Database to ignore known moving object detections from other types of queries.

Third, stars in the general vicinity of the solar system fall in between these first two classes of objects. Their proper motion and parallax response is significant enough ($>$ 1 arcsec in 1 year) that they are not well-described by an average location and a collection of offsets. These objects are described by a distance and a proper motion vector. The AP Database provides the association between the specific detections and an average object which includes finite parallax and proper motion.

Fourth, many detections, especially in their initial states, will not be associated with a specific astronomical object of any of the above classes and are treated as orphans. Most of these will be spurious (not represent real objects), some will be from solar system objects for which orbits are not yet determined, some will be from faint stars near the detection limits, some will be from short-term transients which have only been detected once. The AP Database maintains these detections until they have been associated with one of the objects above. The AP Database provides mechanisms by which individual detections may be migrated back and forth between the orphan state and association with an astronomical object.

For every object, and all orphaned detections, the AP Database also provides the capability to determine the images which observed the location of the object but for which no detection was made. The minimum set of information which must be carried for these non-detections is the image and the associated object or orphan.

The AP Database also stores the relationships between various photometric systems and, in some cases, the evolution of that relationship. It provides mechanisms to convert between the measured instrumental magnitude of a detection with a specific filter, detector, and telescope, and at a particular time and the implied magnitude in the average Pan-STARRS photometry system, given a determined set of calibrations. It also provides the capability to convert magnitudes in one system to the magnitudes in another system; an example of such a conversion is between the average Pan-STARRS filter systems and the various reference systems appropriate for those filters.

The AP Database provides interfaces to extract lists of objects and detections based on various query parameters. It provides the capability to extract all detections associated with a specific object, all non-detections of that object, all non-detections of an orphan, and summary statistics from these collections. It will also return all objects or detections within specified spatial regions including regions bounded by great circles (RA,DEC; GLAT,GLON; ELAT,ELON) and regions described by a location and a search radius. It will also return the image parameters associated with a specific detection including image coordinates of the detection, exposure time, time and date of the detection, etc.

8.6.1.3 Metadata Database

The IPP requires a Metadata Database to store and provide access to metadata of various types and from various sources. Metadata in the context of the IPP represents all data which is not included in the two data stores discussed above (Images and Detection/Objects). Metadata is generated at the telescope and during the various analysis stages

The Metadata Database stores and provides metadata for all raw images, for processed images, for the calibration images (both raw and master), for the extracted object lists. Metadata describing the environmental conditions at the telescope must also be stored and provided as needed.

If analysis results are exchanged via the Metadata Database, it must provide access to the queried data on timescales of < 2 seconds to avoid slowing down the analysis systems.

The IPP also requires a Configuration Database to store and provide access to information about the IPP itself. Examples of data in the configuration database include the default parameters for the various analysis programs, the description of the computing environment, the process status information, etc.

8.6.1.4 IPP Controller

The IPP uses a group of computers to store and process images and to manipulate collections of detections. These computers perform any of a large number of analysis stages or other processing tasks without significant interprocess communication. It is necessary to have a mechanism which initiates computing tasks on the different computers, which monitors the tasks as they are executed, which handles the output and the errors from these tasks, and which reacts to the failure of any of the computing nodes. The system responsible for the tasks in the IPP is the IPP Controller.

The IPP Controller interacts with the collection of computers under its management and with other subsystems in the IPP. The IPP Controller receives a variety of inputs from other subsystems, described below, and initiates actions such as adding a new process to its queue. The IPP Controller also provides information to other subsystems on demand about its processing history and current state. Each physical computer may have multiple processors; since the IPP Controller is managing processing tasks, it treats each processor independently. It is up to the system configuration if each computer needs to reserve one of its CPUs to manage background tasks or if the IPP Controller should attempt to send one task per CPU and let the kernel handle the I/O load.

Computers managed by the IPP Controller are allowed to be in one of several states, and the IPP Controller must interact with it in an appropriate way for each of those states. A computer may be `alive`, `dead` or `off`. If the computer is `alive`, it responds to commands from the IPP Controller and may be used for tasks subject to other constraints. If it is `dead`, the computer is not responsive and must not be used for executing tasks. The IPP Controller must identify computers which have died and occasionally test them to see if they are `alive` again. Computers which are `off` are not available for tests and must not be tested. Computers may be set to the `off` or `dead` states by external subsystems; it is the responsibility of the IPP Controller to return a computer to the `alive` state if possible. An example scenario: a computer crashes. At this point the IPP Controller should detect that the computer is no longer responsive and mark it `dead`. It should occasionally try to re-establish communication with the computer, potentially with longer and longer delays between attempts. A human could be notified if the computer seems to remain `dead` for a very long time. In another circumstance, a person needs to work on a computer. They should have the ability to notify the IPP Controller that the machine is off, perhaps with a prior notification that the machine should be prepared to go off. Only when the person is done working and testing the machine, and tells the IPP Controller that the machine is now `dead` can the IPP Controller attempt to re-start communications and processing on that computer.

CPUs on computers which are in the `alive` state may be in one of two modes: `busy` and `free`. A CPU which is `busy` currently has a task assigned to it. The IPP Controller may only assign one task to one CPU at a time. A CPU which is in the `free` state may have tasks assigned to it. The IPP Controller must also respect a list of task restrictions which may require specific tasks to run on specific CPUs or exclude specific tasks from specific CPUs.

The IPP Controller accepts tasks from other IPP subsystems. The task requests include the specific command to be executed and are in the form of a UNIX command which could be performed on any of the computing nodes. Any input or output data structures in the commands must be a valid resource regardless of the node on which the task is executed. Input and output data resources must be unique where necessary to avoid conflicts. The IPP Controller gives each task a unique identifier, which is returned to the requesting agent. The agent may then use that ID to obtain status information on that task or to send control signals to the specific task.

Task requests may specify a desired node for the task execution. The IPP Controller attempts to honor the request if the node is `alive`, but will execute it on another node if the requested one is `dead` or `off`. Even if a node is `alive`, the IPP Controller will choose another node if the specified task is not allowed on the requested node. In all other cases, the IPP Controller waits until the currently executing processes, and processes with higher priority, are completed before executing the specified task on the requested node.

Task requests may specify an urgency level. The IPP Controller determines the priority of the task on the basis of both the priority and the age of the request. An executing task must be completed on a CPU before any new task is started on that CPU, regardless of priority. Tasks may be assigned a priority of 0 in which case they are maintained in the queue and never executed.

The IPP Controller monitors the output streams from the executing tasks and the exit status of the tasks. Each task is associated with a log file, to which all output is written. The status, including the exit status, of each task is maintained by the IPP Controller so that other subsystems may determine if specific tasks have started or completed.

The IPP Controller must accept commands from other IPP subsystems. These commands include those which govern the processing of specified tasks, those which govern the behavior of specific computing nodes, and those which request information from the IPP Controller. The IPP Controller must be able to halt the execution of a specified task, delete an unexecuted task from the task list, change the priority of tasks, and change the requested nodes for tasks. The IPP Controller must also be able to stop the current execution of a task and push it to the end of the queue and also change its priority.

The IPP Controller must honor requests (normally from the users) to change the mode of any computing node on demand between `off` and `dead`. This would normally be done after a computer has been rebooted and is release to the IPP Controller for its use. It must also be able to change the list of allowed tasks as requested by external commands.

The IPP Controller must respond to informational requests regarding the collection of machines and their states as well as the collection of tasks and their states. The IPP Controller must monitor the execution times of the different tasks and provide summary statistics. Finally, the IPP Controller must respond to three top-level commands: `finish`, `stop` and `abort`. When `finish` is requested, no more new tasks are accepted on the stack of task, and when all tasks in the stack have completed, the IPP Controller must exit. When `stop` is requested, the currently executing tasks must be completed at which point the IPP Controller must exit, but tasks remaining in the stack which have not been started are flushed. When `abort` is issued, the IPP Controller immediately kills all executing tasks and exits.

The IPP Controller and the IPP Image Server have related needs for information from the combined storage-and-processing nodes regarding which nodes are available. It is not yet clear if this information is best stored in a single location (either IPP Controller or IPP Image Server), which provides the information to other systems on demand, or if both systems should maintain the information. Also, it may be necessary to distinguish nodes which are available for processing from those that are available to serve data as part of the IPP Image Server.

It may be useful for the Controller to distinguish between tasks dominated by I/O and tasks dominated by data processing.

It is possible that one of each of these types of tasks may be sent to the same node without significantly impacting the system performance. Alternatively, it may be necessary to limit a single machine with 2 CPUs to only one of each of these types of tasks (i.e., one processor will be working on I/O while the other is working on processing). Such details will be studied by the IfA IPP Team.

8.6.1.5 IPP Scheduler

The IPP is responsible for a variety of analysis tasks: processing of the science images through several stages; routine assessment of the detrend (instrumental calibration) images used in processing the science images; construction of replacement detrend images when needed; generation of astrometric and photometric reference catalogs based on the collected dataset; and the performance of test analysis programs. At any point, decisions need to be made about which of these tasks should be performed, based on an analysis of the contents of the metadata database, the requirements of the people monitoring the IPP, and the near-term observing plans. The IPP Scheduler is the mechanism that assesses these various inputs to guide the decisions and initiate the actions.

The IPP Scheduler acts as an intermediary between several components of the IPP and also between the IPP and external agents such as OTIS and the users who must monitor the behavior of the IPP.

The IPP Scheduler sends commands to the IPP Controller for execution. While the IPP Scheduler chooses the tasks to be performed, it is the IPP Controller's responsibility to manage the specific tasks executing on a given processing node. Examples of these tasks include the process of copying or moving data from the Summit data systems to the IPP Image Server; image processing analysis stages performed on the science images by the appropriate processing nodes; and the analysis of the data in the AP Database. This division of responsibilites allows us to isolate and encapsulate the functionality of the IPP Scheduler and the IPP Controller. With this separation, the IPP Controller does not need to have any information about the details of the tasks which it executes, while the IPP Scheduler does not need to have detailed information about the available computer hardware.

Communication between the IPP Scheduler and the IPP Controller is bi-directional; the IPP Scheduler sends tasks to the IPP Controller, while the IPP Controller informs the IPP Scheduler of the outcome of those tasks. It is not specified whether the IPP Scheduler and IPP Controller are components of a single software system or interacting but distinct software components.

The IPP Scheduler takes as input the current list of pending images, both science and calibration, and a description of the current observing plan or strategy on some time-scale. The IPP Scheduler also takes input from humans who manage the IPP.

The IPP Scheduler must choose between several types of analysis tasks based on the contents of those lists and on the requirements of the users. The list of tasks which the IPP Scheduler must decide between includes:

- moving data from the Summit pixel server ($\sim$ 30 second timescales)
- running the science analysis stages ($\sim$ 30 second timescales)
- testing the validity of the current detrend images ($\sim$ nightly)
- constructing new detrend images ($\sim$ weekly)
- updating and improving the photometric and astrometric reference catalogs ($\sim$ yearly).

The IPP Scheduler chooses between tasks which are relevant on several different time-scales. The time-scales range from 2 times per minute to once or twice a year, as noted in the list above. The IPP Scheduler must also make use of user input in managing such choices. Users have the option to specify that a particular task or set of tasks is of higher or lower priority than the norm.

The IPP Scheduler maintains a set of rules that define the dependency of one type of analysis stage on other analysis products. For example, the nightly science image processing depends on the existence of valid detrend images. The IPP Scheduler must be able to recognize the dependency and initiate the required analysis needed to perform other analysis tasks. The IPP Scheduler must have the ability to decide between postponing an analysis task until the required data are available or initiating the task using a lower-quality or less appropriate substitute. For example, in normal circumstances, a science image must not be processed until the corresponding detrend frame has been produced. However, if such a frame is unlikely to appear soon, and the pressure to process the science image is sufficiently high, then the frame could be processed with an older detrend frame of known lower quality. The IPP Scheduler must have the ability to choose the best, if not ideal, reference data for a particular circumstance. Note that these rules are defined for the IPP Scheduler in an abstract way as a relationship between analysis stages, rather than as a specific rule relating one task to another task.

The IPP Scheduler defines the operating state of the IPP. When the IPP is in the *automatic state*, the IPP Scheduler performs the most appropriate of all possible tasks at a particular time. When the IPP is in the *interactive state*, the IPP Scheduler performs only the requested action regardless of the outcome of the decision trees. In addition, in the interactive state, the IPP Scheduler must only perform the requested actions and not attempt to perform the other normally-required actions. The only exception to this exclusion is that, in the interactive state, data is still copied from the summit system. An additional IPP state is the *paused state*, intended for tests or maintenance, in which case the IPP Scheduler does not perform even the data copy tasks. Every task is performed on demand by the user. The user command sets the IPP Scheduler in one of these three states, *automatic*, *interactive*, and *paused*.

8.6.2 Analysis Stages

8.6.2.1 Overview

We now consider the collection of analysis tasks which must be performed by the IPP. These tasks represent the core of the required IPP functionality; the architectural components discussed above can be viewed as primarily supporting infrastructure to enable the analysis tasks to be executed on the appropriate data and to store the results. The tasks are divided into well-defined analysis stages, each of which operates on a particular unit of data, such as a single OTA image or a collection of astronomical objets.

Depending on the analysis stage, the basic data unit may be individual images, collections of images, or derived data products such as a collection of detections of astronomical objects. Because of the granularity of these data units, a large number of analysis tasks representing the same analysis stage many be performed in parallel. This is particularly true because the analysis tasks from any particular stage do not depend on the results of another analysis task from that stage. For example, the intial analysis of a chip from one image does not depend on the results from another chip. The analysis stages are divided into three categories, and further subdivided as follows:

8.6.2.1.1 **Science Image Analysis** is performed on the night-sky science images to extract the science data from these images. The science image analysis is divided into 4 analysis stages, which we call Phases 1 - 4:

- **Phase 1:** The image processing preparation stage, in which basic astrometric analysis of the complete FPA image is performed.
- **Phase 2:** The image reduction stage, in which the individual detector images (OTAs) are processed as much as possible without reference to other chips in the same FPA image or other exposures.

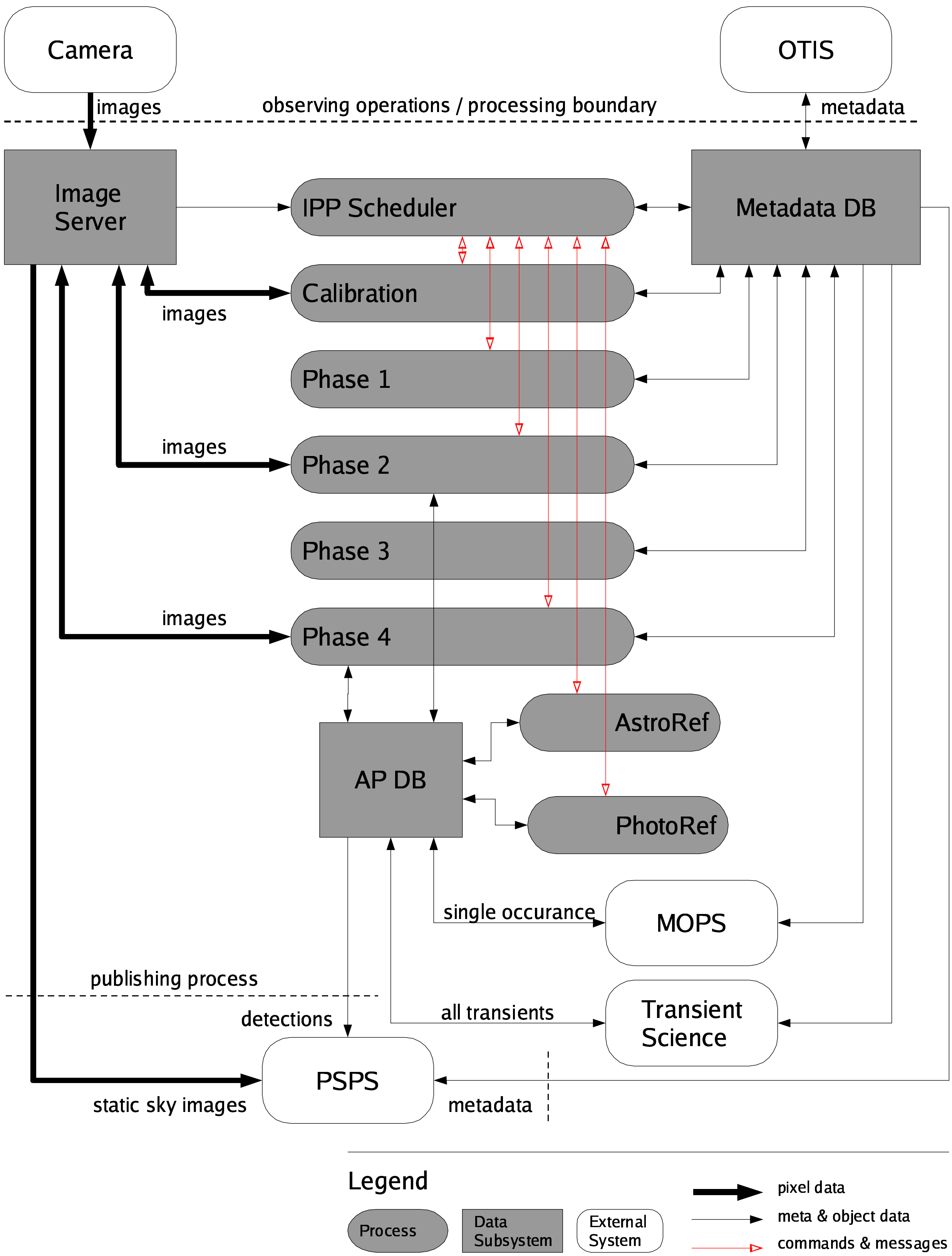

Figure 30: IPP Analysis Stages

- **Phase 3:** The exposure analysis stage, in which the results of the multiple detectors are combined to improve the calibrations for the complete FPA images.
- **Phase 4:** The image combination stage, in which several different exposures of the same part of the sky are combined to produce high-quality difference and summed images.

8.6.2.1.2 **Calibration Image Analysis** is required to generate the calibration images used in the science image analysis. There are many different types of calibration images which must be produced, some of which are derived from other calibration images. The type of calibration image is generated by its own analysis stage. These include the construction of simple bias, dark, and flat-field stacked images, the generation of flat-field correction frames on the basis of stellar photometry, and the construction of sky-model and fringe-model images.

8.6.2.1.3 **Reference Catalog Creation** is required by the IPP to generate improved astrometric and photometric reference catalogs on the basis of Pan-STARRS observations.

Figure 30 shows the flow of data between the various IPP software subsystems and the different analysis stages. The thick lines represent the flow of pixel data, the thin lines represent the flow of metadata and object data, and the grey lines represent the flow of commands. The hatched systems represent external Pan-STARRS systems (OTIS, the Sky Server, the PSPS Object Database, the Moving/Transient Object Pipeline, and other Client Science Pipelines.

The individual analysis stages are implemented as UNIX command-line programs. Each command performs the action of the stage on a single quantum of data. These analysis stages are built of lower-level C-functions which may be wrapped in a higher-level programming language such as Perl or Python.

As discussed above (section 8.6.1.5), the decision to execute a specific analysis stage for a specific dataset is made by the IPP Scheduler, which sends the infomation to the IPP Controller. The IPP Controller executes the analysis tasks constructed by the IPP Scheduler for that stage on an appropriate machine and monitors the success or failure of the job.

An important design decision which must be addressed by the IfA IPP Team is the question of how the analysis stages determine configuration and reference data needed by the analysis. In one scenario, it is always the responsibility of the low-level function to perform the necessary query of the reference databases. In an alternative scenario, it is the responsibility of the scheduler to extract that information and send it as part of the processing command.

8.6.2.2 Science Image Analysis

The Science Image analysis stages together represent the primary data analysis performed by the IPP. The science image analysis which is performed by the IPP consists of:

- detrending the images to remove the instrumental signature
- astrometric and photometric calibration of the individual images
- merging a collection of several images of the same portion of the sky obtained over a short period of time to remove image defects and gaps
- subtracting the appropriate reference static-sky image
- cleaning the image of any transients
- adding the cleaned image to the static sky

- object detection of images at specific stages

We have divided the analysis steps into four analysis stages, which we call Phases 1 - 4. Each of these analysis stages deals with a single data unit.

8.6.2.3 Phase 1 : image processing preparation

The Phase 1 analysis stage is performed on each science exposure (each complete FPA image) to calculate basic astrometric data needed by the later stages. Phase 1 uses the static (pre-determined) telescope distortion model and a table of nominal OTA positions and rotations, combined with the guide star pixel and celestial coordinates, to determine the correct telescope bore-sight, field rotation and magnification. These calculations are performed by comparing the observed guide star detector coodinates with the known astrometic positions of these same stars as reported by an external astrometric reference. The accuracy of the resulting astrometric solution is expected to be **1 arcsec (TBR)**[20] across the field, sufficient in later stages to match the vast majority of astrometric reference stars with their detections with minimal effort.

In some circumstances, science images may have no guide stars. This may occur in the Pan-STARRS system if the detectors are not run in OTA mode, for example for short snapshot images. This may also be the case if the IPP is being run on non-Pan-STARRS data. In such a circumstance, the Phase 1 stage uses the provided boresight coordinates, exposure time, and camera zero-point to predict the pixel coordinates of known bright stars expected to be found on the detectors. It then extracts a large box ($\sim 30 \times 30''$) around these locations and performs extremely basic object detection to determine the detector coordinates of those bright stars which are not saturated but which are significantly above the background level. By targetting known locations in the image files, only a small amount of data will have to be read.

Given the above astrometric solution, the Phase 1 analysis stage constructs a table of the overlaps between the science image to be processed and the static sky images that must be constructed. This table will be used to guide the processing of the static sky in Phase 4. The overlaps should be generously calculated so that small errors in astrometry at Phase 1 will not cause any valid static sky / science image pairs to be missed because of the astrometric error at this phase. It is acceptable for a small number of invalid overlaps to be identified as these will be excluded in Phase 4. Static Sky cells which do not have sufficient science image overlap $< 5\%$ **(TBR)** need not be processed because the few new measured pixels do not add significantly to the Static Sky.

8.6.2.4 Phase 2 : image reduction

The Phase 2 analysis is the detrend stage, in which the images from the detector are processed to remove instrumental signatures. In addition, basic object detection is performed along with improved astrometric and photometric calibration. In each step of the analysis process, an image mask and noise map must be constructed and updated when appropriate. The following operations may be applied during the Phase 2 processing:

8.6.2.4.1 Convolve detrend images with the OT kernel, if appropriate

8.6.2.4.2 Flag bad and saturated pixels

8.6.2.4.3 Bias correction via overscan subtraction

8.6.2.4.4 Dark

8.6.2.4.5 Trim object image to remove overscan and edges corrupted by OT

8.6.2.4.6 Correct for non-linearity

8.6.2.4.7 Cross-talk

8.6.2.4.8 Flat-field correction

8.6.2.4.9 Sky & Fringe subtraction

8.6.2.4.10 Identify CRs

8.6.2.4.11 Find objects in the image

8.6.2.4.12 Model the PSF variations across the image

8.6.2.4.13 Make postage stamps of bright objects.

Of the calibration steps, some may be skipped if they do not contribute to an improved image. The decision to apply or skip a particular step is determined by the Phase 2 recipe, which may specify exposure time or flux limit cutoffs for some of the steps.

8.6.2.4.1 Convolve detrend images with the OT kernel

Certain detrend images are convolved by the OT kernel, so that they accurately represent the detrend images appropriate for the object images, which have been shifted using OT. The detrend images which must be convolved include: the flat-field and the high-spatial-frequency fringe images. The appropriate kernel for each cell of an OTA must be determined from the guide star history, extracted from the IPP Metadata Database[21].

8.6.2.4.2 Flag bad and saturated pixels

A static bad pixel mask is used to identify pixels which are known to be bad in the camera. This mask is then processed with the science image. Bad pixels which are charge traps are grown by the extent of the OT convolution kernel. Bad pixels above a charge trap (i.e. bad colums) must not be grown, since they were not affected by pixel shifting, but only became bad at read-out.

Pixels which are saturated in the A/D converter, or with a signal level at which the response is excessively non-linear, must also be masked, and this area must be grown by an additional pixel to mask excess charge spillover.

The bad pixel mask must be carried with the science images. Different bits must be set to identify different reasons for masking the pixel.

8.6.2.4.3 Bias correction via overscan subtraction

The image bias must be subtracted. Since different detectors behave in different ways, several options for modelling the bias are available. The bias is measured from the image overscan region. The bias subtraction method must be capable of subtracting a single constant from the complete image, or to subtract a 1-D bias which varies as a function along the overscan. The function used to represent the overscan region may be a spline or a chebychev polynomial derived from the data values along the overscan. The values used to determine both the single constant or the inputs to the spline and polynomial fits are derived from groups of pixels on the basis of one of several statistics, including the sample and robust mean, median, and modes. In the case of a single constant, all of the overscan pixel values are used in the calculation of this statistic. In the case of the 1-D functional representation, the input values to the fit must represent the coordinate along the overscan, with the statistic derived from the pixels in the perpendicular direction at each location. Sigma-clipping on the input data values must be an option.

8.6.2.4.4 Trim object image

The image is trimmed to remove the non-imaging pixels, such as the overscan and any pre-scan pixels, along with those pixels near the edges that have been compromised due to OT operation. The definition of the imaging area of the detector is determined from the camera configuration data or from the metadata associated with the image, with the choice a user-configurable option.

8.6.2.4.5 Correct for non-linearity

If required, the object image (after bias correction) must be corrected for the effects of non-linearity through a provided polynomial fit to the pixel data values or a numeric lookup table as a function of pixel flux. The choice to apply the correction must be set by the user.

8.6.2.4.6 Flat-field correction

The object image (after bias correction and non-linearity correction) must be corrected for sensitivity variations as a function of position, dividing by a flat-field image.

8.6.2.4.7 Sky & Fringe subtraction

After the science image has been flat-fielded, the flux contribution of the sky (from both continuum emission and the line emission that causes fringing) must be subtracted from the image. The subtraction needs to remove background (technically, foreground) variations which are not celestial but generated in the atmosphere or by more localized scattering. This background should include the contribution from the zodiacal light. This background subtraction does not address the artifacts generated by bright stars: bleeding columns, ghosts, or other localized reflection effects. This process also produces a superbinned image of the background map which may be used as a debugging diagnostic.

8.6.2.4.8 Identify 'cosmic rays'

Charged particles in the detector frequently cause features which do not have the morphology of astronomical objects. In a well-sampled image, these may be easily identified by the sharpness of the image. In a near critically-sampled image, these 'cosmic rays' may be indistinguishable from stellar objects. The IPP must have the capability of making the morphological identification of cosmic rays if the imaging data is sufficiently well sampled. The identified cosmic rays should be masked with a configurable growth factor so that additional pixels beyond the detected pixels in the feature are also masked.

8.6.2.4.9 Find objects in the image

After the image have been processed by the preceeding steps, the Phase 2 analysis performs a basic object detection analysis. Objects on the flat-fielded object image are found, and general parameters are measured. Object detection is performed at several stages by the IPP, with different object parameters measured in each case. Table 25 gives a list of the different detection stages and the object parameters measured for those stages. For the Phase 2 analysis, the object parameters are: the object centroid and the position covarience matrix, the instrumental PSF magnitude and error, local background level and error, a measurement of the star-galaxy separation, and a measurement of the object shape ($\sigma_x, \sigma_y, \theta$). The detection threshold must be configurable, and be a function of the average background flux or the image noise map. Minimal object classification must be performed to distinguish objects which are consistent with a single PSF, objects which are inconsistent, and objects which are saturated. The resulting collection of detected objects are saved in the AP Database along with the relevant image metadata (i.e., filter, exposure time, etc). In addition, this process constructs a model of the point-spread-function (PSF) as a function of position in the image. This PSF model is saved as part of the image metadata.

8.6.2.4.10 Astrometry

The astrometric parameters determined in Phase 1 have an accuracy of 1 arcsec, sufficient to allow easy association between the newly detected objects and many reference objects in the image. In Phase 2, the detected objects are matched with known astrometric reference objects, using reference object coordinates which have been adjusted for proper motion. The matches are then used to improve the astrometric parameters for the individual OTAs. The OTA astrometric parameters which are determined may include terms up to 3rd order in position, though the terms which are actually fitted are user-configurable. The Cell astrometric parameters are not allowed to vary at this stage. The fit must be robust, rejecting outlier matches (either stars with poorly determined proper motion or spurious matches). The resulting astrometric solution is consistent across the OTA field to within **0.2 arcsec (TBR)**.

8.6.2.4.11 Postage Stamps

The IPP must have the capability of extracting regions surrounding a specified subset of objects from the flattened images. These postage stamp images must be saved for additional use by client science pipelines. The identification of these objects must be on the basis of a set of rules applied to the object's magnitude and position. The postage stamps are not restricted in shape to simple rectangles, but may represent more complex regions. They are written the Image Server.

8.6.2.5 Phase 3 : exposure analysis

The Phase 3 analysis stage works with the results from a complete FPA obtained during Phase 2 to improve the photometric and astrometric calibrations.

Phase 3 uses the objects detected in Phase 2, matched with an appropriate reference catalog, to determine the image photometric zero point and zero-point variations across the field. If zero-point variations are significant, the zero-point variations are modeled with a Chebychev polynomial correction of order 3 or less. The complete FPA image must be categorized as photometric or not on the basis of the zero-point consistency, comparisons between the zero-point of the image and recent longer-term (week or month long) measurements of the zero-point, and the external indicators of photometricity. In addition, statistics of the transparency are measured and saved as part of the related Metadata.

Phase 3 also uses the objects detected in Phase 2, matched with an appropriate reference catalog, to determine improvements to the astrometric solutions. The improved solution is determined by fitting a new distortion model appropriate to this image. The resulting astrometric accuracy is limited by the astrometric reference catalog. (see Table 26 below).

Phase 3 also uses the individual measurements of the background and the superbinned background maps to generate an improved background map over the entire FPA. The large-scale background correction is determined on the basis that the background should be smoothly varying between different chips (OTAs).

Phase 3 also uses the individual chip models of the PSF variations to model the global PSF variations across the field. There will be discontinuities at the chip boundaries due to charge diffusion and chip displacements along the optical axis, but there will also be an overlying trend due to the local coherence of atmospheric seeing variations.

8.6.2.6 Phase 4 : image combination

Phase 4 is the image combination stage, in which multiple images of the same portion of the sky are merged and confronted with the static sky image. Phase 4 operates on the smallest data unit of the static sky, the sky cell, along with the associated pixels from a collection of images which have been processed through phases 1–3. The size and exact representation of a static sky cell are yet to be determined. The working concept is that the static sky cells contain roughly the same number of pixels as an OTA (4k x 4k) and represent a portion of a local tangent plane projection. As mentioned above (Section 8.6.1.1), the pixel scale of the static sky is planned to be 0.2$''$, somewhat smaller than the 0.3$''$ raw image pixel scale.

For each sky cell, the corresponding pixels are extracted from the exposures being processed and mapped to the projection of the sky cell. The pixels from the multiple input processed images are combined into a single, cleaned image. Outlier pixels may be optionally rejected at this stage (optionally, since moving objects will be rejected in images obtained over a wide range of times). This image is then confronted with the static sky cell data to produce a difference image. Residual objects in the difference image above a threshold are detected and excised from the original cleaned image. The remaining pixels are added to the existing static sky image. Object detection must be performed on the difference and cleaned images.

Objects in the difference image are detected and a specific set of object parameters are measured from these detections. Table 25 gives a list of the different detection stages and the object parameters measured for those stages. For the Phase 4 difference image (P4Δ), the measured object parameters consist of: the object centroid and the position covarience matrix, the instrumental PSF magnitude and error, local background level and error, a measurement of the star-galaxy separation, and a measurement of the object shape ($\sigma_x, \sigma_y, \theta$). The detection threshold must be configurable, and be a function of the average background flux or the image noise map. Minimal object classification must be performed to distinguish objects which are consistent with a single PSF, objects which are inconsistent, and objects which are saturated. The resulting collection of detected objects are saved along with the relevant image metadata (i.e., filter, exposure time, etc).

Objects in the cleaned, summed image are detected and a specific set of object parameters are measured from these detections. Table 25 gives a list of the different detection stages and the object parameters measured for those stages. For the Phase 4 summed image (P4Σ), the measured object parameters consist of: the object centroid and the position covarience matrix, the instrumental PSF magnitude and error, local background level and error, a measurement of the star-galaxy separation, a measurement of the object shape ($\sigma_x, \sigma_y, \theta$), the Petrosian radius, magnitude, axis ratio, and angle; and the Sérsic radius, magnitude, axis ratio, angle, and parameter ν. The detection threshold must be configurable, and be a function of the average background flux or the image noise map. Minimal object classification must be performed to distinguish objects which are consistent with a single PSF, objects which are inconsistent, and objects which are saturated. The resulting collection of detected objects are saved along with the relevant image metadata (i.e., filter, exposure time, etc). In this measurement, objects at known positions will also be measured even if they have not been detected.

Objects which are detected in both of the Phase 4Σ and Phase 4Δ images are saved to the AP Database, along with the relevant image metadata (i.e., filter, exposure time, etc). In the process of adding these objects to the database, the transients which are correlated with previous detections of an object (and those which are not) will automatically be determined. An independent process will query the AP Database for such transient objects of interest which are to be sent, along with their associated metadata, to the MOPS and other science client pipelines. This step must be performed at least once per night.

It is essential that the static sky image (which may have been painstakingly accumulated over many months) not be corrupted by adding in transient sources, or data that is of suspect quality (due, e.g., to an error upstream in the processing).

Object analysis of the static sky images is *not* a part of the Phase 4 analysis. This processing is envisioned to take place relatively infrequently (perhaps weekly or even monthly) and is scheduled as a separate analysis task, probably run during the day at a time when the computing infrastructure is not under significant load.

8.6.2.7 Static Sky Analysis

The IPP is responsible for performing object detection and analysis on the static sky. This analysis is performed continuously (every day or week) on those portions of the sky within 15° of the sun. In this analysis, the object measurement is much more detailed than those performed in the real-time analysis. The currently envisioned parameters to be measured for every object are listed in Table 25. The parameters include the object centroid and the position covarience matrix, the instrumental PSF magnitude and error, local background level and error, a measurement of the star-galaxy separation, a measurement of the object shape ($\sigma_x, \sigma_y, \theta$), the Petrosian radius, magnitude, axis ratio, and angle; the Sérsic radius, magnitude, axis ratio, angle, and parameter ν, and a collection of annular aperture flux measurements, all of which are also measured for the P4Σ images. In addition, the galaxy-shape parameters $Gamma_1$&Γ_2, along with the complete 'polarization' terms are measured, as well as a collection of annular aperture flux and variance measurements. Another unique feature of the static sky analysis is that the object detection may be performed simultaneously on all filters, in which case the locations and other parameters may be more strongly constrained by simultaneously fitting between all bands. The analysis to be performed may be substantially more complex than the real-time analysis because of the relatively low data rate. Instead of needed to process thousands of images per night (~ 350Mpix per second), it is only necessary to process the complete sky in a year, or an average rate of $\sim$2 Mpix per second, or $<$ 1% of the object analysis in the other analysis stages.

8.6.2.8 Calibration Stages

The Calibration Analysis Stages construct calibrations from the relevant input data. Some of these combine multiple raw input images together, after processing, to create a high-quality high-signal master calibration image. Some of the calibrations are used to correct other calibrations. Each of the calibration stages must also provide the tools to test the quality of the input data against existing master calibration data and to test the consistency of multiple measurements of the calibration.

The Calibration analysis stages may be performed on whatever timescales are appropriate and necessary to maintain the quality and relevance of the calibration images. Below, we list the specific calibration data which must be constructed in the calibration analysis stages.

The IPP must generate basic calibration images using the raw bias, dark, and flat-field (dome or twilight) images obtained by the telescope as the input. The analysis of these images requires relatively simple stacking of the input set of images. Outlier rejection, both of complete input images as well as pixels within the input stack, must be performed. In addition, each type of image requires an appropriate normalization which may depend on the data levels in other detectors in the input set. Each of these calibration stages must be able to determine from the input stack if the relevant calibration image needs to be updated and perform an initial test to see which input images are consistent and valid.

8.6.2.8.1 Bias Images

Bias images may be needed to correct for structure in the bias. The IPP must have the capability of constructing a master bias image from a stack of raw bias frames. The input bias images, representing offsets from the overscan level, are processed by subtracting the overscan, including 1D structure if needed.

The master bias frame construction uses outlier image and outlier pixel rejection to construct a single high-quality bias frame. The statistic used to determine pixel values from the input stack can be set by the user to be one of the following: the sample mean, median, and mode, robust mean, median, and mode, and the clipped mean and median. Testing of the input images consists of constructing residual images, in which the master bias is applied to the input images. These images may be included or excluded from an additional iteration of the stack on the basis of their pixel-to-pixel statistics.

8.6.2.8.2 Dark Images

Dark images may be needed to correct for structure in the dark current. The IPP must have the capability of constructing a master dark image from a stack of raw dark frames. The input dark images are first corrected for the bias using whatever method is appropriate for the science images. Master dark frames depend on their exposure time. As such, the input dark frames must have a limited range of exposure times, and the output dark frame includes the exposure time as part of its associated metadata.

The master dark frame construction uses outlier image and outlier pixel rejection to construct a single high-quality dark frame. The statistic used to determine pixel values from the input stack can be set by the user to be one of the following: the sample mean, median, and mode, robust mean, median, and mode, and the clipped mean and median. Testing of the input images consists of constructing residual images, in which the master dark image is applied to the input images. These images may be included or excluded from an additional iteration of the stack on the basis of their pixel-to-pixel statistics. A collection of master dark frames with a range of exposure times are used to determine the scaling of the dark frame as a function of exposure time.

8.6.2.8.3 On-Off Dark Images for Light Leaks

A type of image which may be necessary for calibrations will be pairs of images taken at night with the shutter closed with and without the dome shutter closed. Such a pair of images can be used to determine any light-leak in the camera which may contribute additional flux across the mosaic.

8.6.2.8.4 Flat-Field Images

Master flat-field images must be constructed from a collection of input flat-field images. The input flat-field images may be obtained from any of the standard sources: the dome, the twilight sky, and the night-time sky. The choice of flat-field input image must be determined experimentally from observations during the commissioning phase of the telescope. The IPP flat-field construction system must be capable of handling any of these sources.

An appropriate set of input images is selected on the basis of their flux levels, time of observations, and the observing conditions. The input flat-field images are processed (bias and dark corrected if needed) and the resulting images are stacked. The master flat-field construction uses image and pixel outlier rejection to construct a single high-quality master flat-field frame. The statistic used to determine pixel values from the input stack can be set by the user to be one of the following: the sample mean, median, and mode, robust mean, median, and mode, and the clipped mean and median. Testing of the input images consists of constructing residual images, in which the master flat-field image is applied to the input images. These images may be included or excluded from an additional iteration of the stack on the basis of their pixel-to-pixel statistics.

8.6.2.8.5 Mask Images

Preliminary bad-pixel mask images are generated on the basis of comparison between raw flat-field images and a cleaned, stacked master. The mask creation system accepts a collection of flat-field images and identifies pixels which are consistently poorly flattened. Pixels which are under-responsive are also identified as pixels to be masked.

8.6.2.8.6 Sky & Fringe Frames

Fringe-correction frames must be generated to remove the fringe pattern caused by thin-film interference in the top layers of CCDs, particularly in the redder passbands. Fringe correction frames may be constructed on the basis of observations of the night-sky in the appropriate filters or on the basis of dome fringe lamp observations. The choice of the appropriate source will be determined experimentally on the basis of data obtained during the commissioning phase. The IPP must be capable of handing either source. The images are first flattened to remove the pixel-to-pixel sensitivity variations of the detector. The combination of multiple input fringe frames may not be simply stacked since the amplitude of the fringe pattern varies independently of other variations in the image. The amplitude of the fringe pattern in the input frames is measured and the images scaled to normalize the fringe amplitude to a consistent range (-1 to +1) for all input images before they are combined with one of the standard combination statistics (mean, median, mode, etc). The quality of the input frames is tested by flattening the input image and applying the master fringe-frame. The resulting residual image statistics are used to select or exclude specific input images.

8.6.2.8.7 Shutter Correction Map

Shutter correction map images may be generated based on the timing measurements of the shutter itself, or on the basis of dome-flat images of decreasing exposure times down to the shortest available exposures.

8.6.2.8.8 Low-k Sky Models

Large-scale background structure in images which is not caused by thin-film interference must also be detected and corrected. Models of this background structure may be a necessary input to the correction proceedure. The IPP must have the capability of generating image models of the large-scale structure patterns observed with the telescope

8.6.2.8.9 Flat-Field Correction Frame

Flat-field images, whether constructed from the dome, twilight, or night-sky images, do not perfectly correct the detector response in a consistent fashion across the full field of the camera. The IPP must have the capability of generating flat-field photometric correction frames on the basis of the measured photometry of objects which are moved to a variety of

Table 26: Astrometric Reference Catalogs

Name	scatter limit (milliarcsec)	proper motion	depth (mag)	Nstars (millions)	filters
Hipparcos	1	2	7.3	0.1	*V*
Tycho2	10	1	11.5	2.5	*B*,*V*
UCAC-2	20	1	16.0	48.0	*R*
USNO-A2.0	250	N/A	19.0	526.2	*B*,*R*
USNO-B1.0	200	**20 (TBR)**	21.0	1042.6	*B*,*R*
2MASS	70	N/A	**15.0 (TBR)**	470.0	*J*,*H*,*K*

locations on the detector in a sequence of images. The flat-field correction frames analysis stage makes use of targetted observations following a specified dither pattern, and extracts the photometered objects from the AP Database to determine the necessary photometric corrections. The resulting image is applied to the master flat-field image. Testing of the correction is performed by applying the correction to the basic master flat-field image, applying that flat-field image to the dithered photometry observations, and performing the object detections. Comparion of the photometry of individual stars at different locations on the mosaic will demonstrate the consistency of the flat-field image.

8.6.2.8.10 Non-Linearity Correction

The IPP must have the capability of constructing a correction for non-linearity in the detectors. These frames are constructed from exposures of a uniform source with a range of exposure times. The non-linearity correction frames provide polynomial correction coefficients or a lookup table describing the correction. There is likely to be a single non-linear correction for each OTA detector, or potentially for each Cell. The IPP must handle these two cases.

8.6.2.9 Reference Catalog Creation

One of the primary goals inital goals of Pan-STARRS is the creation of photometric and astrometric reference catalogs for the general community and for additional Pan-STARRS calibration. This internally-generated reference catalog is necessary to achieve the photometry and astrometry goals set for the project. The generation of these catalogs is inherently a research project, and will require human control and intervention. The IPP will be required to provide the data access, manipulation and visualization tools needed to construct these reference catalogs and to assess their quality. In this section, we discuss the tools needed for this effort.

8.6.2.9.1 Astrometry Reference Creation

The existing astrometric reference catalogs are known to have limitations in accuracy as noted in Table 26. The internal accuracy of the Pan-STARRS dataset can potentially be much higher than the external reference catalogs. The IPP must have the capability of generating an astrometric reference on the basis of the observations obtained by the AP survey. The IPP must provide the analysis tools needed to generate the master astrometric reference catalog. Much of the required functionality is covered by the AP Database.

The two basic, necessary ingredients for the construction of the Astrometric Reference Catalog are: the observed coordinates of stars and the existing astrometric reference catalogs. Table 26 lists a subset of the reference catalogs which we

Table 27: Photometric Reference Catalogs

Name	scatter mmag	depth mag	filters
SDSS	15	16	*u,g,r,i,z*
CFHT-LS	**10 (TBR)**	18	*u,g,r,i,z*
Landolt	10-20	15	*U,B,V,R,I*

will use at different stages in the analysis process, along with notes about their accuracy.

These catalogs must be available and accessible to the AP Database. It is necessary to have the tools to convert the reference catalog object coordinates to all of the possible coordinate frames of relevance in the telescope and camera system, including:

- Catalog to mean positions
- Mean to apparent positions
- Apparent positions + pointing to arbitrary tangent plane coordinates
- Apparent positions + pointing to focal plane coordinates
- focal plane to specific detector (OTA)
- specific detector to detector cell

In addition to the reference catalogs, it will be necessary to determine and have available for the analysis system a variety of approximate calibration data, including the telescope and camera optical distortion models and the variation of the image PSF across the camera field, as a function of color.

The other necessary ingredient in the astrometry reference creation is the observation of stars by Pan-STARRS. The object detections are produced by several of the analysis stages discussed in the Science Image Analysis section. The likely measurement of relevance to the astrometric reference catalog is the object extraction for the individual, detrended images (section 8.6.2.4). The detected objects must be matched against the reference catalogs, and it must be possible to determine fit coefficients as a function of position alone, or with combinations of magnitude or color. The fitting method must include robust outlier rejection. It is also necessary to have information about the objects which are detected in the catalog, but not the science image or vice-versa, as well as an assessment of the centroiding errors for each object. It must be possible to plot the fit residuals against a wide variety of parameters, including the object positions, magnitudes, colors, etc, and to make subset selections of the objects on the basis of these parameters. .

An alternative measurement of the stellar positions is derived from the guide stars, which are much brighter than the typical saturated stars. It must be possible to compare the coordinates of the guide stars with the coordinates of the other stars in the image. It must also be possible to perform the various fitting steps for the guide stars rather than for the normal image data.

8.6.2.9.2 Photometry Reference Creation

The IPP must provide the analysis tools needed to generate a master photometric reference catalog. The tools needed for generation of the photometric reference catalogs are similar in essence to those used for the astrometric reference catalog. It is necessary to confront the observed objects against the existing reference catalogs to determine the necessary calibrations. Again, much of the required functionality is covered by the AP Database.

The necessary ingredients for the construction of the Photometric Reference Catalog are: the observed magnitudes of stars and the existing photometric reference catalogs. An internally consistent magnitude system will be generated as the primary reference catalog. In addition, comparison of these magnitudes with the reference magnitudes will allow for the determination of color transformations and calibrated magnitudes in the reference system. Table 27 lists a variety of reference catalogs which may be used in the process. These catalogs must be available and accessible to the AP Database.

The other necessary ingredient in the photometry solution is the observation of stars with Pan-STARRS. The photometry is determined by several of the analysis stages discussed in the Science Image Analysis section. The likely measurement of relevance to the photometric reference catalog is the object extraction for the individual, detrended images (section 8.6.2.4). It is necessary to have the tools to convert between different photometric systems, including:

- instrumental to nominal detector magnitude
- nominal detector magnitude to average filter system
- average filter system to reference photometry system

These transformations are based on a set of measured coefficients for the color and airmass dependency of the measurement. In addition to these types of transformations, it is necessary to have the ability to measure and apply relative photometry corrections.

The detected objects must be matched against the reference catalogs, and it must be possible to determine fit coefficients as a function of airmass, magnitude, color and detector coordinates, or with combinations of the above. The fitting method must include robust outlier rejection. It is also necessary to perform exclusions on the basis of object locations, instrumental magnitudes, observed and reference errors, and time of the observations. It must be possible to plot the fit residuals against a wide variety of parameters, including the object positions, magnitudes, colors, etc, and to select a subset of the objects on the basis of these parameters. It will likely be necessary to maintain individual color transformations for each detector and filter combination to a single internal system for each filter.

An alternative measurement of the stellar photometry is derived from the guide stars, which are much brighter than the typical saturated stars. It must be possible to relate the magnitudes of the guide stars with the magnitudes of the other stars in the image. It must also be possible to perform the above fitting steps for the guide stars rather than for the normal image data.

8.6.3 Modules

In order to encapsulate functionality, the analysis stages are constructed of a sequence of steps. The analysis stages consist of scripts in a high-level language, likely to be either Python or Perl, which executes a sequence of C-level functions. The C-level functions called by the script are called *modules* and represent basic data analysis operations.

8.6.4 Pan-STARRS IPP Library

In order to facilitate testing and development, and to encourage flexibility, the IPP is built in a layered fashion. The lowest level functions are written in C and collected together into a Pan-STARRS library, `PSLib`.

The Pan-STARRS Data Library consists of C structures describing the basic data types needed by the IPP and C functions which perform the basic data manipulation operations. The library is organized into four topics: System Utilities, Basic Data Collections, Data Manipulation, and Astronomy-Specific Functions. The Modules are constructed using these low-level Library functions as needed.

8.7 Summary of Derived Requirements

8.7.1 The IPP Image Server shall accept raw images from the summit at a sustained rate of 1 exposure (4 FPAs or 8 GB) per **40 seconds (TBR)**.

8.7.2 The IPP Metadata Database shall accept metadata from the summit at a sustained rate of **1 MB per 40 second (TBR)**.

8.7.3 The IPP Calibration Analysis shall produce master calibration images from the raw calibration images in less **2 hours (TBR)**.

8.7.4 Master calibration images shall not introduce systematic uncertainties in the photometry greater than **0.2% (TBR)**.

8.7.5 The IPP Science Analysis shall pre-process the science images with the master calibration images at a sustained rate of 1 exposure per **40 seconds (TBR)**.

8.7.6 The IPP Science Analysis shall merge multiple pre-processed science images into stacked images with corresponding signal-to-noise maps at a sustained rate of 1 exposure per **40 seconds (TBR)**.

8.7.7 The IPP Science Analysis shall excise pixels from the input images which are outliers for the ensemble of corresponding pixels with an efficiency of $> 99\%$.

8.7.8 The IPP Science Analysis shall merge the cleaned images into the static sky image, and update the corresponding exposure (S/N) maps, at a sustained rate of 1 exposure per **40 seconds (TBR)**.

8.7.9 The IPP Science Analysis shall detect and measure parameters of objects on the pre-processed science images.

8.7.10 The IPP Science Analysis shall detect and measure parameters of objects on the stacked science images.

8.7.11 The IPP Science Analysis shall detect and measure parameters of objects on the difference images.

8.7.12 The IPP Science Analysis shall detect and measure parameters of objects on the static sky images.

8.7.13 The IPP Science Analysis shall determine astrometry of the detected objects relative to an external astrometric reference with an accuracy of **750 mas (TBR)** (for bright objects) in the Commissioning phase of the telescope.

8.7.14 The IPP Science Analysis shall determine astrometry of the detected objects relative to an external astrometric reference with an accuracy of **250 mas (TBR)** (for bright objects) during the construction of the Pan-STARRS Astrometric Reference Catalog.

8.7.15 The IPP Science Analysis shall determine astrometry of the detected objects relative to the Pan-STARRS Astrometric Reference with an accuracy of **100 mas (TBR)** (for bright objects) during normal operations.

8.7.16 The IPP Science Analysis shall determine photometry of the detected objects within an internal photometric system with scatter less than **25 millimags (TBR)** (for bright objects) during the Commissioning phase of the telescope in photometric weather.

8.7.17 The IPP Science Analysis shall determine photometry of the detected objects within an internal photometric system with scatter less than **10 millimags (TBR)** (for bright objects) during the construction of the Pan-STARRS Photometric Reference Catalog in photometric weather.

8.7.18 The IPP Science Analysis shall determine photometry of the detected objects within an internal photometric system with scatter less than **5 millimags (TBR)** (for bright objects) during normal operations in photometric weather.

8.7.19 The IPP Science Analysis shall determine photometry of the detected objects in an external photometric system with scatter less than **10 millimags (TBR)** (for bright objects) during normal operations in photometric weather.

8.7.20 The IPP Reference Creation System shall produce an astrometric reference catalog from the extracted objects within 6 months of the end of the AP Survey.

8.7.21 The IPP Reference Creation System shall produce an astrometric reference catalog with an absolute accuracy of **100 mas (TBR)** and a local relative accuracy of **30 mas (TBR)** for bright objects.

8.7.22 The IPP Reference Creation System shall produce an astrometric reference catalog with proper motions measurements for non-solar-system objects with an accuracy of **20 mas / year (TBR)** for unsaturated, bright stars.

8.7.23 The IPP Reference Creation System shall produce a photometric reference catalog from the extracted point-source objects within 6 months of the end of the AP Survey.

8.7.24 The IPP Reference Creation System shall produce a photometric reference catalog with a consistency across the sky of **5 millimag (TBR)**.

8.7.25 The IPP Reference Creation System shall produce a photometric reference catalog with an absolute calibration to the external system (defined by **SDSS (TBR)** and the CFHT Legacy Survey Standards) with an accuracy of **10 millimag (TBR)** (for bright objects).

8.7.26 The IPP shall publish the static sky images to the Pan-STARRS PSPS on a time-scale of **6 month (TBR)**.

8.7.27 The IPP shall publish the detected objects to the Pan-STARRS PSPS on a time-scale of **1 month (TBR)**.

8.7.28 The IPP shall publish the IPP and OTIS metadata to the Pan-STARRS PSPS on a time-scale of **1 week (TBR)**.

8.7.29 The IPP shall provide to the MOPS subsystem the detected single-occurrence transient objects **by the end of every night (TBR)**.

8.7.30 The IPP shall provide to the MOPS subsystem the metadata appropriate to the images from which single-occurrence transient objects were detected **by the end of every night (TBR)**.

8.7.31 The IPP shall provide to external Pan-STARRS clients the detected objects within **5 minute (TBR)** after the image is obtained.

8.7.32 The IPP shall store the raw images for a period of **1 month (TBR)**.

8.7.33 The IPP shall store the detected objects for a minimum of **1 year (TBR)**.

8.7.34 The IPP shall store the metadata for the lifetime of the project.

8.8 Internal Interfaces

The IPP has internal interfaces between several of the architectural components and between the architectural components and the analysis stages.

8.8.1 IPP Scheduler - IPP Controller. The IPP Scheduler must send to the IPP Controller information about the tasks to be performed and must receive from the IPP Controller descriptions of the success or failure of these tasks.

8.8.2 IPP Scheduler - Metadata DB. The IPP Scheduler must query the Metadata DB to determine an appropriate course of action. The IPP Scheduler must send result and status information to the Metadata DB.

8.8.3 IPP Controller - Analysis Tasks. The IPP Controller must initiate the Analysis Tasks and monitor their output and exit status.

8.8.4 Analysis Tasks - Metadata DB. The Analysis Tasks must be able to query the Metadata DB as needed to extract metadata needed for a given task. The Analysis Tasks must be able to send results and updates to the Metadata DB.

8.8.5 Analysis Tasks - Image Server. The Analysis Tasks must be able to extract relevant images from the Image Server. The Analysis Tasks must be able to send output images to the Image Server.

8.8.6 Analysis Tasks - AP DB. The Analysis Tasks must be able to extract information related to specific objects from the Astrometric and Photometric Database. The Analysis Tasks must be able to send result detections to the AP Database.

8.9 Requirements Trace Matrix

Subsystem Requirements		**System/Subsystem Requirements**	
Number	**Caption**	**Number**	**Caption**
8.2.1	Photometrically consistent images to 1%	3.2.2.5	Photometric precision of 0.01 mag
8.2.2	Photometrically calibrated images to 1%	3.2.2.5	Photometric precision of 0.01 mag
8.2.3	Absolute astrometry to 100 mas	3.2.2.6	Absolute Astrometric precision of 100 mas
8.2.4	Relative astrometry to 30 mas	3.2.2.7	Relative Astrometric precision of 100 mas
8.2.5	Background correction to 1%	3.5.12	remove foregrounds to $<$ 1% of background
8.2.6	Construct Static Sky for g filter images	3.2.2.10	construct static sky images
8.2.7	Construct Static Sky for r filter images	3.2.2.10	construct static sky images
8.2.8	Construct Static Sky for i filter images	3.2.2.10	construct static sky images
8.2.9	Construct Static Sky for z filter images	3.2.2.10	construct static sky images
8.2.10	Construct Static Sky for y filter images	3.2.2.10	construct static sky images
8.2.11	Construct Static Sky for w filter images	3.2.2.10	construct static sky images
8.2.12	Detect & classify objects on science images	3.2.2.16	classify detected objects
8.2.13	Detect & classify objects on science image stacks	3.2.2.16	classify detected objects
8.2.14	Detect & classify objects on static sky images	3.2.2.16	classify detected objects
8.2.15	Detect & classify transients	3.2.2.16	classify detected objects
8.2.16	Degrade image size by $<$ 10 mas	3.5.2, alloc.	Degrade image size by $<$ 27% of median seeing
8.2.17	Process images arriving at cadence of 40 seconds	3.2.2.3	processing for transients within 5 min
8.2.18	Limit false alarm rate for transients	3.2.2.13	false alarm rate of $< 1\%$
8.2.19	Publish static sky images to PSPS	3.2.2.18	Data Products shall be made available
8.2.20	Publish detected objects to PSPS	3.2.2.18	Data Products shall be made available
8.2.21	Publish metadata to PSPS	3.2.2.18	Data Products shall be made available
8.2.22	Provide access to preferred science clients	3.5.10	allow interface to preferred science clients
8.2.23	Store raw images for 1 month	allocated	
8.2.24	Store detected objects for 1 year	allocated	
8.2.25	Store metadata for project lifetime	allocated	

Derived Subsystem Requirements		Top-level Subsystem Requirements	
Number	**Caption**	**Number**	**Caption**
8.7.1	Accept images from summit at rate...	8.2.17	Process images arriving at cadence of 40 seconds
8.7.2	Accept metadata from summit at rate...	8.2.17	Process images arriving at cadence of 40 seconds
8.7.3	Produce master calibration images in...	allocated	
8.7.4	Master cal. image introduce less than 1%	8.2.1	Photometrically consistent images to 1%
8.7.5	Pre-process science image at rate...	8.2.17	Process images arriving at cadence of 40 seconds
8.7.6	Merge images into stacked images at rate...	8.2.17	Process images arriving at cadence of 40 seconds
8.7.7	Excise $>$ 99% of outlier pixels from stack	8.2.18	Limit false alarm rate for transients
8.7.8	Merge cleaned images into static sky at rate...	8.2.17	Process images arriving at cadence of 40 seconds
8.7.9	Measure objects on pre-processed images	8.2.12	Detect & classify objects on science images
8.7.10	Measure objects on stacked images	8.2.13	Detect & classify objects on science image stacks
8.7.11	Measure objects on difference images	8.2.15	Detect & classify transients
8.7.12	Measure objects on static sky images	8.2.14	Detect & classify objects on static sky images
8.7.13	astrometric accuracy for commissioning phase	allocated	
8.7.14	astrometric accuracy for reference catalog phase	allocated	
8.7.15	astrometric accuracy for normal operations	8.2.3	Absolute astrometry to 100 mas
8.7.16	photometric accuracy for commissioning phase	allocated	
8.7.17	photometric accuracy for reference catalog phase	allocated	
8.7.18	relative photometric accuracy for normal operations	8.2.2	Photometrically calibrated images to 1%
8.7.19	absolute photometric accuracy for normal operations	8.2.2	Photometrically calibrated images to 1%
8.7.20	astrometric reference within 6 mo	8.2.3, allocated	Absolute astrometry to 100 mas
8.7.21	astrometric reference astrometry accuracy	8.2.3	Absolute astrometry to 100 mas
8.7.22	astrometric reference proper motion accuracy	8.2.3	Absolute astrometry to 100 mas
8.7.23	photometric reference within 6 mo	8.2.2, allocated	Photometrically calibrated images to 1%
8.7.24	photometric reference global consistency	8.2.2	Photometrically calibrated images to 1%
8.7.25	photometric reference absolute accuracy	8.2.2	Photometrically calibrated images to 1%
8.7.26	publish static sky images every 6 mo.	8.2.19	Publish static sky images to PSPS
8.7.27	publish detected objects every 1 mo.	8.2.20	Publish detected objects to PSPS
8.7.28	publish metadata every 1 week	8.2.21	Publish metadata to PSPS
8.7.29	provide transients to MOPS rate...	8.2.22	Provide access to preferred science clients
8.7.30	provide metadat to MOPS at rate...	8.2.22	Provide access to preferred science clients
8.7.31	provide transients to other clients at rate...	8.2.22	Provide access to preferred science clients
8.7.32	store raw images for 1 month	8.2.23	Store raw images for 1 month
8.7.33	store detected objects for 1 year	8.2.24	Store detected objects for 1 year
8.7.34	store metadata for project lifetime	8.2.25	Store metadata for project lifetime

Notes

[20]we will test the output accuracy using sample Megacam data

[21]or image header

9 MOPS Conceptual Definition

9.1 Subsystem Overview

The MOPS will be the only Pan-STARRS-funded preferred science client. There are two clear motivations for this distinction as described in the following two sub-sections: the planetary science benefit of identifying ten million new asteroids and comets, and the Earth impact risk reduction that will be achieved by tracking the location of thousands of Potentially Hazardous Objects.

9.1.1 Asteroid & Comet Science

- Pan-STARRS's tremendous throughput allows the opportunity for a 50-fold increase in the database of known asteroids and comets. In a single lunation Pan-STARRS may detect as many asteroids and comets as were detected in the last two centuries. We predict that roughly 10^7 solar system objects will be discovered in ten years of Pan-STARRS operations.
- The IPP component of the Pan-STARRS system will detect moving solar system objects, but their attribution to known objects, linking new observations together, maintaining a list of orbits, identifying orbit 'stubs' by their similarity in orbit parameters, etc., is large and complicated effort that requires an independent processing subsystem (also known as a "science client"). To establish the reliability and significance of the scientific results requires a system with a well-determined and monitored efficiency.

9.1.2 Impact Risk Reduction

- $\sim$50% of the sub-global Earth impact risk (impacts that cause less than global damage) is carried by objects with D$>$300m (H$<$21.2) (Stokes et al. 2003). Pan-STARRS can significantly reduce the risk of impact due to these objects.
- Detection and monitoring of Near Earth Objects (NEO) and Potentially Hazardous Objects (PHO) is a high-profile topic of strong public interest with outreach, educational and associated funding opportunities.

9.2 Subsystem Top Level Requirements

To address the system motivation of Section 9.1, Pan-STARRS's top-level science requirements for the solar system are as follows:

9.2.1 MOPS shall create and maintain a data collection of detections and object parameters (e.g. orbit elements, absolute magnitudes) for $>$90% (TBR) of the PHOs that reach R=24 (corresponding to m$_w \sim TBD$ in the solar system filter) for $\geq$ 12 (TBR) contiguous days during the course of Pan-STARRS operations.

9.2.2 MOPS shall create and maintain a data collection (DC) of detections and object parameters (e.g. orbit elements, absolute magnitudes) for $>$90% (TBR) of the members that reach R=24 (corresponding to m$_w \sim TBD$ in the solar system filter) for $\geq$ 12 (TBR) contiguous days within each class of solar system object (Main Belt, Trojan, Centaur, TNO, Comet, etc, except NEO and PHO) during the course of Pan-STARRS operations.

Table 28: 90% Completion Levels

Survey Year	Risk	D_{PHO}	H_{PHO}	H_{MB}	H_{TRO}	H_{CEN}	H_{TNO}	H_{SDO}
1	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
2	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
5	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
10	50% (TBR)	$\sim$ 300m	(TBR) $\sim$ 21.2 (TBR)	$\sim$ 19.2 (TBR)	$\sim$ 17.0 (TBR)	$\sim$ 9.3 (TBR)	$\sim$ 7.0 (TBR)	$\sim$ 4.0 (TBR)

9.2.3 MOPS shall calculate the efficiency and false-positive rates for detection, attributing, linking, orbit identification, etc, for solar system objects as a function of (at minimum) semi-major axis, eccentricity, inclination, absolute magnitude, position with respect to opposition and galactic latitude.

9.2.4 Data products created by MOPS shall be published to the Pan-STARRS Published Science Products Subsystem (PSPS).

Table 28 gives the equivalent absolute magnitude (H) at which a population is 90% complete after the specified number of surveying years. It also gives the reduction in Earth impact risk due to discovering unknown PHOs and the approximate equivalent diameter at which the survey will be 90% complete.

Derived MOPS requirements from these top-level requirements in the course of developing this System Concept Definition are highlighted in bold face in the text and are summarized in Section 9.7

9.3 Subsystem Top-level Description

9.3.1 Top-level View

Figure 31 shows the MOPS System Concept of Operations.

9.3.2 Component Description

- Metadata DC
- 3σ Single Occurrence DC
- 5σ Single Occurrence DC
- Attributed Observations DC
- Derived Objects DC
- Synthetic Objects DC
- Tracklet DC

9.3.3 Data Products

- Attributed Observations
- Tracklets

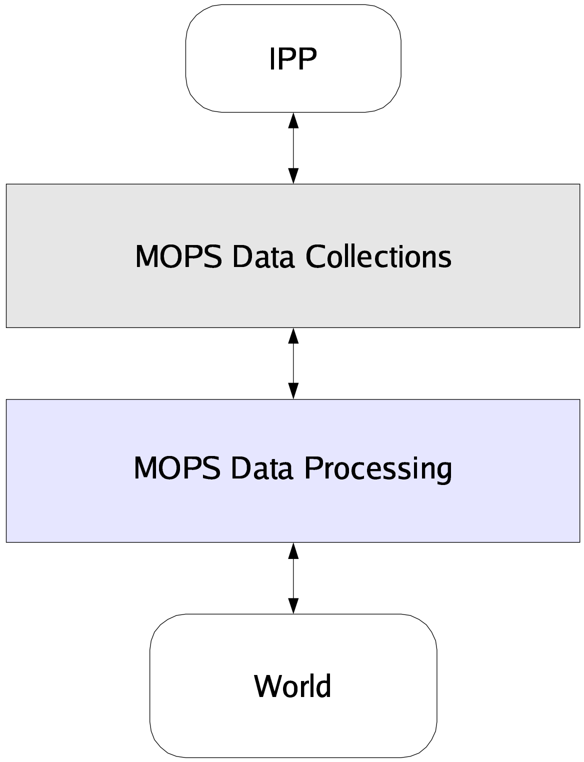

Figure 31: MOPS System Concept of Operations

9.4 Subsystem Tasks and Functions

In order to satisfy the top-level science requirements listed in the previous section, the primary responsibilities of the MOPS will be to perform the following tasks:

9.4.1 Determining ephemerides of known objects in images,

9.4.2 Attributing detections to known orbits,

9.4.3 Identifying detections of likely moving objects,

9.4.4 Linking detections of the same unknown object together,

9.4.5 Calculating and fitting orbits to detections,

9.4.6 Integration of osculating orbit elements,

9.4.7 Storing and maintaining data collections (DC) of astro-photometry for attributions,

9.4.8 Storing and maintaining DCs of orbit and object parameters,

9.4.9 Measuring the system efficiency for moving object studies,

9.5 Operational Scenarios

The MOPS system is fed by data from the Image Processing Pipeline (IPP) after the IPP has processed survey images from the telescopes and identified 'single-occurrence' detections. The MOPS will require that a single occurrence detection have no other detection identified at that location during the previous Transient Time Interval (TTI, about 15-30 minutes).

The MOPS itself will need to maintain a variety of DCs some of which will be copies of sub-sets of data retrieved from the IPP. Some of the DCs will be transient, useful only for a short period of time. Other DCs will be permanent and grow with time as new detections and object parameters are added.

After processing of Pan-STARRS data by the MOPS, the information will be published to the larger planetary science community. In particular, since Pan-STARRS is concerned about reducing the risk of an Earth impact but will not develop the in-house expertise to perform the risk analysis, the PHO data will be released relatively quickly to a pre-arranged and limited set of groups. All solar system data will be generally released as soon as practicable. Pan-STARRS will take advantage of the large set of historical asteroid and comet detections available from the IAU's Minor Planet Center as well obtaining new detections by other surveys that will assist Pan-STARRS's orbit determination and linking processes.

9.6 Conceptual Design

The MOPS will handle all detections of new and known solar system objects identified in the course of Pan-STARRS surveying. A schematic representation of the MOPS is given in Figure 32. Each process or DC within the system assists in addressing at least one of the primary responsibilities listed in Section 9.4. Each of the conceptual design elements of Figure 32 is described briefly in the following subsections. Conceptual details of some elements are given in the following section.

The fundamental data processed by the MOPS is that obtained through surveying the sky with the telescope. Every Pan-STARRS survey mode will adopt an observing cadence with at least two images taken at each location separated in time by a Transient Time Interval (TTI). This will allow Pan-STARRS to separate stationary from non-stationary transient detections, and thereby allow the MOPS to attribute serendipitous detections of solar system objects to known orbits. The survey will need to occur in a manner consistent with MOPS operational requirements. The Pan-STARRS input to the MOPS is filtered through the Image Processing Pipeline (IPP) so that the MOPS has only two 'direct' inputs from Pan-STARRS as shown in Figure 32. The MOPS will also be capable of accepting external sources of input data, in particular from the International Astronomical Union's (IAU) Minor Planet Center (MPC) in order to start the system with a known sample of object orbits and positions.

9.6.1 Pan-STARRS Components

This section deals with those elements contained in Figure 32 that are components of the Pan-STARRS system but not part of the MOPS system.

9.6.1.1 Pan-STARRS Telescope & Survey

All Pan-STARRS survey modes will survey in a manner suitable for identification of moving solar system objects. The Solar System Survey (SSS) mode will be specially designed to enhance the efficiency of linking detections of the same object over many nights. The final details of the SSS will be based on simulations with a prototype MOPS and telescope scheduler. In general, the MOPS will require that multiple images of the same portion of sky be acquired within a relatively

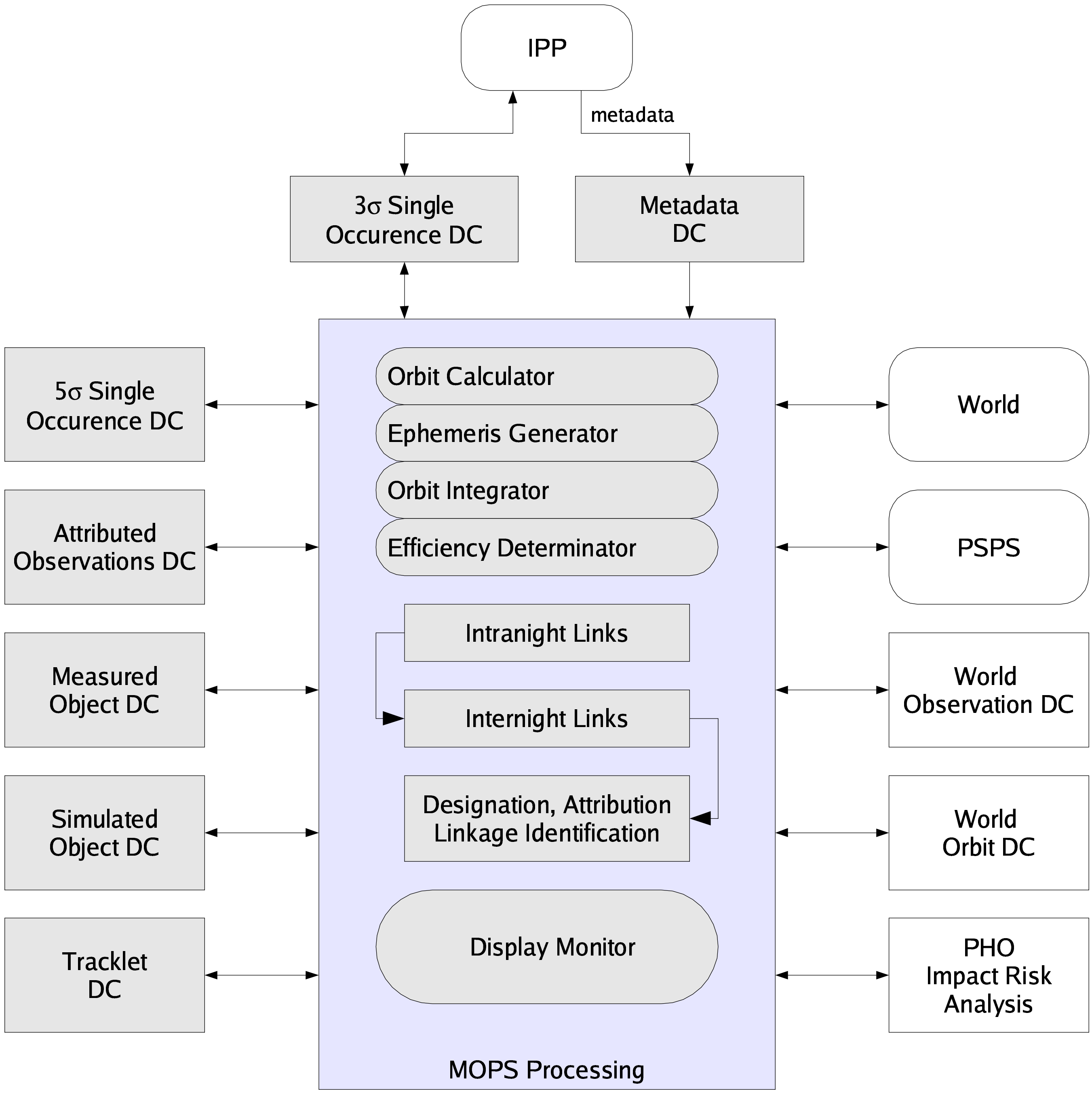

Figure 32: MOPS System Concept Design

short time interval. At least one pair of images of each FOV will be acquired within a TTI on each night. The surveyed ecliptic region will be covered in a manner that provides a high probability of obtaining at least three pairs of detections of the same object in a lunation over a time period of at least a week. The PS Telescope & Survey (the OTIS system) and the IPP will generate a corresponding set of 'metadata' including items such as the telescope bore sight pointing and a detection efficiency parameterization that will be saved as part of the MOPS metadata DC (Section 9.6.2.1).

As mentioned in the previous paragraph, Pan-STARRS will also survey in other modes from which positions and magnitudes of known SS objects may be extracted. The alternate surveying modes will, whenever possible, implement a policy of separating pairs (at least) of images at the same location by a TTI to allow separation of stationary and non-stationary transient objects. Thus, serendipitous observations of known moving objects during these surveys may be used for attribution of detections (positions and extraction of color information) and possibly for linking of detections. Some other survey modes may adopt re-observing cadences suitable to linking SS objects and the MOPS will use these data to feed the MOPS linking process in a manner otherwise identical to the processing of the SS survey data.

9.6.1.2 Image Processing Pipeline (IPP)

The IPP is described in detail in PSDC-430-005. Among the tasks carried out by the IPP is the identification of single-occurrence detections of 3σ significance or greater. The IPP will create a difference image by subtracting a deep, low-noise reference image from the current image. Single-occurrence detections are those identified in a difference image for which another detection at the same location does not exist in previous images within the last TTI. The MOPS will create its own permanent DC of these detections as described in Section 9.6.2.2. The IPP will also generate a corresponding set of metadata including items such as a parameterization of detection efficiency, exposure time, etc., that will be saved as part of the MOPS metadata DC (Section 9.6.2.1).

9.6.2 MOPS Data Collections

Development is anticipated for the primary data collections of the MOPS conceptual design as shown in Figure 32. In addition to the need for developing, implementing, and testing the DC logical and physical models, the MOPS requires a C API for the anticipated functionality of common calls to the DCs.

9.6.2.1 Metadata DC

The IPP will provide the MOPS a metadata DC of the exposure history of all images that contribute to the single occurrence DC (Section 9.6.2.1). This DC will include parameters such as the image time and location, seeing characterization, and efficiency. In order to avoid access clashes with the IPP metadata DC, and because the MOPS will require a significantly smaller sub-set of the available metadata, the MOPS will create a separate version of a metadata DC.

9.6.2.2 3σ Single Occurrence DC

The IPP will provide a list of single-occurrence detections with their (TBD) characteristics to the MOPS. In order to avoid access clashes with the IPP detections DC, and because the MOPS will only require a sub-set of the available detections, the MOPS will create a separate version of a 3σ single occurrence DC. The MOPS will search through the single occurrence DC for detections that are consistent with known moving objects, and also search for detections that are consistent with being the same unknown moving object.

It is important to recognize that '3σ' really means 'x-σ' where x$\sim$3. The actual cut-off on the S/N for inclusion in this DC will be determined by the overall system performance and the level at which the MOPS can handle the false positive detection rate.

9.6.2.3 5σ Single Occurrence DC

In order for the MOPS to identify unknown solar system objects, moving objects must first be identified in the Pan-STARRS data. This will set requirements on Pan-STARRS surveying and the IPP as described in Section 9.6.1.1.

It is likely that dealing with the 3σ single occurrence DC will provide too many false positive candidates so the MOPS will extract single occurrence detections of $> 5\sigma$ significance from the 3σ single occurrence DC and store them in a separate DC. If there are n detections in the 3σ Single Occurrence DC and the MOPS reduces that number by a factor of $\sim$1000 in the 5σ Single Occurrence DC, the search time through the smaller database is faster by a factor of

$$\frac{1000n\log(1000n)}{n\log n} = 1000\left[1+\frac{3}{\log n}\right] > 1000$$

for large n. This DC will be used when searching for brighter attributions and when attempting to link detections to identify new unknown objects. Still, the 5σ DC will include about 10^6 real detections per night as well as 10^6 synthetic detections per night and a roughly equal number of real and synthetic false positive detections.

It is important to recognize that '5σ' really means 'y-σ' where y$\sim$5. The actual cut-off on the S/N for inclusion in this DC will be determined by the overall system performance and the level at which the MOPS can handle the false positive detection rate.

9.6.2.4 Attributed Observations DC

The process of identifying detections of known objects is known as attribution. The Attributed Observations DC will provide a link between an object (see Section 9.6.2.5) and the detections with which it has been associated. The IAU's MPC maintains a list of observations of all known objects so the MOPS will periodically coordinate the contents of its attributed observations DC with the MPC's version of the same information.

9.6.2.5 Derived Objects DC

Once detections have been linked to one another over a sufficiently long period of time it is possible to derive various parameters for the object and its orbit including its orbit elements and absolute magnitude. The MOPS will maintain a DC of all these parameters and update them periodically. The derived parameters for real objects will be uploaded periodically to the IAU's MPC.

9.6.2.6 Synthetic Object DC

In order to test the efficiency and noise-rejection capability of the sub-system the MOPS will 'inject' synthetic detections and noise into the system that will be processed along with the actual data. The Synthetic Object DC will contain all the parameters necessary to simulate the position and brightness of synthetic objects. The MOPS will determine the observables for any object in the synthetic object DC that appears in every difference image that contributes to the MOPS

3σ DC (Section 9.6.2.2). Every synthetic object that appears in the image will be added to the 3σ single occurrence DC and there will be a flag in that DC indicating that the entry is a synthetic detection.

It would be preferable to have many more objects in the Simulated Object DC than will eventually be measured by Pan-STARRS. A large number of objects would ensure a better measure of the system efficiency. On the other hand, injecting a large number of synthetic objects into the data stream would artificially increase the computational load and probably reduce the system efficiency. Furthermore, a large DC of synthetic objects requires a larger DC for storage. In order to balance these effects with the necessity of measuring the system efficiency, the MOPS will create a synthetic object DC that re-creates the actual (selection effect corrected) orbit distribution of all solar system objects that might be acquired by Pan-STARRS in ten years of operation. We anticipate about 10^7 objects, dominated by the MB but also including NEOs, Centaurs, Trojans, TNOS (classical, resonant and scattered) and comets (short, medium and long term).

The orbit distribution of the synthetic objects must mimic the expected orbit distribution as closely as possible for two reasons: 1) in order to generate a better measure of the efficiency in those bins that have more data and 2) because when the observational selection effects are determined as a function of a particular parameter the 'hidden' parameters in the bin are required to have the proper distribution in order to provide a good estimate of the selection effects.

The MOPS will also incorporate a population of extremely rare or unknown types of orbits in the synthetic population. While no survey has yet detected a bona fide interstellar object (on a hyperbolic orbit with respect to the Sun) or retrograde MB asteroid our synthetic database will contain a small number of these orbits to test the extremes of the system. Since they are not members of the expected actual population of objects they will be specially flagged throughout the process so that they are not used when calculating observational selection effects.

9.6.2.7 Tracklet DC

The MOPS will search the 5σ single occurrence DC in order to identify sets of detections (tracklets) taken within a TTI that are likely to be the same object. The number of detections included in a tracklet will depend on the SS survey mode. The simplest tracklet will be a pair of detections obtained within a TTI. In the 5σ single occurrence DC there are roughly 200 false detections deg^{-2}, which is comparable to the expected sky-plane density of asteroids on the ecliptic (and therefore also comparable to the density of synthetic detections on the sky). At 1 deg/day an object will move about 75 arcsec ($\sim$375 pixels) in a 30-minute TTI. To identify objects moving this fast requires an attempt at linking all possible pairs of detections in an image that lie within 375 pixels of one another. Fully 50% of pairings attempted in this manner will be incorrectly linked tracklets (**REF (TBD)**). However, the vast majority of solar system objects move slower than about 1 deg/day, there is other information available to reduce the false tracklet rate (detection flux and shape), the inter-night linking procedure (Section 9.6.3.2) will be very effective at eliminating false tracklets, and the final choice of TTI may be sky location dependent and may be smaller than 30 minutes.

Greater than 98% of PHOs with $V < 24$ over the entire night sky move at less than 5 deg/day or 375 arcsec ($\sim$1875 pixels) in a 30-minute TTI. The false pairing rate becomes significant at these rates of motion and will lead to a large number of false tracklets. The false tracklet probability at these rates of motion will be reduced by making use of the shape and flux levels of the detections within the tracklets. At 5 deg/day an object will trail by $\sim$31 pixels during the course of a single 30s exposure. Adding only those objects with similar flux levels, shapes and orientations will maintain the false tracklet rate below an acceptable threshold. If there is any ambiguity in adding detections to tracklets all possible tracklets will be considered. Each tracklet's velocity vector will be extrapolated to its expected location at local midnight to facilitate the linking (Inter-Night Links) and attribution processes (Attribution).

9.6.3 MOPS Development Tasks

The following sub-Sections introduce each of the major sub-processes within the MOPS.

9.6.3.1 Intra-Night Links

Linking detections of objects on a night will consist of creating tracklets of detections (not necessarily unique) as described in Section 9.6.2.7.

9.6.3.2 Inter-Night Links

On a regular basis the MOPS will accumulate all likely moving object tracklets (as identified in Section 9.6.2.7) and attempt to link them between nights. The simplest manner to envisage the process is to extrapolate each tracklet's motion vector to midnight on every other night (Section 9.6.2.7) specified that all tracklets have their extrapolated position at midnight stored in the Tracklet DC). If the extrapolated position and motion vector coincides with another tracklet on another night then assume that both tracklets represent the same object and use the inter-night motion to predict the object's location and motion vector on other nights. Once multiple nights of detections are identified for an object an orbit will be fit to the astrometric positions to determine if the detections are consistent with a single object in orbit about the Sun (or perhaps in orbit around a major planet or in a hyperbolic orbit with respect to the Sun). If a good orbit is obtained with low residuals then the MOPS will eliminate detections that have unacceptable residuals with the orbit and place them back into the pool of unassigned detections for further processing.

This scenario has many avenues for improving the linking efficiency or speed of the process. The extrapolated motion may be achieved through a simple linear or quadratic propagation in RA and Dec or it might be achieved using circular or Väisälä orbits or more sophisticated probabilistic techniques (e.g. Tholen's TwoObs routine as described in PSDC-500-001).

The combinatoric complexity of linking millions of tracklets together over many nights may be very difficult. A promising approach is a kd-tree implementation of the linking process that has already demonstrated efficient and fast linking of a preliminary simulation of one lunation of Pan-STARRS data. A kd-tree is a data structure designed for 'orthogonal range searching' (**REF (TBD)**). It is useful, for instance, to find the set of points that fall into a given range within a k-dimensional space. This is exactly the problem in linking together detections of tracklets in a position, velocity and flux space.

In the kd-tree linking process the location of an object is predicted at some time step and then all detections consistent with that prediction must be identified. Given a kd-tree of all detections (position, velocity, flux) it is possible to find the resulting points in $O(\sqrt{n} + k)$ time where n is the number of points and k is the number of points in the result. In a simulated lunation of Pan-STARRS data this technique achieved $> 97\%$ efficiency for linking MBO and $> 90\%$ efficiency for NEOs over the entire sky. The false linking rate is small and the linking is achieved in less then two minutes on a typical high-end desktop workstation. The technique has been shown to be insensitive to the introduction of astrometric and photometric errors and to the introduction of false positive detections at the 1:1 level.

Even though these results are impressive there are a number of improvements that will be implemented. At the moment the technique uses no physics and no *a priori* information about the probability distribution of accelerations at each location on the sky. The search is already very fast but might be sped up even further by sub-dividing the sky into smaller analysis blocks since typical rates of motion of objects over the entire sky are calculable.

9.6.3.3 Designation

Once a track has been established to correspond to a good orbit (and therefore a real object) its calculated parameters must be stored in the Measured Objects DC (Section 9.6.2.5). The object will be assigned a unique but temporary internal (to Pan-STARRS) identifier known as a designation. The object will eventually be assigned an official IAU designation that will replace the internal identifier but it will still be necessary to maintain a record of the different designations assigned to an object. Future observations of the object may not be immediately recognized as the same object and may be assigned a new designation. When multiple orbit 'stubs' are identified (Section 9.6.3.5) as belonging to the same object there will be a system to decide which designation is to be associated with the combined orbits. The MOPS will maintain a record of the designations assigned to an orbit.

9.6.3.4 Attribution

At the 5σ detection level Pan-STARRS will detect $\sim$200 asteroids deg^{-2} on the ecliptic. It will also detect about 200 false positive detections per deg^{-2} over the entire sky. Most of the false positive detections will be eliminated in the tracklet creation process (Section 9.6.2.7). Eliminating attributable detections to known orbits prior to attempting to link detections together (Section 9.6.3.2) will reduce the combinatoric complexity of the linking process. Furthermore, attributing detections to known orbits increases the arc-length of observations for an orbit and will enable a new and improved determination of the orbit for the object.

At the 3σ detection level Pan-STARRS will detect about 200,000 false positive detections per deg^{-2}. It will be possible to attribute detections to known moving objects in each field-of-view. By predicting the location of each object (with error estimates) and matching the prediction to tracklets of detections with the correct location (and therefore directions and rates of motion), flux and shape parameters (e.g. orientation of the trail axis) it should be possible to attribute detections down to the 3σ detection level with high fidelity.

9.6.3.5 Identification

Each lunation a large number of apparently new objects will be found and their orbital and other derived parameters will be stored in the Measured Objects DC (Section 9.6.2.5). Before an object is placed in that DC its orbit will be extrapolated to other nights in the current and past lunations to search for other detection tracklets consistent with this orbit. This search will necessarily be limited by the accuracy of the extrapolated ephemeris position. After some time the error on the predicted position becomes so large that it is impossible to attribute detections to the orbit. However, the orbital parameters themselves may be accurate enough to allow a comparison with other orbits in the DC. If two orbit's shapes and orbital planes agree well then an attempt will be made to fit all the detections in both orbit 'stubs' to a single orbit. This process is known as 'orbit identification'.

9.6.3.6 Orbit Calculator

Given a set of detections of (presumably) the same object it is necessary to calculate a preliminary orbit for the detections and then differentially correct (fit) the orbit elements. The orbit calculator(s) will be capable of robustly determining an orbit for a wide range of arc lengths from (perhaps) minutes to tens of years. The algorithms shall use estimated ephemeris errors in the differential correction process. All the major perturbers in the solar system (all nine planets and the major asteroids) will be accounted for using an accepted solar system ephemeris for those objects such as JPL's DE405.

Various software packages are available for each type of ephemeris generator as detailed in PSDC-500-001. The industry standard is set by software developed at JPL while other packages developed at the IAU MPC, NEODys, and Lowell Observatory perform nearly as well.

OrbFit is not good at fitting short arcs of detections so it will be necessary develop or obtain a set of orbit determination routines applicable to different arc lengths. Circular and Väisälä orbits will be useful for preliminary orbits for very short arcs (even to as short as a few minutes) as well as Tholen's TwoObs routine (see PSDC-500-001) that can provide an entire suite of orbits that are consistent with the detections.

Calculation of orbital parameter errors will be critical to fast and accurate attribution of detections and will be a critical component of an ephemeris software package.

9.6.3.7 Ephemeris Generator

To test the linkage of detections (Section 9.6.3.2), attribute detections to objects (Section 9.6.3.4), create synthetic detections (Section 9.6.3.9), etc, requires the ability to quickly and accurately predict the location of objects in each image.

The proper method of determining the ephemeris is to use an N-body integrator. Given an osculating orbit the N-body integrator accounts for all interactions between solar system objects in predicting the apparent location of the object as viewed from Earth at any other time. But this is a very slow process. N-body integrators require an accepted solar system ephemeris for those objects such as JPL's DE405 ephemeris.

A fast technique for determining an object's ephemerides is a 2-body code that takes into account only the Sun and object. The 2-body calculation is quick but also inaccurate, especially for times far from the epoch of osculation for an orbit and for objects that are close to another massive object (e.g. NEOs to Earth).

The Goldilocks approach is to integrate all orbits (Section 9.6.3.8) to a time near the time of observation, use a 2-body ephemeris generator to quickly determine the approximate observables of all objects at midnight for the night of observation, and then use an N-body integrated ephemeris for each object close to the field of view at the time of an image. The IPP psLib can then determine the pixel location of the object for the FOV and whether it was detected based on its location, brightness, and rate of motion.

Calculation of ephemeris errors are critical to fast and accurate attribution of detections and will be considered a critical component of an ephemeris software package.

Various software packages are available for each type of ephemeris generator as detailed in PSDC-500-001. The industry standard is set by software developed at JPL while other packages developed at the IAU MPC, NEODys , and Lowell Observatory will be evaluated.

It is also possible that a suite of other ephemeris routines will need to be used. For instance, Tholen's TwoObs routines (see PSDC-500-001) allows targeted recovery of short-arc orbits by exploring the entire phase space of allowed ephemeris positions.

9.6.3.8 Orbit Integrator

It is likely that performing an N-body ephemeris calculation as described in Section 9.6.3.7 for every single object will be computing intensive and unnecessary. There will be many times where a simple and fast 2-body (Sun + object) ephemeris calculation will be appropriate. In this case, it is necessary to have orbit elements with epochs of osculation close to the time at which the ephemeris is desired. The actual time difference between the epoch of osculation and the epoch of the ephemeris may vary with the type of object for which the calculation is being performed. Objects far from the Sun, Earth and other major planets will not be sensitive to the time difference and epochs of osculation every lunation would be appropriate. For objects very close to Earth it is likely that the 2-body calculation is inappropriate but the number of these objects is small in any event.

Various software packages are available for each type of ephemeris generator as detailed in PSDC-500-001. The industry standard is set by software developed at JPL while other packages developed at the IAU MPC, NEODys , and Lowell Observatory will be evaluated.

9.6.3.9 Efficiency Determination Processor

The MOPS will be capable of characterizing itself and the Pan-STARRS system efficiency for detecting solar system objects as a function of an object's orbital elements, other object-specific parameters (e.g., absolute magnitude), and against various survey parameters (e.g., galactic latitude).

Regularly measuring the efficiency of the MOPS is important for two reasons:

- to determine when the system breaks:
  By consistently monitor the system efficiency changes in the efficiency will signal a problem in the system.
- to correct for observational and operational selection effects: From a science analysis perspective, the Pan-STARRS data is almost useless unless it is possible to correct for the effects of observational and operational selection. The MOPS end-user must be able to distinguish between a reduction in a population of asteroids and a reduction in the efficiency for detecting that population.

Probably the best mechanism for monitoring the system efficiency is to generate synthetic data along with the real data and treat all data sets identically in the process flow. The accuracy of the efficiency determined in this way will be limited by the ability to generate realistic synthetic data mimicking the properties of the real objects. More importantly, the increased combinatoric complexity of introducing sythetic data and noise into the real data flow may reduce the overall system efficiency.

One approach would be to generate synthetic detections directly in the images from each telescope to test the IPP's ability to detect moving objects. But this is in the realm of the IPP and it will have its own techniques for determining and monitoring its efficiency.

Instead, the MOPS will inject synthetic data ($> 3\sigma$) and noise ($> 5\sigma$) at the root of its process flow directly into its 3σ single occurrence DC (see Section 9.6.2.2) from which all the MOPS analysis derives. The synthetic data and noise shall be analysed in exactly the same manner parallel to the actual data analysis.

The synthetic noise is injected into the data stream to test the ability of the MOPS to reject false detections and to monitor the number of false detections that are incorporated into real orbits.

The synthetic orbits appropriate to the efficiency determination have already been discussed in Section 9.6.2.6. It might be useful to incorporate other parameters that could eventually be measured for real objects into this data base such as pole orientation, light curve amplitude, period and phase, etc. In this manner it would be possible e.g. to determine the efficiency with which Pan-STARRS detects objects of a given light curve amplitude.

9.6.3.10 Display Monitor

To allow quick assessment of the health of the MOPS a GUI will be developed that will summarize the current state of the system for internal use only. The GUI will be updated in nearly real-time when the MOPS is operational and provide summary statistics and important ratios. Expected ranges for the various values and ratios will be incorporated into the design. When a parameter is in-range it will be displayed in green but if it falls out of range the value will be displayed in red. The list of possible parameters and ratios to monitor is extremely large but an illustrative set includes:

- Number of 3σ single occurrence transients in the most recent image
- Running average number of 3σ single occurrence transients in the most recent N images
- ratio of the number of 3σ to 5σ single occurrence transients
- total number of detected objects
- linking efficiency this lunation
- attribution efficiency this lunation
- identification efficiency this lunation

A web-based interface to the daily operations of the MOPS may be made available to the public. This version of the GUI might be a single page, nearly real-time presentation of global MOPS statistics such as the total number of new objects detected by the project and in the last lunation, current sky coverage rates, etc.

9.6.4 External Components

The major external I/O interfaces to the MOPS are shown on the right side of Figure 32. They are described briefly in the following four Sections.

9.6.4.1 World Observations DC

The IAU's MPC maintains a DC of all attributed detections of known objects. The MOPS will regularly upload new Pan-STARRS detections to representatives of the solar system community, download new detections by other observatories to the equivalent MOPS DC, and ensure that the DCs are synchronized in terms of designations for the attributions. Observations from other observatories shall be weighted appropriately when they incorporated into Pan-STARRS's orbit determinations.

9.6.4.2 World Orbits DC

The IAU's MPC is the clearinghouse for all astrometric and photometric measurements of objects in the solar system. The MOPS system will be initiated by downloading derived parameters for all known objects before beginning MOPS operations. The MOPS will then continue to periodically download updates to the IAU's MPC DC of known objects in order to keep the MOPS DC up to date.

9.6.4.3 World

The rest of the world will want access to Pan-STARRS's DC of observations and orbits. To promote Pan-STARRS's contribution to solar system science the MOPS will provide a web-based interface to a sub-set of the data available in its DCs.

9.6.4.4 PHO Impact Risk Analysis

The MOPS will not be responsible for quantifying the impact risk of each object except in the sense of determining the Minimum Orbital Intersection Distance (MOID) for each object. The impact risk analysis will be calculated by other groups around the world who currently do so in an automated manner. These groups include the Jet Propulsion Laboratory (JPL), the University of Pisa's Dynamics Group (NEODyS), the IAU's MPC and a few others. The MOPS will allow special access to its objects DC (Section 9.6.2.5) by these groups or specifically upload updated object parameters for each object with less than a critical MOID to them on a regular basis.

9.6.5 MOPS Sub-Process Flowcharts

The following four sub-sections provide high-level conceptual overviews of the flow through four critical MOPS sub-processes in order to implement the MOPS functionality shown in Figure 32.

As new images are acquired the MOPS will generate synthetic detections and noise and inject them into the data stream. When a set of new images is acquired within a TTI the MOPS will attempt to attribute detections to the predicted location of derived objects. After multiple nights of observations have been acquired in the same region of sky the MOPS will attempt to link detections of the same moving object between nights. The linking process will be iterative as the ability to link detections will depend on the set of detections that are still unlinked. e.g., as the number of unlinked detections decreases the combinatoric difficulty of the problem decreases and the opportunity of linking objects with unusual motion vectors will increase. The attribution and linking process will take place on both actual and synthetic detections in a parallel fashion. The MOPS will then utilize the results of the linking, attribution and orbit identification sub-process for sythetic data to determine the system efficiency and noise rejection capabilities.

9.6.5.1 Known Object Attribution

On a regular basis the MOPS will sift through all Single Occurence Detections and attempt to attribute them to known objects. At a fundamental level this involves simply predicting the location and flux of every object within every image and attributing detections to the predictions. Once the attribution has taken place the object's orbit can be updated.

The operation of Pan-STARRS and the IPP has already been described in Section 9.6.1.1. The IPP produces two DCs as input to the MOPS: the Pan-STARRS (IPP+OTIS) metadata and the IPP's 3σ detections DC. The IPP's version of the 3σ detections DC contains much more information and many more detections than the MOPS version. For instance, the IPP DC will include all 3σ detections rather than only those 3σ detections that do not correspond to another detection at the same location within a TTI. The MOPS will extract all the information it requires from the IPP DCs and fill its own versions of the Metadata DC and 3σ Single Occurence Detection DC. These then become the source of all further MOPS analysis.

To streamline the computing time required to calculate accurate ephemerides (position, apparent magnitude, motion vector, error estimates on each, etc) for all objects in each image each night, a coarse 2-body ephemeris will first be generated for

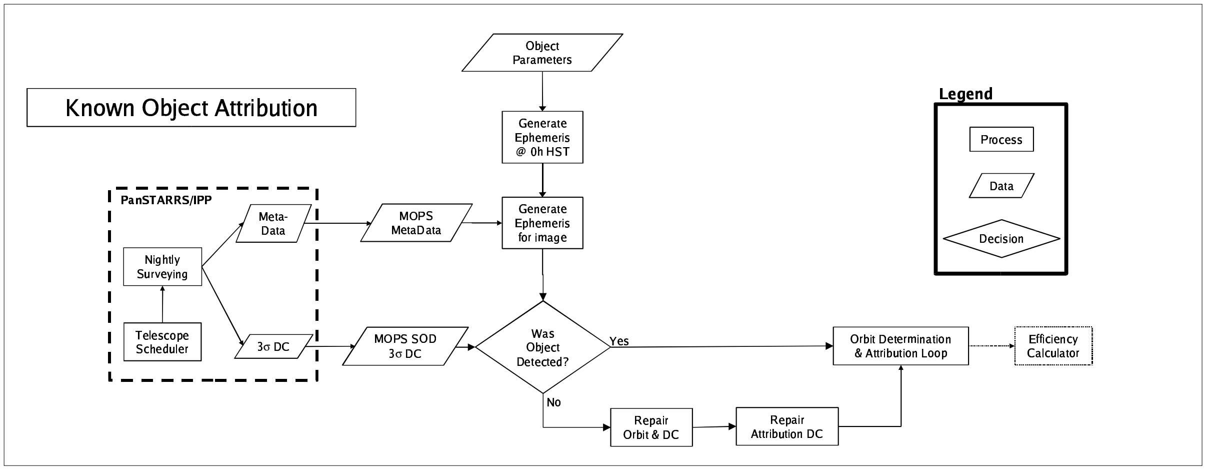

Figure 33: Process Flow for Attributing Detections to Known Objects

every object at local midnight. This process requires that orbital elements for the derived objects have all been integrated to an epoch near the desired date. Only those objects above the horizon after/before astronomical twilight has begun/ended and that are sufficiently bright that Pan-STARRS might detect them need be maintained for the remainder of this process. There will be $\sim 10^6$ objects detectable by Pan-STARRS each night.

For every image acquired on each night an N-body ephemeris with error estimates for each object will be generated in order to attribute detections. N-body ephemerides need only be calculated for the set of objects near the telescope boresight as determined with the coarse ephemerides calculated in the previous paragraph. The determination of which objects are close to the boresight will be sped up by application of a kd-tree (see Section 9.6.3.2). This should narrow down the number of objects predicted to lie in each field to $<\sim 1500$.

When a set of images are available within a TTI the MOPS will determine if any set of detections matches the predicted ephemerides of known objects. This calculation will be sped up by application of a kd-tree (see Section 9.6.3.2). If the MOPS predicts that an object should have been detected and can attribute a set of detections it then the orbit for that object shall be re-calculated after which the various associated DCS will be updated.

If the MOPS predicts that an object should have been multiply detected and it was not, then it may imply that there is something wrong with the object's derived parameters. In this case the MOPS will invoke a sub-process that will carefully examine the orbit calculation for the object, the detections attributed to it, etc, in order to determine the source of the inconsistency between the prediction and lack of a set of detections.

9.6.5.2 Linking New Detections

The previous sub-section described the process of attributing detections to known objects, but most of Pan-STARRS's detections will be of previously unknown small solar system bodies. These detections need to be linked together, an orbit should be fit to the detections, and the associated DCs need to be updated for valid new objects and attributions.

On a regular basis, which could be anywhere from per TTI image set to per lunation depending on the MOPS design, the MOPS will extract 5σ detections from its 3σ detections DC. The higher S/N data will then be used to extract tracklets and to fill the 'Tracklets DC'. Section 9.6.2.7 described how creating likely tracklets will dramatically reduce the combinatoric difficulty of inter-night linking of detections in Section 9.6.3.2.

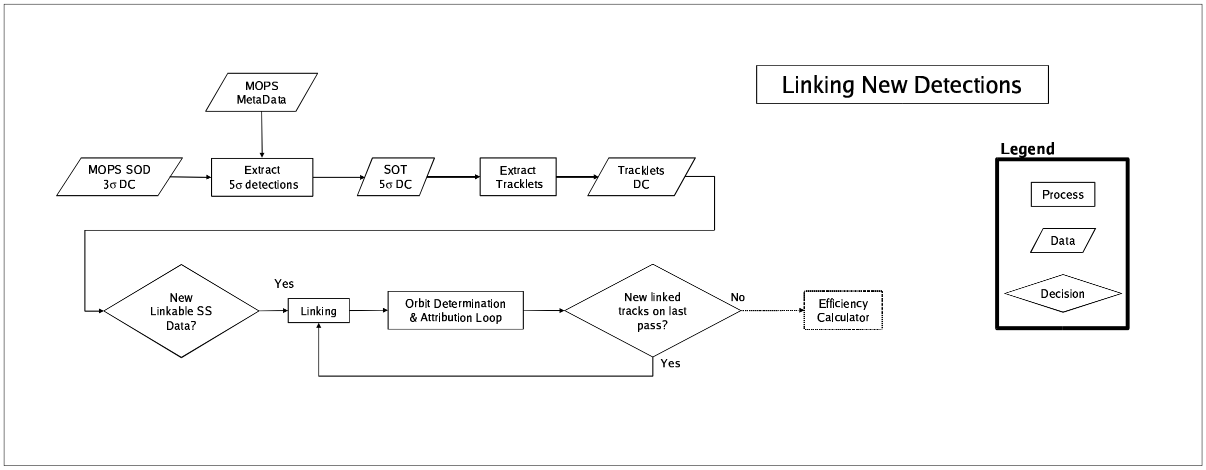

Figure 34: Process Flow for linking new detections

As Pan-STARRS surveying proceeds there will occur natural times at which it makes sense to attempt linking detections/tracklets. Very loosely, to be able to fit a good orbit to a set of detections requires a total arc-length spanning a few days with at least three (TBR) separate nights of observations. On the other hand, the linking efficiency will decrease substantially if the time between successive observations is too long: perhaps greater than one week between successive nights or greater than a couple weeks over the set of three nights (TBR). The appropriate limits on the arc-length and time between observations will be left until late in the design process so as to incorporate realistic simulations of the MOPS performance. In any event, linking detections of SS objects will proceed whenever suitable multi-night data becomes available.

The tracklet linking process to create inter-night tracks of detections has already been described in Section 9.6.3.2. The process will err on the side of creating too many false positive tracks because the final determination of whether a track is 'real' is decided by fitting a physical orbit to the track. The Orbit Determination & Attribution Loop is described in detail in Section 9.6.5.3 but the result of that loop is that only high probability valid orbits will remain. It is also responsible for updating the various DCs when new orbits and attributions are determined.

The process of searching for linkable detections/tracklets and orbit identification iterates until no more new objects are found. New links may be found on subsequent iterations since the pool of available tracklets is modified on each pass.

9.6.5.3 Orbit Determination and Attribution Loop

Each time an orbit needs to be calculated for a set of detections it raises the possibility that the orbit may be improved enough that new attributions or orbit identifications may be identified. Thus, the process flow shown in Figure 35 is invoked each time new detections are attributed to a known orbit, detections are removed from the attribution list for a known orbit, or a set of detections are linked and identified as a new object. The exact set of steps in this process flow may be modified depending on the history of the set of input detections. e.g., Accurate and established orbits need not check for precoveries on every iteration because they will have already been identified on prior passes through the loop. The flow shown in Figure 35 is representative of the process for newly linked detections.

Given a set of detections with no pre-existing orbit a fast 2-body Initial Orbit Determination (IOD) will be calculated and the residual to the orbit for each of the detections in the track may then be used to remove detections that are not consistent with an orbit. This process will be iterative until the track contains only detections consistent with the IOD or the track

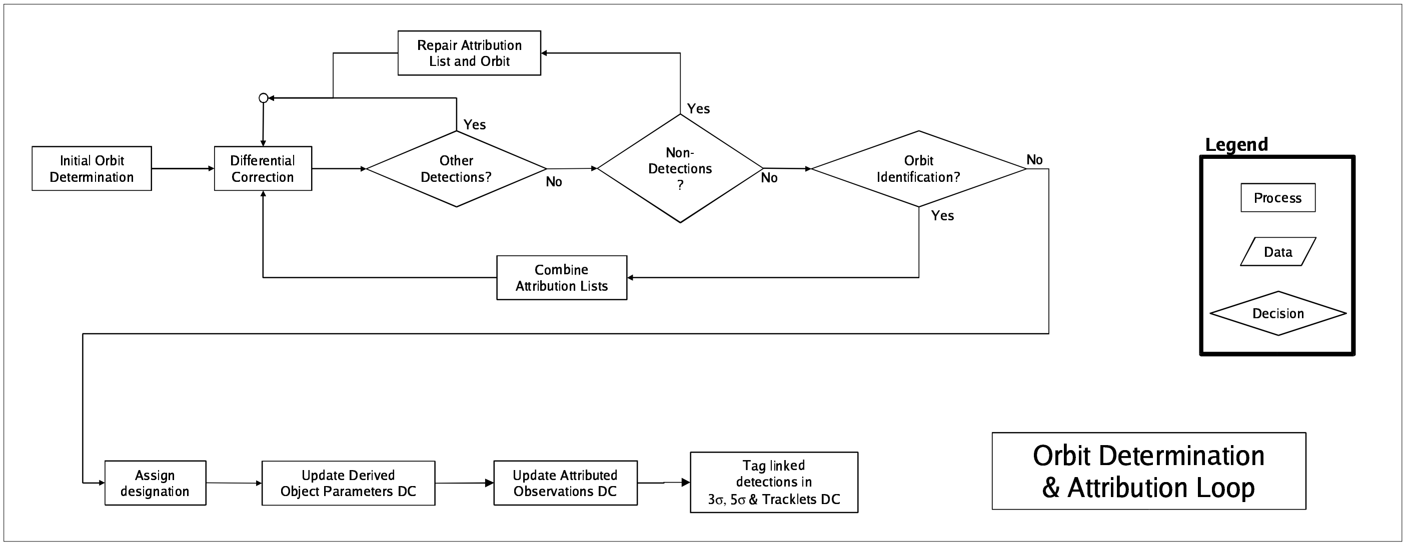

Figure 35: Orbit Determination and Attribution Process Flow

contains too few detections to calculate an orbit. Detections that have been removed from the track will be made available to future iterations through the detections/tracklets DCs.

The nature of the IOD will be flexible with an anticipated need for Gaussian, circular, Väisälä and statistically ranged orbits. Furthermore, different software packages converge on slightly different sets of data so that there will be a suite of IOD packages available that can be used in a cascading scheme until a preliminary orbit is determined for the set of detections in the track. Since some of the detections in a track may not be an observation of the object the software will try many different combinations of detections within a track for the IOD before the track is discarded as false.

After the IOD an attempt will be made to differentially correct (fit) the orbit using a full N-body calculation. On every pass through this loop there is the opportunity for rejecting attributions that are inconsistent with the current orbit.

Once an acceptable orbit is available it can be used to generate an ephemeris for the object's positions at the time of other Pan-STARRS images and an attempt will be made to identify other detections/tracklets that are associated with this object. It is likely that with short-arc orbits the ephemeris prediction will not be accurate and other approaches such as Tholen's KNOBS routine may be invoked to predict the object's location at other times. In any event, identifying which of thousands of recent images may include other detections of this object may be computationally expensive for tens of thousands of new short-arc orbits per month. This is another avenue for expedient use of kd-tree techniques (e.g. Section 9.6.3.2).

At the same time that ephemeris predictions are used to identify other detections of the object, it is likely that some of the possible orbit element phase space can be excluded by the lack of detections in a set of images in which they were predicted.

Once all possible detections/tracklets have been linked to this orbit 'stub' a search will be implemented to determine if other orbit stubs exist in the Derived Objects DC (Section 9.6.2.5) that are similar to this one and may represent the same object. If the orbits are similar a new attempt at differentially correcting an orbit to the combined set of detections in the orbit can be attempted to determine an improved orbit. The orbit identification process (through similarity of orbit parameters) is another avenue for expedient use of kd-tree techniques (Section 9.6.3.2).

When the iterative process of orbit determination $\rightarrow$ orbit identification has converged a number of bookkeeping tasks need to be performed:

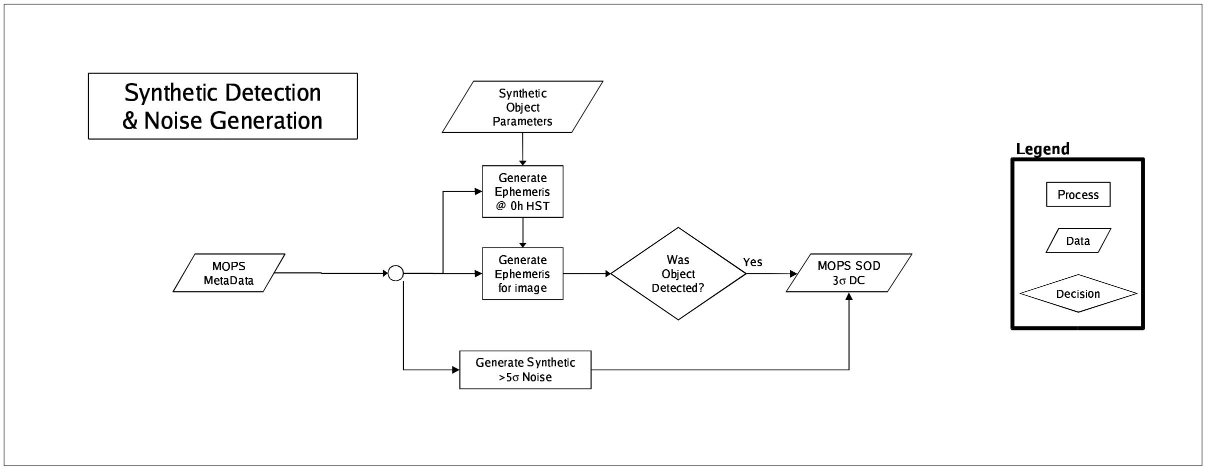

Figure 36: Generation of Synthetic Detections & Noise

- The object/orbit will receive an internal designation that will uniquely identify it forever (Section 9.6.3.3).
- The orbit must be appended or updated in the Derived Objects DC (Section 9.6.2.5).
- All observations of the object need to be added to the Attributed Observations DC (Section 9.6.2.4).
- All the detections and tracklets that were linked to the orbit need to be flagged in the MOPS 3σ, 5σ and Tracklets DCs (Section 9.6.2.5) as having already been assigned to a detected orbit.

9.6.5.4 Synthetic Detection & Noise Generation

The determination of the MOPS efficiency and rejection capability is critical to monitoring the system performance and to science data analysis. These measurements will be made using synthetic data (both detections and noise). Figure 36 shows the process flow for generating the synthetic data.

The MOPS will inject synthetic $> 3\sigma$ detections into the MOPS $> 3\sigma$ DC in a manner that borrows from the process shown in Figure 33. For every image acquired by Pan-STARRS and processed by the IPP the exact location of synthetic objects (see Section 9.6.2.6) in the image shall be calculated and their synthesized detections will be injected into the MOPS 3σ Single Occurrence DC. The synthetic object's location and flux measurements will be 'fuzzed' to mimic typical Pan-STARRS performance. To speed this process the 2-body ephemerides of all synthetic objects shall first be calculated at local midnight. The precise locations of each synthetic object then need only be calculated for objects that lie close to the field-of-view of the image as described in Section 9.6.5.1.

To test the ability of the MOPS to reject false detections it will also inject synthetic noise into the data stream starting. Synthetic noise of $> 5\sigma$ significance shall be injected into the 3σ detections DC. By injecting the noise into the 3σ Single Occurence Detections DC the MOPS will be capable of monitoring its noise rejection capability while creating and linking tracklets (see Section 9.6.5.2).

9.6.5.5 Efficiency Determination

The determination of the MOPS efficiency and rejection capability is critical to monitoring the system performance and to science data analysis. These measurements will be made using the synthetic data (both detections and noise) generated as described in Section 9.6.5.4. The synthetic data will be run through the same analysis code (e.g. Sections 9.6.5.1, 9.6.5.2 and 9.6.5.3) as the actual data in a parallel but separate process. Once the analysis of the synthetic data is complete (for a given time period) the MOPS can determine the system efficiency with which it e.g., attributes detections to orbits, links detections into tracklets, tracklets into tracks, tracks into orbits. The MOPS will monitor the accuracy of the determination of orbital parameters, absolute magnitude and other object characteristics. It will also be able to determine the rate at which false detections are incorporated into orbits. By calculating cumulative and running values for each of the monitored parameters it will be possible to identify when the system is operating properly and which part of the system has gone awry (or been improved) should anything change.

The difference between the synthetic and actual data analysis streams is that each analyzes only those detections that are synthetic and non-synthetic respectively. A small complication is the treatment of noise in the $(3\sigma, 5\sigma])$ range. Since the 3σ Single Occurrence DC will be a very large DC, adding synthetic noise to it over the full range of S/N detections, would double the size of an already large DC. Roughly 99.999% of the detections in the S/N range $(3\sigma, 5\sigma])$ are already false so the synthetic data analysis stream will treat *all* detections in this range as noise in its analysis.

9.7 Summary of Derived Requirements

This section calls out all the derived requirements identified in bold face in this SCD. Recall that the MOPS TLRs are given in Section 9.2.

9.7.1 The MOPS shall operate on single occurence detections of transient objects.

9.7.2 The MOPS shall import metadata from the IPP.

9.7.3 The MOPS shall import single occurance detections from the IPP.

9.7.4 The MOPS shall identify tracklets from the 5σ DC with a false identification probability of $\leq 5\%$ **(TBR)**.

9.7.5 The MOPS shall accumulate all likely moving object tracklets and attempt to link them between nights at least **once per lunation (TBR)**.

9.7.6 The MOPS shall eliminate detections with residuals greater than **5 times the astrometic uncertainty (TBR)**.

9.7.7 Newly identified objects shall be assigned a unique internal identifier.

9.7.8 The MOPS shall cross-reference IAU-designated objects with the internal identifiers.

9.7.9 The MOPS orbit calculator shall be capable of determining an orbit for arc lengths ranging from **1 minute (TBR)** to 100 years to a precision of **(TBD)**.

9.7.10 The ephemeris software package shall include the capability of calculating ephemeris errors.

9.7.11 The MOPS shall provide subsystem status information through an internal user interface.

9.7.12 The MOPS shall integrate orbits for derived objects **at least once every 100 days (TBR)** to an epoch within **100 days (TBR)** of the current date.

9.7.13 The MOPS requires precalculated ephemerides and their errors for objects that may be observable on a given night.

9.7.14 The MOPS shall monitor the accuracy of the orbital parameters

9.7.15 The Synthetic Object DC shall incorporate **at least** 10^8 **(TBR)** synthetic detections with noise.

9.7.16 The Synthetic Object DC shall contain all the parameters necessary to simulate the position and brightness of synthetic objects.

9.7.17 The Synthetic Object DC shall incorporate a population of extremely rare types of orbits.

9.7.18 The MOPS shall determine the rate at which false detections are incorporated into orbits.

9.7.19 The MOPS shall publish attributed detections of Solar System objects to the PSPS **at least once per month (TBR)**.

9.7.20 The MOPS shall publish derived Solar System objects to the PSPS **at least once per month (TBR)**.

9.7.21 The MOPS shall periodically coordinate the contents of its attributed observations DC with the Minor Planet Center (MPC).

9.7.22 The MOPS shall periodically coordinate the derived parameters for real objects with the MPC.

9.7.23 The MOPS shall provide data access to approved end-users.

9.7.24 The MOPS shall have a C API for the anticipated functionality of common calls to the DCs.

9.7.25 The MOPS requires C APIs to existing orbit and ephemeris software packages that are not already written in C .

9.8 Internal Interfaces

The are two classes of major interfaces required for the MOPS. Interfaces to the various DCs and interfaces to pre-existing software critical to MOPS operations.

9.8.1 Data Collection Interfaces

Each of the major DCs identified in Figure 32 requires a MOPS C API. The C interfaces will simplify interaction with the DCs for typical access requirements. It will also be possible to direct SQL queries directly to the DCs.

9.8.2 Pre-existing software interfaces

To speed the MOPS development it will make use of a variety of pre-existing orbit and ephemeris determination software packages (see PSDC-500-001). These packages are in various states of organization and will be brought under Pan-STARRS revision control. Furthermore, they are often written in other languages (e.g. C++, Fortran 90, Fortran 77) and will require C APIs for compatibility with the rest of the MOPS system.

9.9 Requirements Trace Matrix

Subsystem Requirements		System/Subsystem Requirements	
Number	**Caption**	**Number**	**Caption**
9.2.1	detections and orbits for PHOs	3.2.2.17	
9.2.2	detections and orbits for other Solar-system objs.	3.2.2.17	
9.2.3	characterize false-positive rate	3.2.2.13	
9.2.4	publish data products	3.2.2.18	Science data products made available via the Internet

Derived Subsystem Requirements		Top-level Subsystem Requirements	
Number	**Caption**	**Number**	**Caption**
9.7.1	operate on single occurence detections	9.2.1	detections and orbits for PHOs
9.7.1	operate on single occurence detections	9.2.2	detections and orbits for other Solar-system objs.
9.7.2	import metadata from the IPP	9.2.1	detections and orbits for PHOs
9.7.2	import metadata from the IPP	9.2.2	detections and orbits for other Solar-system objs.
9.7.3	import single occurance detections from the IPP	9.2.1	detections and orbits for PHOs
9.7.3	import single occurance detections from the IPP	9.2.2	detections and orbits for other Solar-system objs.
9.7.4	identify tracklets from the 5σ DC	9.2.1	detections and orbits for PHOs
9.7.4	identify tracklets from the 5σ DC	9.2.2	detections and orbits for other Solar-system objs.
9.7.5	link tracklets between nights	9.2.1	detections and orbits for PHOs
9.7.5	link tracklets between nights	9.2.2	detections and orbits for other Solar-system objs.
9.7.6	eliminate detections with large residuals	9.2.1	detections and orbits for PHOs
9.7.6	eliminate detections with large residuals	9.2.2	detections and orbits for other Solar-system objs.
9.7.7	assigned a unique internal identifier	9.2.1	detections and orbits for PHOs
9.7.7	assigned a unique internal identifier	9.2.2	detections and orbits for other Solar-system objs.
9.7.8	cross-reference IAU-designated objects	9.2.1	detections and orbits for PHOs
9.7.8	cross-reference IAU-designated objects	9.2.2	detections and orbits for other Solar-system objs.
9.7.9	orbit calculator capability	9.2.1	detections and orbits for PHOs
9.7.9	orbit calculator capability	9.2.2	detections and orbits for other Solar-system objs.
9.7.10	ephemeris software capability	9.2.1	detections and orbits for PHOs
9.7.10	ephemeris software capability	9.2.2	detections and orbits for other Solar-system objs.
9.7.11	subsystem status information interface	9.2.1	detections and orbits for PHOs
9.7.11	subsystem status information interface	9.2.2	detections and orbits for other Solar-system objs.
9.7.12	integrate orbits for derived objects	9.2.1	detections and orbits for PHOs
9.7.12	integrate orbits for derived objects	9.2.2	detections and orbits for other Solar-system objs.
9.7.13	precalculate ephemerides for observable objects	**from OTIS (TBD)**	
9.7.14	monitor the accuracy of the orbital parameters	9.2.3	characterize false-positive rate
9.7.15	incorporate **at least** 10^8 **(TBR)** synthetic detections	9.2.3	characterize false-positive rate
9.7.16	Synthetic Object DC contents	9.2.3	characterize false-positive rate
9.7.17	incorporate rare types of objects	9.2.3	characterize false-positive rate
9.7.18	determine the rate of false detections	9.2.3	characterize false-positive rate
9.7.19	publish attributed detections to the PSPS	9.2.4	publish data products
9.7.20	publish derived Solar System objects to the PSPS	9.2.4	publish data products
9.7.21	coordinate attributed observations DC with MPC	allocated	
9.7.22	coordinate derived parameters with the MPC	allocated	
9.7.23	provide data access to approved end-users	allocated	
9.7.24	C API to the DCs	allocated	
9.7.25	C APIs to existing software packages	allocated	

10 Published Science Products Subsystem Conceptual Definition

10.1 Subsystem Overview

The Published Science Products System (PSPS) will consist of both computer hardware and software necessary to distribute and deliver the Pan-STARRS data products to several classes of end-users. In general, end-users will have access to the Pan-STARRS data products over the Internet via a web interface. For certain types of data the end-user will be able to submit database style queries to the PSPS data store through the web interface.[22] Other types of data may be small enough in size to be displayed on one or several web pages, or contained in sets of files that may be selected and downloaded.

The remainder of this section will describe the PSPS subsystem requirements, the subsystem concept of operations, and the PSPS conceptual design. Wherever possible, the PSPS design has leveraged similar work and lessons learned from other astronomical survey applications including, but not limited to the Sloan Digital Sky Survey, Two Micron All-Sky Survey and Large Synoptic Survey Telescope.

10.2 Top Level Requirements

10.2.1 System Level Requirements

The requirements presented in this section are the system top level requirements, found in Sections 3.2.2 and 4.7, that apply to the PSPS.

3.2.2.18 The science data products created by the collection and reduction of Pan-STARRS data shall be made available for analysis through an accessible data archive system via the Internet.

4.7.19 The system shall be capable of archiving up to **3 (TBR)** petabytes of raw science data.

4.7.20 The system shall possess a computer security system to protect potentially vulnerable subsystems from malicious external actions.

10.2.2 Subsystem Level Requirements

The requirements presented in this section derive from the Pan-STARRS system level requirements found in Sections 3.2.1, 3.2.2 and 4.7. A flowdown to the PSPS lower level subsystem requirements can be found in section 10.7.

10.2.2.1 The PSPS shall provide end-users access to detections of objects in the Pan-STARRS.

10.2.2.2 The PSPS shall provide end-users access to the cumulative static sky images generated by the Pan-STARRS.

10.2.2.3 The PSPS shall provide end-users with metadata required to interpret the observational legacy and processing history of the Pan-STARRS data products.

10.2.2.4 The PSPS shall provide end-users with Pan-STARRS detections of objects in the Solar System for which attributions can be assigned.

10.2.2.5 The PSPS shall provide end-users with derived Solar System objects deduced from the Pan-STARRS attributed observations and observations from other sources.

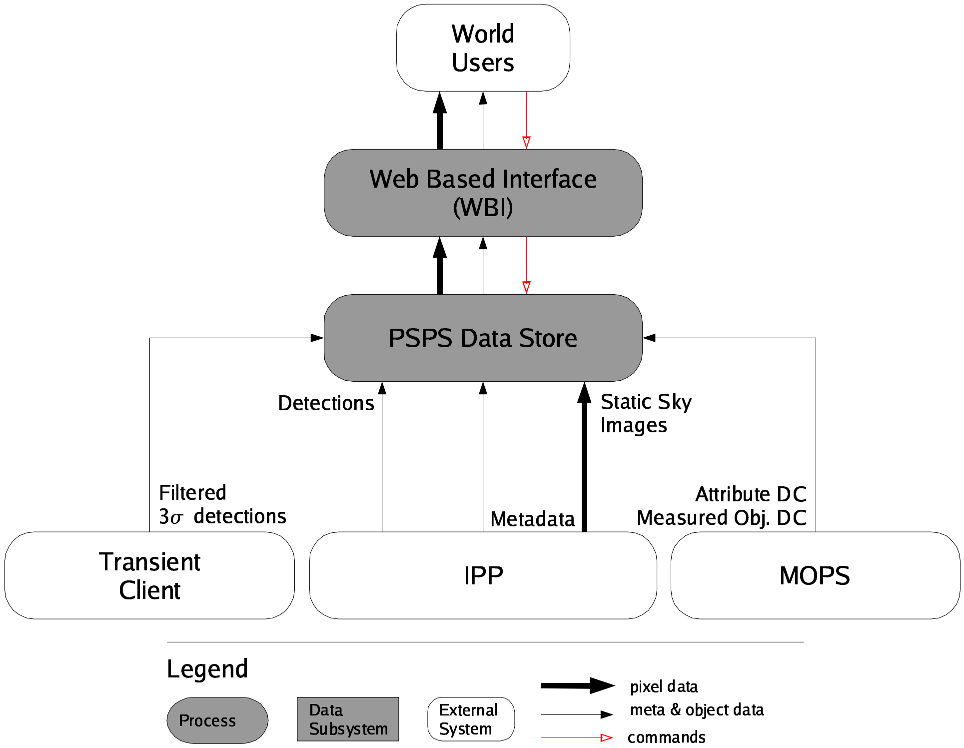

Figure 37: PSPS Overview

10.2.2.6 The PSPS shall have the capability to provide end-users with data products internally delivered by other science clients.

10.2.2.7 The PSPS shall archive the data products listed in Table 29.

10.2.2.8 The PSPS shall provide the capability for end-users to construct queries to search the Pan-STARRS data products data over space and time to examine magnitudes, colors and proper motions.

10.2.2.9 The PSPS shall provide layers of Internet security to prevent unauthorized access to the PSPS data stores or other Pan-STARRS subsystems.

10.2.2.10 The PSPS shall provide a mass storage system with a reliability requirement of **99.9% (TBR)**.

10.3 Subsystem Top Level Description

10.3.1 Diagrams

The PSPS and its major components are shown in Figure 37.

10.3.2 Subsystem and Component Descriptions

The PSPS services requests for data from end-users through a Web-Based user Interface (WBI). The WBI is the only access point an external user has to the Pan-STARRS data products. The WBI software processes requests for the Pan-

Table 29: Published Science Product Subsystem (External Data Products)

Product Name	*Description*	*Reference*	*TB/(year or copy)*
P2 detections	Source catalog for the individual focal plane $> 20\sigma$	8.6.2.4	9.27
P4Σ detections	Source catalog for the major frames $> 5\sigma$	8.6.2.6	9.27
P4Δ detections	Source catalog for the major difference frames $> 3\sigma$	8.6.2.6	17.17
Static sky detections	Source catalog for the cumulative static sky images	8.6.1.1	23.33
P2 image metadata	Description of the images and processing history	8.6.2.4	0.026
P4Σ image metadata	Description of the images and processing history	8.6.1.3	0.026
P4Δ image metadata	Description of the images and processing history	8.6.1.3	0.026
Static sky image metadata	Description of the images and processing history	8.6.1.3	0.026
Collected metadata	IPP and summit metadata	8.6.1.3	1.000
Static sky images	Cumulative sky image pixel data	8.6.1.1	167.960
P2 postage stamps	Postage stamps from phase 2 images	8.6.2.4	1.260
Attributed MOPS det.	Observation of identified objects	9.6.2.4	0.030
Derived MOPS objects	Properties deduced from the observation, orbits, abs magnitude	9.6.2.5	0.500

STARRS data products. Requests for specific data are then sent to and processed by the PSPS data store, shown in Figure 37.

10.3.3 Data Products

The PSPS data products that correspond to the Pan-STARRS data products are listed in Table 29. Note the program lifetime is assumed to be 10 years, and database overhead is not included in Table 29.

10.3.4 Data Flow

Data flow from other Pan-STARRS subsystems to the PSPS is unidirectional; i.e., the PSPS can only receive data from the IPP, the MOPS and other internal science clients. Moreover, the PSPS will not send commands to any other Pan-STARRS subsystem.

10.4 Subsystem Tasks and Functions

The following tasks must be accomplished to satisfy the requirements listed in Section 10.2.2.

10.4.1 Web Based User Interface Tasks

The Pan-STARRS data products are available through the WBI interface. Each fundamental data product is given a separate section in the WBI. Depending on the data product type, the end-users will have a range of data access options. The concept of the WBI generates the following necessary tasks and functions:

10.4.1.1 The WBI must provide end-users with a choice of the Pan-STARRS data product to access.

10.4.1.2 The WBI must be designed to incorporate database style queries for those data products accessed and stored by means of a database.

10.4.1.3 The WBI must be designed to accept database style queries in the from of a script, read from an ASCII text file.

10.4.1.4 The WBI must provide end-users with a graphical user interface that accepts less sophisticated database queries.

10.4.1.5 The WBI must provide access to other types of data stores including, but not limited to, simple web pages displaying current results, a browseable index of files end-users can download, etc.

10.4.1.6 The WBI will accommodate multiple users submitting a variety of queries under severe workloads.

10.4.1.7 The WBI will provide end-users with an estimate of the query completion time.

10.4.1.8 The WBI will throttle queries appropriately, so as to allow quick searches to complete first, while saving enough throughput to maintain progress on remaining time consuming queries.

10.4.1.9 The WBI will provide temporary storage space for end-users who submit queries with large return volumes.

10.4.1.10 The WBI will expunge the temporary storage area of stale query results on an as need basis.

10.4.2 Query Tasks

10.4.2.1 The PSPS must receive a user generated query over the WBI

10.4.2.2 The data store must translate queries received by the WBI into requests for data from the individual component data stores.

10.4.2.3 The individual component data store must receive and process a data request.

10.4.2.4 The individual component data store must send the query results back to the WBI or save the results to the temporary storage area and send the location.

10.4.2.5 The WBI must display query results or the location of the data set.

10.4.3 Update Tasks

The possibility of new data becoming available when long running queries are active is a distinct possibility for the Pan-STARRS data store. The Pan-STARRS data store will need an update procedure that ensures data validity for this circumstance and other potential race conditions relating to data access.

10.5 Operational Scenarios

10.5.1 PSPS Modes

The main PSPS modes are operational, update and maintenance.

10.5.1.1 Operational Mode

The default PSPS mode will be operational, i.e., waiting for data requests that trigger operations within one or more of the PSPS components.

10.5.1.2 Update Mode

The PSPS is in the update mode when the data store is receiving additional data from other Pan-STARRS subsystems. The PSPS will be designed to receive and service queries from one component data store, while updating another. To avoid returning invalid data, a query submitted to a component data store during an update will return an estimated time for query completion.

Each Pan-STARRS subsystem that provides data to a PSPS component data store is responsible for scheduling the updates. These updates will be scheduled depending upon the data generation rate of the subsystem feeding the PSPS data store, with the feeding system controlling the data flow. The component data store updates will not be synchronized between the PSPS data store clients; the following table is an example of potential data update rates:

Table 30: PSPS Data Store Update Rates

Cumulative Sky Images	Semi-Annually
Cumulative Sky Source Catalog	Semi-Annually
Time History DB	Daily
MOPS Derived Objects DB	Monthly
MOPS Attributed Observations	Monthly
Metadata DB	Daily
Filtered Transients Data Storage	Hourly

10.5.1.3 Maintenance Mode

The PSPS also has a maintenance mode for both hardware and software on the various component systems. The down time for maintenance may vary between the PSPS components depending upon the complexity of a particular system.

10.5.2 Database Operational and Performance Goals

10.5.2.1 The PSPS web based interface should support **100 (TBR)** simultaneous end-users.

10.5.2.2 In order to restrict the complexity of a given query, acceptable queries will accommodate logical strings of less than **20 (TBR)** predicates.

10.5.2.3 The PSPS will provide end-users with an estimated time to complete the query.

10.5.2.4 The PSPS will detect and report to the end-user, unacceptable queries.

10.5.2.5 The PSPS will provide one or more levels of privileged access to qualified end-users.

10.5.2.6 The PSPS will provide one or more levels of query processing priority to qualified end-users.

10.5.2.7 The PSPS will guard against accidental data corruption and loss caused by end-users.

10.5.2.8 The PSPS will perform database benchmark testing assuming **100 (TBR)** simultaneous end-users with a work-load of **10 (TBR)** queries per minute.

10.5.2.9 The PSPS will return queries according to standard astronomical work package target times.

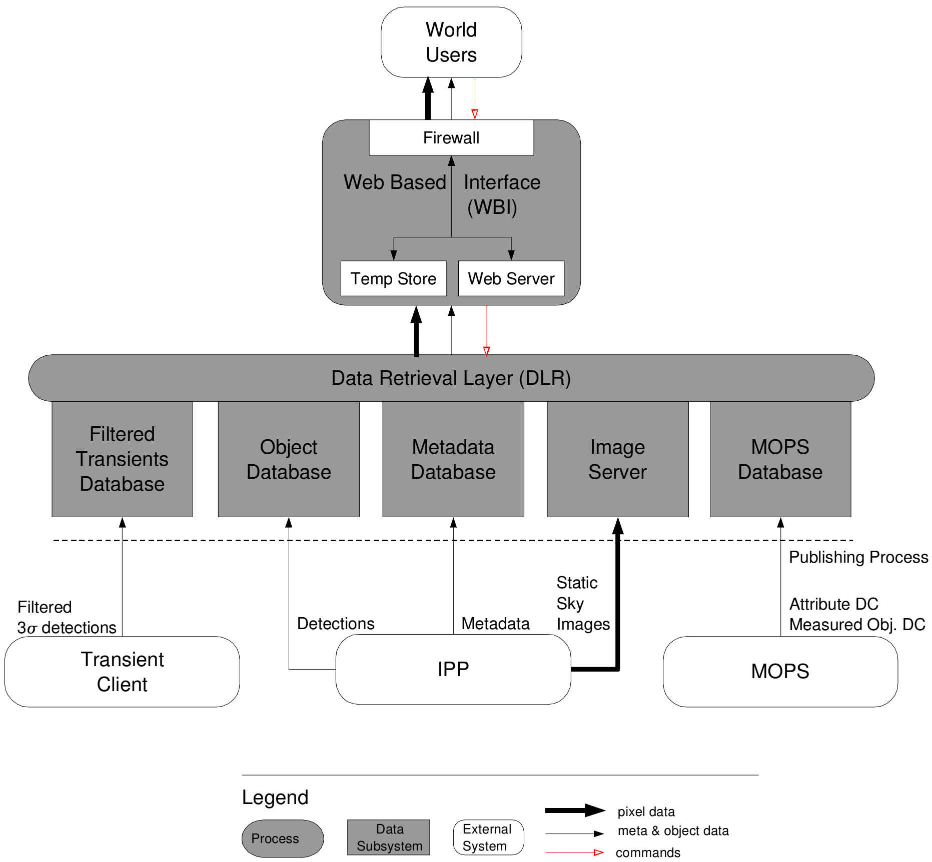

Figure 38: PSPS Conceptual Design

10.5.3 Quality Attributes

10.5.3.1 Data Persistence

The PSPS will have an **99.9% (TBR)** probability against loosing data.

10.5.3.2 Flexibility

As new operational scenarios and requirements arise, the PSPS, and in particular all components thereof will need to be flexible; e.g., databases must have provisions to be re-indexed or have new tables added depending on future query requirements, the WBI must be reconfigurable to process future query types, and the data store must be expandable to handle additional preferred science clients.

10.6 Conceptual Design

The observing programs for the various Pan-STARRS survey modes will generate an unprecedented volume of astronomical imaging data, primarily due to the storage of time series data. The large storage requirements present many database design challenges. The data have been partitioned into natural divisions based on the type of data and the source. Figure 38 shows the component data storage systems: the object database, the metadata database, the image server, the MOPS database, etc. Tables 32-35 list The PSPS data products by component data store.

It is important to note which Pan-STARRS data products grow with time. Those data products that do are denoted **historical** *and those data products that are of constant size once generated are denoted* **cumulative** *in Tables 32-35. For the reader's convenience, a table is provided below.*

Table 31: Database Growth

P2 detections	Historical	Grows with time
P4Σ detections	Historical	Grows with time
P4Δ detections Static Sky detections	Cumulative	Constant size once generated
P2 image metadata	Historical	Grows with time
P4Σ image metadata	Historical	Grows with time
P4Δ image metadata	Historical	Grows with time
Static Sky image metadata	Historical	Grows with time
Collected Metadata	Historical	Grows with time
Static sky images	Cumulative	Constant size once generated
P2 postage stamps	Historical	Grows with time
MOPS data	Cumulative	Constant size once generated

In addition to the component data stores, this section will also present conceptual designs for the WBI and the data retrieval layer (DRL).

10.6.1 The Web-Based Interface (WBI)

The web-based interface gives end-users access to the Pan-STARRS public data products. From this portal, end-users will be able to submit astronomical queries and retrieve results. The Internet host machine will also be configured to provide an additional layer of security between the Pan-STARRS data collections and the outside world. End-users will not be able to access these data collections directly, but only through the web interface and its applications.

Table 32: Object Catalog Data Store

Product Name	*Description*	*Reference*	*Size(TB)*
	Historical Data (TB/Year)		
P2 detections	Source catalog for the individual focal plane $> 20\sigma$	8.6.2.4	9.27
P4Σ detections	Source catalog for the major frames $> 5\sigma$	8.6.2.6	9.27
P4Δ detections	Source catalog for the major difference frames $> 3\sigma$	8.6.2.6	17.17
Total	Raw bytes per year		35.71
Total	Historical raw bytes (10 year life)		357.10
	Cumulative Data (TB/Copy)		
Static sky detections	Source catalog for the cumulative static sky images	8.6.1.1	23.33
Total	Cumulative raw bytes (2 Copies)		46.66
Total	Raw bytes		403.76
	Database overhead		4
Total			1615.04

Table 33: Metadata Data Store

Product Name	*Description*	*Reference*	*Size(TB)*
Historical Data (TB/Year)			
P2 image metadata	Description of the images and processing history	8.6.2.4	0.026
P4Σ image metadata	Description of the images and processing history	8.6.1.3	0.026
P4Δ image metadata	Description of the images and processing history	8.6.1.3	0.026
Static sky image metadata	Description of the images and processing history	8.6.1.3	0.026
Collected metadata	IPP and summit metadata	8.6.1.3	1.000
Total	Raw bytes		1.102
Total	Historical raw bytes (10 year life)		11.02
	Database overhead		4
Total			44.08

Table 34: Image Server Data Store

Product Name	*Description*	*Reference*	*Size(TB)*
Cumulative Data (TB/Copy)			
Static sky images	Cumulative sky image pixel data	8.6.1.1	167.96
Total	Cumulative raw bytes (9 copies)		1510.00
Historical Data (TB/Year)			
P2 postage stamps	Postage stamps from phase 2 images	8.6.2.4	1.26
Total	Historical raw bytes (10 year life)		12.60
	Database overhead		1
Total			1522.60

Table 35: MOPS Data Store

Product Name	*Description*	*Reference*	*Size(TB)*
Historical Data (TB/Year)			
Attributed MOPS obs.	Observation of identified objects	9.6.2.4	0.030
Measured MOPS objects	Properties deduced from the observation, orbits, abs magnitude.	9.6.2.5	0.500
Total	Raw bytes per year (10 year life)		5.300
	Database Overhead		4
Total			21.2

The WBI will support two types of user interfaces: a text user interface (TUI) and a graphical user interface (GUI). The GUI will be designed for interactive use. The TUI will be designed for scripted queries. The underlying support structure will take advantage of the model,view,controller pattern of modern user interface design to promote code reuse with a robust design.

The WBI will also need to provide temporary storage space to users who make requests that either result in long response times or large data sets. Those users would have their results spooled to a temporary storage device and be notified by email. The WBI will be able to purge the temporary storage device of stale query results.

The WBI will also provide the first line of defense against unwelcome visitors directing malicious acts of network violence toward the Pan-STARRS system. The temporary storage device is also part of this security measure. The WBI will have a security hardened OS, hardware firewalls, etc.

10.6.2 The Data Retrieval Layer (DRL)

The DRL will consist of a network of data server machines isolated from the end-users by the web interface. Further they would be on a private network separate from those of the other Pan-STARRS subsystems and science clients. Data will only flow into the DRL machines from the other Pan-STARRS components, but never back to them. This design provides an additional layer of safety to the science operations machines from unauthorized access.

Within the DRL, the details of the various component data stores will depend upon the complexity and size of the data collection to be exported. Some of these, such as the object data collection, will almost certainly consist of a network of multiple server machines, while others, like the MOPS export data, may fit on a single host machine.

10.6.2.1 The Object Data Collection

The PSPS solution for this data base is to provide to the science users, catalogs of source detections derived from the image data, but not pixel level image data. This approach provides considerable data compression in terms of the information the PSPS must provide to the end-user, but presents some challenges in terms of the choice of attributes to include and how to organize the data for export. This data factory will rely on two relational database engines to process the Pan-STARRS source catalogs: one for the time history of the sky and a second for sources measured in the cumulative static sky images. The Object data collection needs to be searchable over user defined combinations of source attributes including, but not limited to, spatial coordinates, time, exposure metadata, etc.

These databases will contain as described in the Pan-STARRS data product description in Section 3.2.1.

10.6.2.1.1 Temporal history of astrometry and photometry for all sources greater than 20σ above sky detected in at least 3 of the 4 focal plane cameras (a P2 image) in any major frame

10.6.2.1.2 Postage stamp cutouts of bright sources taken from the P2 images

10.6.2.1.3 Temporal history of astrometry and photometry for all sources greater than 5σ above the sky detected in the major frame image for exposure (a P4Σ image)

10.6.2.1.4 Temporal history for all transient sources greater than 3σ above the background level in the difference images formed from an individual major frame exposure and the static sky (a P4Δ image)

10.6.2.1.5 Astrometry, photometry, and source description parameters for all sources greater than 5σ above the sky in the cumulative static sky images taken in any filter

Astrometric and photometric catalog data will be published from the IPP's AP database, Section 8.6.1.2, to the Object Database in the DRL. There will be a different number of attributes measured for a detection depending upon its origin (a P2, P4Σ, P4∆, or Cumulative Static Sky image). These attributes will closely parallel those stored in the Astrometry-Photometry database with the IPP (see Table 25, although it is possible that not every attribute stored in the AP database will be present in the Object Database in the DRL.

For the time history measurements of position and photometry, we will only record a limited number of attributes. For the cumulative static sky images, where we will have higher signal-to-noise from the co-addition of many individual images, we will be able to measure many more attributes for each detection, in particular those that help characterize the spatial distribution of the flux within the object. In addition to the attributes describing the sources themselves, the object databases will include a subset of the IPP metadata that characterize the individual focal plane images and the major frames derived from them.

The most basic measurements that the Pan-STARRS IPP will provide on an arbitrary astronomical source is its flux (magnitude) and position on the sky, and the errors associated with these quantities. These fundamental attributes will be recorded for sources both over the sky (as in current surveys such as 2MASS and SDSS) and time. Searching over these fundamental parameters and simple combinations of them (colors and proper motions) will allow users to address many of priority 1 and 2 science goals developed in the SGS. Some science programs, e.g., weak lensing and mapping the dark matter distribution in the universe, will involve extracting galaxy shape information from the cumulative static sky object data collection. The size and high volume of regular input into the database present several interesting challenges. The first relates to indexing the database to facilitate efficient searches. Given the overall large number of objects spread across the sky, an efficient index scheme for searching over the spatial coordinate is essential. And, as one loads a new increment of sources, each load will require re-indexing that region or regions of sky. A partitioned index strategy is a promising approach for dealing with this issue.

Also related to indexing is the issue of whether to utilize a database schema with intermediate tables created to optimize certain types of queries. Another approach is *not* to use intermediate tables for derived quantities, e.g., photometric colors, but rather compute them on the fly. In principle the former approach improves query performance, at the expense of additional storage in the database, if the types of requests made on the database could defined in advance. In practice, it may not be possible to anticipate many of the queries users will pose to the object database. However, it is desirable to create intermediate tables for storing quantities that are not easily calculated from simple combinations of other object attributes, e.g., proper motions which would require a linear fit to the position of the detections of a given object over the period of observations.

10.6.2.2 The Cumulative Static Sky Image Server

The Cumulative Static Sky Image Server will provide the image data for the static sky. The IPP will have an internal version of the static sky image server, see Section 8.6.1.1, that will contain the current "best" version of the sky. In this context the best image means the one which allow the IPP to generate P4∆ images that show minimal stellar residual artifacts due to proper motions. This component of the DRL will contain the current working static sky image in each filter, and previous versions of the static sky in each filter.

10.6.2.3 The Metadata Database

The metadata database will be the public clone of the same database used by the IPP, see Section 8.6.1.3 . Unlike the IPP, where the lifetime of entries in this database will be finite, the public version will act as the historical archive of the IPP metadata.

10.6.2.4 The Filtered Transient Science Products

The Stationary Transient Science Client of the IPP will flag as potentially interesting objects a large number of sources, many of which may turn out to be data processing artifacts. In order to provide a useful alert service to the astronomical community, the transient source lists generated will be filtered by the IPP to support a false alarm rate of less than 0.01% before being exported via the PSPS.

It would consist of a simple listing giving a time order list of position and magnitude(s) of the objects found by processing pipeline. In addition to these basic descriptors, for each source postage stamp cutouts from the P4Σ and P4Δ images would be linked to the page to provide users with a digital finding chart for followup observations. It is anticipated that the lifetime of an object on this list to be on the order of several months (e.g., times typical of the decay rate on SNe).

As the sophistication of the Transient Science Client grows, it will be able to begin to automatically classify the transients. In particular, many Galactic variable stars will be recognized and filed accordingly within the database. The same will be true of Galactic novae and supernovae. Once this is demonstrated on a consistent basis, we anticipate that this information will also be included in the web listing.

10.6.2.5 The MOPS Science Products

Two of the data collections internal to the MOPS system will be available for export. These are the attributed observations, Section 9.6.2.4, and measured objects data Section 9.6.2.5. The former is essentially the listing of all observations of Solar System objects that have been attributed to a known body, while the former is that tabulation of parameters deduced for objects from their observations, e.g., orbital elements, absolute magnitude, etc.

The web application for the MOPS will allow users to retrieve

10.6.2.5.1 All the Pan-STARRS observations for a particular object

10.6.2.5.2 The derived properties of any individual object (orbital elements, absolute magnitude)

10.6.2.5.3 Searches of derived properties with user specified limits or ranges

10.6.2.5.4 Statistics on the completeness of the MOPS survey efficiency as derived from the analysis of artificial objects injected into the processing and analysis system.

10.7 Summary of Derived Requirements

10.7.1 The PSPS shall accept object detections, metadata, and static sky images from the IPP, as outlined in Table 29.

10.7.2 The PSPS shall accept attributed detections and derived Solar System objects from the MOPS, as outlined in Table 29.

10.7.3 The PSPS shall be capable of accepting data for publication from other client science pipelines.

10.7.4 The PSPS shall implement the storage, retrieval and interface to the objects catalog using a database.

10.7.5 The PSPS shall implement the storage, retrieval, and interface to the collection of static sky images using a database.

10.7.6 The PSPS shall provide **3.19 (TBR)** petabytes of mass storage dedicated to archiving the Pan-STARRS data products.

10.7.7 The PSPS shall provide end-users with access to the Pan-STARRS data products through a web based interface via the Internet.

10.7.8 The PSPS shall have the capability to accept queries that perform logical operations on stored attributes.

10.8 Requirements Trace Matrix

Subsystem Requirements		System/Subsystem Requirements	
Number	**Caption**	**Number**	**Caption**
10.2.2.1	provide access to detections	3.2.2.18	science data products made available via the Internet
10.2.2.2	provide access to static sky images	3.2.2.18	science data products made available via the Internet
10.2.2.3	provide access to metadata	3.2.2.18	science data products made available via the Internet
10.2.2.4	provide access to attributed solar-system objects	3.2.2.18	science data products made available via the Internet
10.2.2.5	provide access to derived solar-system objects	3.2.2.18	science data products made available via the Internet
10.2.2.6	provide access to data from other science clients	3.2.2.18	science data products made available via the Internet
10.2.2.7	archive the data products	3.2.2.18	science data products made available via the Internet
10.2.2.8	allow queries of data products	3.2.2.18	science data products made available via the Internet
10.2.2.9	layers of Internet security	4.7.20	security requirement
10.2.2.10	mass-storage reliability	allocated	

Derived Subsystem Requirements		Top-level Subsystem Requirements	
Number	**Caption**	**Number**	**Caption**
10.7.1	accept data from IPP	10.2.2.1	provide access to detections
10.7.1	accept data from IPP	10.2.2.2	provide access to static sky images
10.7.1	accept data from IPP	10.2.2.3	provide access to metadata
10.7.2	accept data from MOPS	10.2.2.4	provide access to attributed solar-system objects
10.7.2	accept data from MOPS	10.2.2.5	provide access to derived solar-system objects
10.7.3	accept data from other clients	10.2.2.6	provide access to data from other science clients
10.7.4	implement objects catalog as database	allocated	
10.7.5	implement static sky access as database	allocated	
10.7.6	provide adequate storage	4.7.19	system operational storage requirement
10.7.7	end-user web-based interface	allocated	
10.7.8	acceptance of queries	10.2.2.8	allow queries of data products

10.9 Definitions

See Table 36 for the PSPS definitions.

Table 36: PSPS Definitions

Published Science Products System	PSPS
Web-Based user Interface	WBI
Data Retrieval Layer	DRL
Text User Interface	TUI
Graphical User Interface	GUI

10.10 External Interfaces

The PSPS will interface to the following Pan-STARRS subsystems

10.10.1 IPP AP database, Section 8.6.1.2.

10.10.2 IPP metadata database, Section 8.6.1.3.

10.10.3 IPP cumulative static sky image server, Section 8.6.1.1.

10.10.4 Stationary Transient Client

10.10.5 MOPS Client

The World Interface is considered to be part of the PSPS itself.

Notes

[22] In this context, end-users are defined as any individual or group of individuals that access the Pan-STARRS data products through the Internet interface and not other Pan-STARRS subsystems.

11 System Interfaces

11.1 Major Subsystem Interfaces

The interfaces between major subsystems are summarized in Table 37, and the symbols are defined as follows: $\rightarrow$, $\leftarrow$ and $\leftrightarrow$ denote either data or command and control signals, where the direction of the arrow corresponds to the direction of the data. Pixel data and its direction are denoted by $\Rightarrow$ and $\Leftarrow$.

Table 37: Pan-STARRS Subsystem Interfaces

Interface	Mechanical	Electrical	SW	
			Command	Data
TEL - CAM				
Telescope - GPC	X	X		
Shutter - DHC			$\leftarrow$	$\rightarrow$
TEL - OTIS				
Telescopes - TCS		X	$\leftarrow$	$\rightarrow$
Dome - TCS		X	$\leftarrow$	$\rightarrow$
CAM - OTIS				
DHC - OBS			$\leftrightarrow$	$\rightarrow$
DHC - ODB				$\rightarrow$
DDS - ODB				$\leftarrow$
DHC - TCS			$\leftrightarrow$	
CAM - IPP				
DDS - ImgSrv		X		$\Rightarrow$
OTIS - IPP				
ODB - MDB				$\leftrightarrow$
OTIS - EXT				
OWS - Met				$\leftarrow$
Tool - Mission				$\leftarrow$
IPP - MOPS				
MDB - DC				$\rightarrow$
APDB - DC				$\leftrightarrow$
IPP - PSPS				
MDB - MDB			$\rightarrow$	$\rightarrow$
APDB - APDB			$\rightarrow$	$\rightarrow$
ImgSrv - ImgSrv			$\rightarrow$	$\Rightarrow$
MOPS - PSPS				
DC - MOPSDB			$\rightarrow$	$\rightarrow$
MOPS - EXT				
DC - SolarSys			$\rightarrow$	$\leftrightarrow$

11.2 TEL - CAM

11.2.1 TEL:Telescope - CAM:GPC

11.2.1.1 Mechanical

11.2.1.1.1 The camera will be physically located behind the primary mirror and attached to the instrument rotator. The camera will rotate with the shutter and the filter assembly around the central axis of the telescope and will require cable management and support to permit this movement.

11.2.1.1.2 The complete removal of the camera assembly will be required for major service, repair and maintenance. The mechanical interface must permit repeated reassembly of the telescope - GPC components without degrading performance.

11.2.1.2 Thermal

Working Fluid	Propylene glycol or approved alternative
Supply Temperature	**10 degrees C (TBR)**
Flow Rate	**(TBD)**
Max temperature rise	**10 degrees C (TBR)**
Thermal load	**(TBD)**
connection location	Camera backplane (electronics heatsink plates)
connection location	Compressor unit (enclosure service floor)
connection location	Power supply rack (air-liquid heat exchange)
connection location	**Camera Host computer/data store (TBR)**

11.2.2 TEL:Shutter - CAM:DHC

11.2.2.1 Software Command and Control Interface

Type of Interface	Soft/hard real-time
Size	**Small (TBD)**
Data type	Encapsulated data in **XML (TBR)**
Data transfer rate	**10 Mbit/sec (TBD)**
Frequency	$>$ 1/40 Hz
Latency	**20 msec (TBR)**
Periodic	False
Required Protocol	TCP/IP
Direction	TEL:Shutter $\leftarrow$ CAM:DHC

11.2.2.2 Software Data Interface

Type of Interface	Soft/hard real-time
Size	**Small (TBD)**
Data type	Encapsulated data in **XML (TBR)**
Data transfer rate	**10 Mbit/sec (TBD)**
Frequency	$>$ 1/40 Hz
Latency	**20 msec (TBR)**
Periodic	False
Required Protocol	TCP/IP
Direction	TEL:Shutter $\rightarrow$ CAM:DHC

11.3 TEL - OTIS

11.3.1 TEL:Telescope - OTIS:TCS

The TCS component of OTIS implements the interface between OTIS and the telescope internal subsystems by providing a high-level command structure that translates executive directives from the Observation Sequencer into low-level primitives to actuators and sensor elements.

11.3.1.1 Software Command and Control Interface

Type of Interface	Soft real-time
Size	**Small (TBD)**
Data type	Encapsulated data in **XML (TBR)**
Data transfer rate	**10 Mbit/sec (TBD)**
Frequency	**1 - 10 Hz (TBD)**
Latency	**20 msec (TBR)**
Periodic	False
Required Protocol	TCP/IP
Direction	TEL:Telescope ← OTIS:TCS

11.3.1.2 Software Data Interface

Type of Interface	Soft real-time
Size	**Medium (TBD)**
Data type	Encapsulated data in **XML (TBR)**
Data transfer rate	**10 Mbit/sec (TBD)**
Frequency	**10 - 100 Hz (TBD)**
Latency	**20 msec (TBR)**
Periodic	True
Required Protocol	TCP/IP
Direction	TEL:Telescope → OTIS:TCS

11.3.2 TEL:Dome - OTIS:TCS

11.3.2.1 Software Command and Control Interface

Type of Interface	Soft real-time
Size	**Small (TBD)**
Data type	Encapsulated data in **XML (TBR)**
Data transfer rate	**100Mbit/sec (TBD)**
Frequency	**1 Hz (TBD)**
Latency	**20 msec (TBR)**
Periodic	False
Required Protocol	TCP/IP
Direction	TEL:Dome ← OTIS:TCS

11.3.2.2 Software Data Interface

Type of Interface	Soft real-time
Size	**Medium (TBD)**
Data type	Encapsulated data in **XML (TBR)**
Data transfer rate	**10 Mbit/sec (TBD)**
Frequency	**10 - 100 Hz (TBD)**
Latency	**20 msec (TBR)**
Periodic	True
Required Protocol	TCP/IP
Direction	TEL:Dome $\rightarrow$ OTIS:TCS

11.4 CAM - OTIS

11.4.1 CAM:DHC - OTIS:OBS

11.4.1.1 Software Command and Control Interface

OTIS will command camera operation and provide a data sink collecting status and metadata from the camera and its subsystems.

Type of Interface	Soft real-time
Size	**Small (TBD)**
Data type	Encapsulated data in **XML (TBR)**
Data transfer rate	**10 Mbit/sec (TBD)**
Frequency	$>$ 1/40 Hz
Latency	**20 msec (TBR)**
Periodic	False
Required Protocol	TCP/IP
Direction	CAM:DHC $\leftrightarrow$ OTIS:OBS

11.4.1.2 Software Data Interface

Type of Interface	Soft real-time
Size	**Medium (TBD)**
Data type	Encapsulated data in **XML (TBR)**
Data transfer rate	**10 Mbit/sec (TBD)**
Frequency	$>$ 1/40 Hz
Latency	**20 msec (TBR)**
Periodic	True
Required Protocol	TCP/IP
Synchronization	Synchronous driven by CAM
Direction	CAM:DHC $\rightarrow$ OTIS:OBS

11.4.2 CAM:DHC - OTIS:ODB

The Camera system will autonomously transmit metadata recording its internal performance and conditions to the OTIS database during operations.

11.4.2.1 Software Data Interface

Type of Interface	Storage and retrieval of data
Size	**Large (TBD)**
Data type	Encapsulated data in **XML (TBR)**
Data transfer rate	**100 Mbit/sec (TBD)**
Frequency	**10 - 100 Hz (TBD)**
Latency	**20 msec (TBR)**
Periodic	True
Required Protocol	TCP/IP
Direction	CAM:DHC $\rightarrow$ OTIS:ODB

11.4.3 CAM:DDS - OTIS:ODB

11.4.3.1 Software Data Interface

Type of Interface	Storage and retrieval of data
Size	**Medium (TBD)**
Data type	Encapsulated data in **XML (TBR)**
Data transfer rate	**10 Mbit/sec (TBD)**
Frequency	**10 - 100 Hz (TBD)**
Latency	**20 msec (TBR)**
Periodic	True
Required Protocol	TCP/IP
Direction	CAM:DDS $\leftarrow$ OTIS:ODB

11.4.4 CAM:DHC - OTIS:TCS

During exposures, the detector host computer will compute and accumulate average tracking errors based on OT guide cell operation. A low-latency data path will be provided to transmit these errors to the telescope control system for tracking corrections.

11.4.4.1 Software Data Interface

Type of Interface	Hard real-time
Size	**Small (TBD)**
Data type	**Integer (TBD)**
Data transfer rate	**(TBD)**
Frequency	**10 - 100 Hz (TBD)**
Latency	**1msec (TBD)**
Periodic	True during exposures
Required Protocol	TCP/IP
Direction	CAM:DHC $\rightarrow$ OTIS:TCS

11.5 CAM - IPP

11.5.1 CAM:DDS - IPP:ImgSrv

11.5.1.1 Software Data Interface

Type of Interface	Soft/hard real-time
Size	8.08 GB [23]
Data type	Encapsulated data in FITS
Data transfer rate	$>$ 1616 Mbit/sec
Frequency	$>$ 1/40 Hz
Latency	**20 msec (TBR)**
Periodic	False
Required Protocol	TCP/IP
Direction	CAM:DDS $\Rightarrow$ IPP:ImgSrv

11.6 OTIS - IPP

11.6.1 OTIS:ODB - IPP:MDB

11.6.1.1 Software Data Interface

Type of Interface	Storage and retrieval of data
Size	2 MB[24]
Data type	Encapsulated data in **XML (TBR)**
Data transfer rate	$>$ 0.4 Mbit/sec
Frequency	$>$ 1/40 Hz
Latency	**20 msec (TBR)**
Periodic	False
Required Protocol	TCP/IP
Direction	OTIS:ODB $\leftrightarrow$ IPP:MDB

11.7 OTIS - EXT

11.7.1 OTIS:OWS - EXT:Met

11.7.1.1 Software Data Interface

Type of Interface	Data retrieval from external server
Size	**Medium (TBD)**
Data type	**ASCII (TBD)**
Data transfer rate	**100 Mbit/sec (TBD)**
Frequency	**1 per minute to 1 per hour (TBD)**
Latency	**20 msec (TBR)**
Periodic	True
Required Protocol	**HTTP, HTTPS, FTP (TBD)**
Direction	OTIS:OWS ← EXT:Met

11.7.2 OTIS:Tool - EXT:Mission

11.7.2.1 Software Data Interface

Type of Interface	Storage and retrieval of data
Size	**Medium (TBD)**
Data type	Encapsulated data in **XML (TBR)**
Data transfer rate	**10 Mbit/sec (TBR)**
Frequency	
Latency	**20 msec (TBR)**
Periodic	False
Required Protocol	TCP/IP
Direction	OTIS:Tool ← EXT:Mission

11.8 IPP - MOPS

11.8.1 IPP:MDB - MOPS:DC

11.8.1.1 Software Data Interface

Type of Interface	Storage and retrieval of data
Size	4 MB[25]
Data type	Encapsulated data in XML
Data transfer rate	> 0.8 Mbit/sec
Frequency	> 1/40 Hz
Latency	**20 msec (TBR)**
Periodic	False
Required Protocol	TCP/IP
Direction	IPP:MDB → MOPS:DC

11.8.2 IPP:APDB - MOPS:DC

11.8.2.1 Software Data Interface

Type of Interface	Storage and retrieval of data
Size	40 MB[26]
Data type	Encapsulated data in XML
Data transfer rate	$>$ 8 Mbit/sec
Frequency	$>$ 1/40 Hz
Latency	**20 msec (TBR)**
Periodic	False
Required Protocol	TCP/IP
Direction	IPP:APDB $\leftrightarrow$ MOPS:DC

11.9 IPP - PSPS

The IPP will transmit data products to the public interface as they are available.

11.9.1 IPP:MDB - PSPS:MDB

11.9.1.1 Software Command and Control Interface

Type of Interface	Soft real-time
Size	**1 KB (TBR)**
Data type	Encapsulated data in **XML (TBR)**
Data transfer rate	**10 Mbit/sec (TBR)**
Frequency	1 per day
Latency	**20 msec (TBR)**
Periodic	True
Required Protocol	TCP/IP
Direction	IPP:MDB $\rightarrow$ PSPS:MDB

11.9.1.2 Software Data Interface

Type of Interface	Storage and retrieval of data
Size	20 MB
Data type	Encapsulated data in **XML (TBR)**
Data transfer rate	**40 Mbit/sec (TBR)**
Frequency	1 per day
Latency	**20 msec (TBR)**
Periodic	True
Required Protocol	TCP/IP
Direction	IPP:MDB $\rightarrow$ PSPS:MDB

11.9.2 IPP:APDB - PSPS:APDB

11.9.2.1 Software Command and Control Interface

Type of Interface	Soft real-time
Size	**1 KB (TBR)**
Data type	Encapsulated data in **XML (TBR)**
Data transfer rate	**10 Mbit/sec (TBR)**
Frequency	1 per day
Latency	**20 msec (TBR)**
Periodic	True
Required Protocol	TCP/IP
Direction	IPP:APDB → PSPS:APDB

11.9.2.2 Software Data Interface

Type of Interface	Storage and retrieval of data
Size	140 GB
Data type	Encapsulated data in **XML (TBR)**
Data transfer rate	**1300 Mbit/sec (TBR)**
Frequency	1 per day
Latency	**20 msec (TBR)**
Periodic	True
Required Protocol	TCP/IP
Direction	IPP:APDB → PSPS:APDB

Type of Interface	Storage and retrieval of data
Size	47000 GB[27]
Data type	Encapsulated data in **XML (TBR)**
Data transfer rate	**2400 Mbit/sec (TBR)**
Frequency	1 per 6 months
Latency	**20 msec (TBR)**
Periodic	True
Required Protocol	TCP/IP
Direction	IPP:APDB → PSPS:APDB

11.9.3 IPP:ImgSrv - PSPS:ImgSrv

11.9.3.1 Software Command and Control Interface

Type of Interface	Soft real-time
Size	**1 KB (TBR)**
Data type	Encapsulated data in **XML (TBR)**
Data transfer rate	**10 Mbit/sec (TBR)**
Frequency	1 per 6 months
Latency	**20 msec (TBR)**
Periodic	True
Required Protocol	TCP/IP
Direction	IPP:ImgSrv → PSPS:ImgSrv

11.9.3.2 Software Data Interface

Type of Interface	Storage and retrieval of data
Size	169 TB[28]
Data type	Encapsulated data in FITS
Data transfer rate	**437 Mbit/sec (20 paths) (TBR)**
Frequency	1 per 6 months
Latency	**20 msec (TBR)**
Periodic	True
Required Protocol	TCP/IP
Direction	IPP:ImgSrv → PSPS:ImgSrv

11.10 MOPS - PSPS

11.10.1 MOPS:DC - PSPS:MOPSDB

The MOPS will transmit data products to the public interface as they are available.

11.10.1.1 Software Command and Control Interface

Type of Interface	Soft real-time
Size	**1 KB (TBR)**
Data type	Encapsulated data in **XML (TBR)**
Data transfer rate	**10 Mbit/sec (TBR)**
Frequency	1 per month
Latency	**20 msec (TBR)**
Periodic	True
Required Protocol	TCP/IP
Direction	MOPS:DC → PSPS:MOPSDB

11.10.1.2 Software Data Interface

Type of Interface	Storage and retrieval of data
Size	530 GB
Data type	Encapsulated data in **XML (TBR)**
Data transfer rate	**164 Mbit/sec (TBR)**
Frequency	1 per month
Latency	**20 msec (TBR)**
Periodic	True
Required Protocol	TCP/IP
Direction	MOPS:DC → PSPS:MOPSDB

11.11 MOPS - EXT

11.11.1 MOPS:DC - EXT:Solar System Community

11.11.1.1 Software Command and Control Interface

Type of Interface	Soft real-time
Size	**1 KB (TBR)**
Data type	Encapsulated data in **XML (TBR)**
Data transfer rate	**10 Mbit/sec (TBR)**
Frequency	1 per month
Latency	**20 msec (TBR)**
Periodic	True
Required Protocol	TCP/IP
Direction	MOPS:DC → EXT:SolarSys

11.11.1.2 Software Data Interface

Type of Interface	Storage and retrieval of data
Size	530 GB
Data type	Encapsulated data in **XML (TBR)**
Data transfer rate	**164 Mbit/sec (TBR)**
Frequency	1 per month
Latency	**20 msec (TBR)**
Periodic	True
Required Protocol	TCP/IP
Direction	MOPS:DC ↔ EXT:SolarSys

11.12 Definitions

TEL	Telescope Subsystem
CAM	Camera Subsystem
OTIS	Observatory Telescope Instrument Subsystem
IPP	Image Processing Pipeline Subsystem
EXT	External Parties
PSPS	Published Science Products Subsystem
MOPS	Moving Object Processing System
GPC	Giga-Pixel Camera
DHC	Detector Host Controller
TCS	Telescope Control System
OBS	Observation Sequencer
DDS	Detector Data Store
ImgSrv	Image Server
ODA	OTIS Data Archive
MDB	Metadata DataBase
OWS	OTIS Weather Server
Met	External Weather Server
DC	Data Collection
APDB	Astrometry-Photometry DataBase
MOPSDB	MOPS DataBase
SolarSys	Solar System Community

Notes

[23] Includes FITS Overhead Factor: 1.01

[24] Includes XML Overhead Factor of 2

[25] Includes XML Overhead Factor of 2

[26] Includes XML Overhead Factor of 2

[27] Includes XML Overhead Factor of 2

[28] Includes FITS Overhead Factor of 1.01