UNIVERSITY OF HAWAI‘I AT MĀNOA
Institute for Astronomy

Pan-STARRS Project Management System

System/Subsystem Specification

for the

Pan-STARRS PS-1 Telescope Subsystem

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Revision History

Version/Revision	Date	Explanation of Change or Other Comments
DR	07/01/2004	Initial reformatting of PSDC_Requirements34
00	08/02/2004	Initial version of Telescope SSS
01	11/26/04	Revision from EOC review and for EOS
02	4/15/05	Added M2 and M1 blank dimension specs., revised telescope motion specs., moved image budget alloc. tables to PSDC-300-011-00, included EOST comments, included Bonn's suggested changes to shutter specs, backed off earthquake spec., included refs. to PSDC-300-018-01 (cooling), fixed scratch and dig spec., fixed aerosol monitor spec., improved section 6.4, and added section 6.5, added sections 3.1 & 3.2 to qualification tables!
03	8/3/05	Added safety specs. to filter mechanism, section 6.6 added

TBD/TBR Listing

Paragraph No.	Page No.	TBD/TBR No.	Description
3.3.9.1	26	1	Calibration facility spec.
3.3.9.2	26	2	Calibration facility spec.
3.3.9.3	26	3	Calibration facility spec.
3.3.9.4	26	4	Calibration facility spec.

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1 Scope

1.1 Identification

Project sponsor: AFRL, United States Air Force
Acquirer: University of Hawaii Institute for Astronomy
Users: Astronomical community
Developer: University of Hawaii Institute for Astronomy, participating institutions, and associated subcontractors
PS-1 Operating site: Haleakala Observatory, the Lunar Ranging Experiment (LURE) site.

This document is the System/Subsystem Specification (SSS) for the prototype telescope system of the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS), also known as PS-1, 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 System Concept Definition (SCD) is a document (PSDC-250-002-00) that includes high level system requirements which dictate many of the design specifications given here. The Prototype Telescope System (PS-1) consists of one unit of a planned array of four 1.8m telescopes each with a $7\ \mathrm{deg}^2$ field of view (FOV). It includes a 1 billion pixel (giga-pixel) CCD camera with low noise ($\sigma_r \leq 6\ e^-$) and rapid read-out (~4 seconds), an automated filter changing mechanism, a wide-field shutter and the software to acquire and autonomously analyze high-resolution multi-band images of the night sky in a timely fashion.

Figure 1 is a block diagram that serves to illustrate the basic conceptual design for the PS-1 telescope. This diagram is a modified version of Figure 9 in the SCD. Colorless boxes or circles in this figure denote components that are not considered to be part of the telescope subsystem. In some cases, like the camera, this is because these components are complex enough to form their own subsystem and are described elsewhere in the Pan-STARR documentation. Likewise, open arrows denote control lines that are not considered to be part of the telescope subsystem.

The PS-1 telescope is to be a conventional Cassegrain layout with a 3 element corrector on an alt-az mount in a co-rotating dome with an enclosure shutter. In the figure L1 and L2 denote the first two corrector lenses. The addition of the ADC label to the L1 block is discussed below. The third corrector lens (L3) is not shown in this figure because it forms the window for the camera and is therefore considered to be part of that subsystem. The telescope will have an automated filter changing mechanism, an instrument shutter, and a giga-pixel camera mounted behind the primary mirror cell on an instrument rotator. The shutter will be implemented as a pair of blades that move across the field separated by a gap. The gap would be small for short exposures.

There is an option under consideration to add an Atmospheric Dispersion Corrector (ADC) to the telescope optics. If an ADC is added to the system, it will be a drop-in replacement for the L1 corrector. With the addition of the ADC, the dashed control line in Figure 1 that goes between the L1/ADC block and the OTIS OCS will be added to the system interfaces.

The light grey blocks labeled UCC and LCC in Figure 1 signify parts of the telescope's instrument package that are mounted together. UCC is the Upper Cassegrain Core. It is fixed with respect to the M1 mirror cell. As shown in the figure, the corrector lenses L1 and L2 are mounted in the UCC structure. LCC is the Lower Cassegrain Core. The LCC structure supports the camera, filter mechanism, and the shutter. The entire LCC turns with the instrument rotator.

The baffling will be a 3 element Sloan-like design (denoted by B1-B3 in Figure 1). There will be a calibration facility enclosed in the dome which will be used for throughput, flat-field, and wavelength calibrations of the camera and telescope optics. The telescope environment sensors will include temperature, humidity, and dust sensors as well as sky transparency monitors which will be bore-sighted to the telescope. The transparency monitors are called SkyProbes, which are wide field cameras/spectrographs. The SkyProbes will probably mount to the center section of the telescope support structure. The telescope temperature sensors will be monitored via the Telescope Control Software (TCS), but the rest of these sensors will be monitored through the Observatory, Telescope, and Instrument Software (OTIS).

The blue and red lines in the figure denote mechanical and control interfaces, respectively. Red lines that have open arrows denote control interfaces that will not be described in this document. The mechanical and closed arrow interfaces are described in more detail in Section 3.4 below. The Observatory Control System (OCS), the Observing Sequencer (OBS) and the Detector Hardware Controller (DHC) are parts of the observing software that will be developed by Pan-STARRS personnel. The OCS and OBS are both part of the OTIS which is responsible for the high-level automatic control of the observatory. The DHC is part of the camera control software. The TCS and the Dome Control Software (DCS) represent low-level programs that control both the telescope and enclosure hardware. This software will probably be supplied by the telescope vendor. Almost all user intervention to the TCS will be done via OTIS with probable exceptions to this during maintenance, servicing, and engineering efforts.

Requirements for the support space for the PS-1 telescope will be discussed in the PS-1 Observing Site Plan, not in this document. However, it is useful in the context of this document to understand the basic concepts of how this support space will be used.

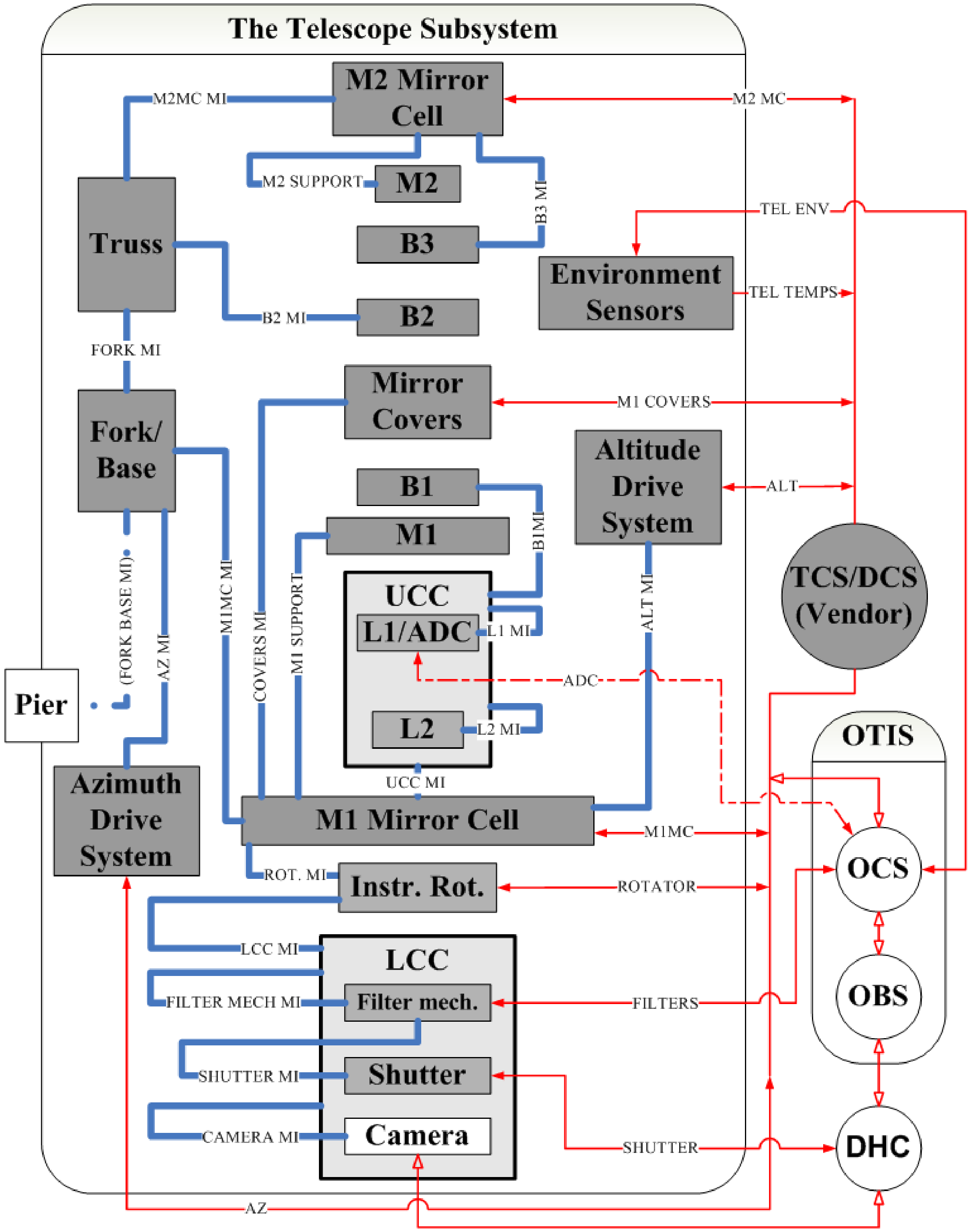

Figure 1. Telescope Subsystem Block Diagram

The support space for the PS-1 telescope is not intended to be a full support facility. Significant maintenance work on the camera, filter mechanism, camera shutter, or rotator will be done off of the mountain top. Likewise, there will be no coating facility on the mountain for PS-1. Instead, the mirrors will be taken to a facility on the Big Island whenever recoating is necessary. There will be no machining facilities, and, since much of the observing will be done remotely, the "creature comforts" normally necessary to an on-site staff will be kept to a minimum. The support space will be primarily used for preparing components for shipment off of the mountain top, for receiving them from transportation to the mountain, for routine maintenance tasks like pumping out the camera dewar, and for small scale repairs on non-critical items like cables and harnesses.

There will be a series of specialized carts which will double as the bottom of shipping containers for the handling of the mirrors and Cassegrain Core components. Storage for most of the instrument and mirror handling carts and fixtures will be off-site, but it will be necessary to have simultaneous storage room for at least three of these carts when one component of the Cassegrain Core breaks down and other components have to be removed to get at the broken component.

1.3 Document Overview

The Pan-STARRS System/Subsystem Specification contains a complete specification of the Pan-STARRS system intended to meet the top-level specifications and operational requirements contained in the SCD. The requirements flow begun in the SGS and developed in the SCD is further detailed in the SSS to provide additional derived system and subsystem requirements.

This document is specific to the requirements specification of the telescope, the telescope enclosure, and the instrument support subsystems mounted to the telescope. These include the instrument rotator, the filter changing mechanism, the telescope environment monitors, and the camera shutter mechanism. This document will not specify the camera itself, the software that runs the telescope, nor the support spaces that will be in close proximity to the telescope enclosure. Examples of these are the control room and the computer room specifications. These items will be discussed in the PS-1 Observing Site Plan.

These requirements are intended, in part, to serve as requirements to vendors who will be bidding and building components for the project. Suggested revisions are invited that will improve this function.

2 Referenced Documents

2.1 UH-IfA and Pan-STARRS Documents

Document Number	Document Title	Revision	Date	Originating Organization
PSDC-250-002	System Concept Definition	00	7/21/04	Pan-STARRS
PSDC-230-001	Pan-STARRS Telescope #1 Reference Mission	00	2/20/04	Pan-STARRS
PSDC-330-002	The Pan-STARRS Filter Set Specifications	00	2/03/05	Pan-STARRS
PSDC-300-011	The PS-1 Telescope Image Budget Allocations	02	4/5/05	Pan-STARRS
PSDC-300-018	Power, Cooling, and Cable Wraps in the PS-1 Telescope	01	4/12/05	Pan-STARRS
PSDC-300-019	The PS-1 Lens Mount Designs	00	7/14/05	Pan-STARRS
PSTD-020-001	PS-1 Primary Mirror Blank	01	5/5/04	Pan-STARRS
PSTD-020-003	PS-1 Secondary Mirror, Ribbed Meniscus Mirror Blank	00	12/19/04	Pan-STARRS
PSTD-240-001	Lower Cassegrain Core Design Subsystem Envelopes	00	3/8/05	Pan-STARRS

3 Requirements

The requirements given here flow down and are derived in large part from the top-level telescope requirements and the conceptual design given in the SCD. The requirements shown here are specific to the PS-1 prototype telescope, which means that items in the SCD that are specific to the full array of telescopes do not apply. Also, owing to the fact that the PS-1 telescope is conceived to be a prototype to the full array, some things that will be required for the final array of telescopes will be relaxed for the PS-1 telescope. In particular, those top level telescope requirements that do not apply to the PS-1 telescope are:

- 5.2.2 The number of telescopes shall be ≥ 3 .
- 5.2.13 The telescope shall be remotely operable.

Lower level requirements that will be different for the full array and PS-1 are:

- Ghosting in the optics [see section 6.1].
- Photometric precision [3.1.9]
- Support space requirements [as detailed in section 1.2]
- Telescope efficiency and throughput requirements [as detailed in section 6.2]

3.1 Top Level Requirements

The PS-1 top level requirements are derived in part from the SCD top level requirements with the modifications mentioned above. The top-level requirements which apply to the PS-1 prototype are given here. The reasoning behind these requirements is that given in the SCD unless specially noted here.

3.1.1 The telescope aperture shall be 1.8 m in diameter

3.1.2 The telescope operational altitude range shall be 10° to 70° zenith angle.

This specification refers to the tracking capabilities of the telescope, not its range of motion in zenith angle.

3.1.3 The half-angle of the telescope field of view shall be 1.5°

3.1.4 The telescope focal length shall be 8.0m

3.1.5 The PS-1 complement of filters shall be the *g,r,i,z,y and w* filters.

3.1.6 The telescope shall deliver a PSF ≤ 0.41″ FWHM at a zenith angle of 70° for the full complement of filters

3.1.7 The telescope shall deliver a PSF ≤ 0.32″ FWHM at a zenith angle of 0° for the full complement of filters.

Note that the altitude range of the telescope is not specified to include a zenith angle of 0° (3.3.8.6), but it is very likely that this is where most of the optics shall be tested when polishing. The difference is not considered significant for these purposes.

3.1.8 The PS-1 telescope shall utilize an altitude-over-azimuth mount.

3.1.9 The sum of systematic contributions to the photometric error in PS-1 data is to be less than 0.025 magnitudes.

One of the PS-1 Astrometric and Photometric Survey Goals is that the standard star zero points are to have a dispersion of 0.010 magnitudes RMS or less. Global consistency of the Pan-STARRS photometric reference stars is to have a peak-to-peak consistency of ±0.025 magnitudes. There are to be no systematic discrepancies that exceed the ±0.025 magnitude limits.

3.1.10 The PS-1 stray light management shall include a fully baffled focal plane, contamination control and other measures to mitigate the impact of stray light.

3.1.11 The PS-1 state shall be reported and logged.

3.1.12 PS-1 telescope shall support maintenance and service.

3.1.13 The altitude and azimuth axes of the PS-1 telescope shall have maximum velocities ≥ 1.0°/second and ≥ 2.0°/sec, respectively.

The impacts of this requirement are detailed in paragraphs 6.4 and 6.5 of the Notes section below.

3.1.14 The PS-1 telescope axes shall be capable of slewing 3.0° and settling to the nominal open loop tracking errors in a 5 second time interval.

The 5 second time interval shall include both the time to move the telescope and the time for the telescope and mirror supports to settle to tracking a stable position on the sky. It is assumed that the telescope move will begin while the telescope is tracking at a sidereal rate. The open loop tracking errors are specified in paragraph 3.3.8.4. However, for verification of this specification, a time interval of only 3 seconds after the move will be used to measure the post-move tracking error. The commencement of this measurement interval will start 5 seconds after the beginning of the telescope move.

This performance will be dependent on the telescope's initial starting zenith position as specified in paragraph 6.5 of the Notes section below. The zenith angle restrictions to this specification are driven primarily by the maximum azimuth velocity specified in paragraph 3.1.13 above.

3.1.15 For intermediate step angles (from 0.002 to 0.01 degrees) the PS-1 telescope shall be capable of slewing and settling to the nominal open loop tracking errors in a 2 second time interval.

The open loop tracking errors are specified in paragraph 3.3.8.4. However, for verification of this specification, a time interval of only 2 seconds after the move will be used to measure the post-move tracking error. The commencement of this measurement interval will start 2 seconds after the beginning of the telescope move.

3.1.16 For small step angles (from 0.00003 to 0.002 degrees) the PS-1 telescope shall be capable of slewing and settling to the nominal open loop tracking errors in a 1 second time interval.

The open loop tracking errors are specified in paragraph 3.3.8.4. However, for verification of this specification, a time interval of only 2 seconds after the move will be used to measure the post-move tracking error. The commencement of this measurement interval will start 1 second after the beginning of the telescope move. Note that this specification has the largest impact on the telescope's ability to accept guiding inputs from the Pan-STARRS camera.

3.1.17 The time between the initiation and completion of a filter change shall be less than 45 sec.

3.1.18 The telescope mirror cell design shall be compatible with the PS-1 primary mirror blank.

The physical dimensions of the M1 mirror blank are described in PSTD-020-001-01. This drawing is reproduced below in Figure 2. The weight of the M1 mirror blank is approximately 1100 lbs. The blank is made out of ULE glass. Note that the Pan-STARRS project is responsible for providing this blank, polished to the proper optical specifications.

3.1.19 The telescope secondary support structure shall be compatible with the PS-1 secondary mirror blank.

The physical dimensions of the M2 mirror blank are described in PSTD-020-003-00. This drawing is reproduced below in Figure 2. The weight of the M2 mirror blank is approximately 126 lbs. The M2 blank is made out of ULE glass. Note that the Pan-STARRS project is responsible for providing this blank, polished to the proper optical specifications.

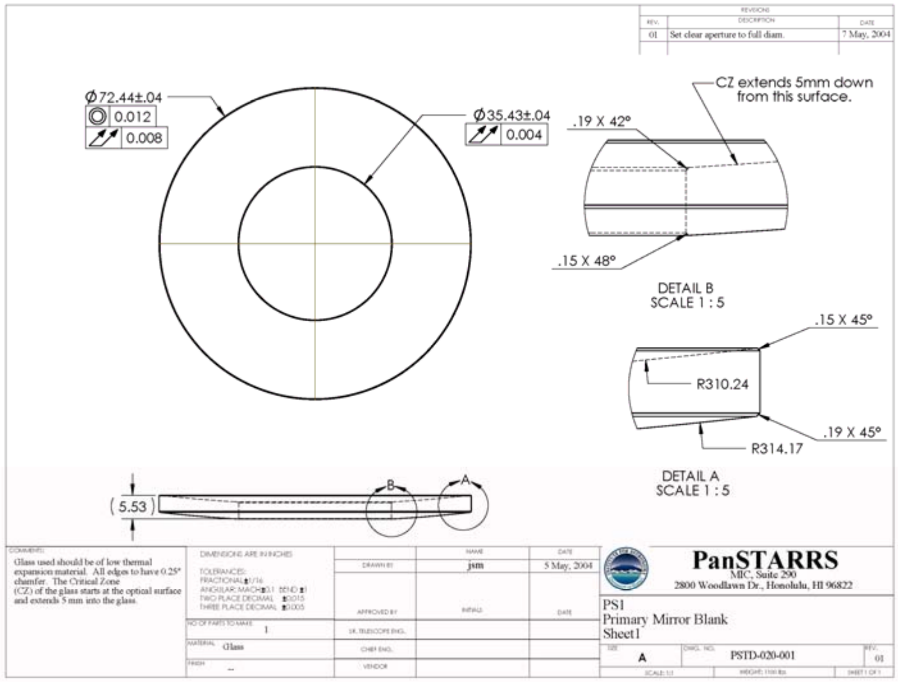

Figure 2. The PS-1 Primary Mirror Blank Dimensions.

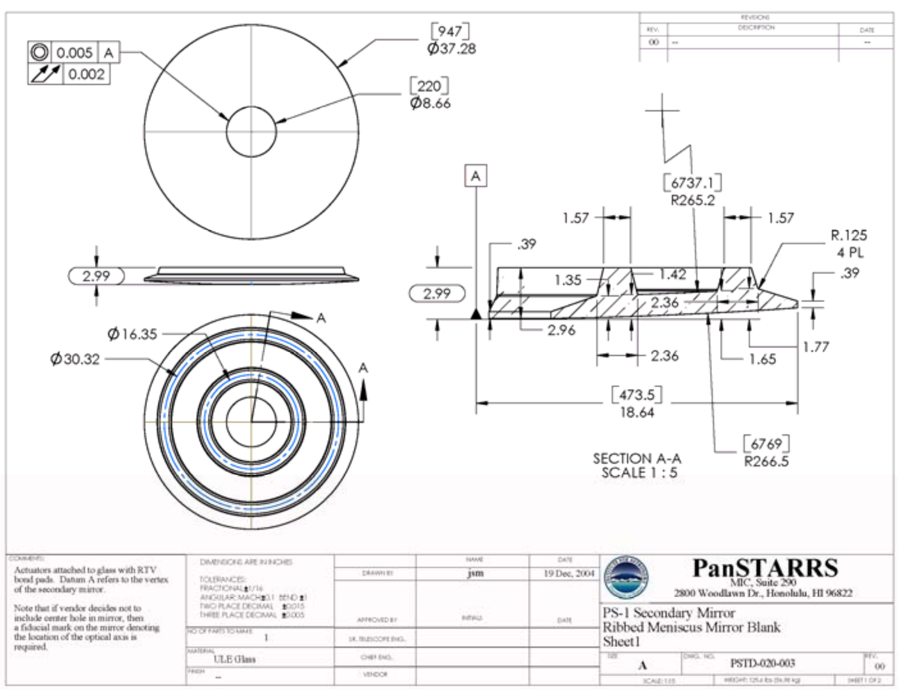

Figure 3. The PS-1 Secondary Mirror Blank Dimensions

3.2 Required States and Modes

The SCD calls out several operational states for the telescope/enclosure subsystem. These states will apply for the PS-1 telescope as well. Currently the only state-specific requirements on the telescope/enclosure hardware are for equipment which will allow the transition between the states specified below and for the calibration hardware. There are no requirements whose values or limits change as a function of state. Usually, the telescope states are controlled via the OTIS. But, there are exceptions to this. The telescope interlock system is the prime example of hardware that controls the telescope subsystem states. The operational states for the PS-1 telescope are as follows:

3.2.1 Observing

The telescope is operational and is taking or is about to take data on the sky. The enclosure and mirror covers are open (SCD state 5.5.1). The camera, filter mechanism, and shutter have signaled the OTIS that they are operational. User intervention via the OTIS user interface will be required to initially enter this state. This state can be subsequently left and re-entered autonomously, but after entering the off, servicing, and failure states, a return to this state will once again require user intervention.

3.2.2 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 (SCD state 5.5.2). This state is entered and exited autonomously by the OTIS and by user intervention via the OTIS.

3.2.3 Hibernating

The telescope is up and running, but the mirror covers are closed and the enclosure is closed. This state needs to be automatically triggered by bad weather conditions (SCD state 5.5.3). It is entered and exited by means of the OTIS software and by user intervention via the OTIS.

3.2.4 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 and all computers in the enclosure that can be safely shut down have been. This state needs to be automatically triggered by power outages or computer failures (SCD state 5.5.4). This state can be entered and exited both autonomously and by user intervention via the OTIS.

3.2.5 Servicing

The telescope is quasi-static, moved only as required to allow removal of optics, mechanisms, or the camera. It is possible that the 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 (SCD state 5.5.5). This state can be entered and exited only by user intervention via the OTIS.

3.2.6 Off

The power to the telescope, enclosure, and camera is off (SCD state 5.5.6). This state can be entered only by user intervention via the OTIS or long-term failure of power to the site.

3.2.7 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 (SCD state 5.5.7). This state can be entered autonomously and by user intervention (for testing) via the OTIS. It can only be exited through user intervention.

3.3 System Capability Requirements

3.3.1 Image Quality

Except where specifically noted, the image budget requirements shown below flow down from the two top level PSF requirements for the PS-1 telescope, 3.1.6 and 3.1.7. Table 2 in section 3.4 of the SCD and the discussion found there shows how these requirements translate into the requirements

$$\left\langle r^2 \right\rangle_{Total}^{1/2} = 9.00\ \mu\text{m at } z=0^{\circ}$$

$$\left\langle r^2 \right\rangle_{Total}^{1/2} = 12.57\ \mu\text{m at } z=70^{\circ}$$

where $\left\langle \boldsymbol{r^2} \right\rangle_{\boldsymbol{Total}}^{\boldsymbol{1/2}}$ is the total image budget allocation for the telescope subsystem assuming a telescope focal length of 8 m. Given these numbers as a starting point, Table 1 shows how the allocation of the telescope image budget has been distributed amongst the various telescope subsystem components. Note that the table lists requirements at a zenith angle of 0° even though the range of zenith angles that the telescope will use starts at 10°. This is done because the optics will likely be tested at 0° during fabrication. Specifics to the allocation of this telescope image budget between the various design components are given in requirements 3.3.1.1 through 3.3.1.9. A more detailed breakdown of each of these items can be found in the document PSDC-300-011-02, The PS-1 Telescope Image Budget Allocations. For vendors dealing with the support systems of the optics, the detailed level breakdown of the error allocations shown in that document can be considered as advisory. That document represents working notes on the image budget allocations and is therefore relatively unstable. In contrast, the allocations shown below in Table 1 should be stable.

Table 1. PS-1 Telescope Image Budget Summary

Paragraph No.	Component	$\langle r^2 \rangle^{1/2}$ (µm)		R_0 (cm)	
		$z = 0^\circ$	$z = 70^\circ$	$z = 0^\circ$	$z = 70^\circ$
3.3.1.1	**Optical Design**	6.6	6.6	42	42
3.3.1.2	**Primary Mirror (M1)**	3.1	4.4	89	63
3.3.1.3	**Secondary Mirror (M2)**	1.4	1.7	198	163
3.3.1.4	**L1 Corrector**	2.3	3.3	120	84
3.3.1.5	**L2 Corrector**	2.2	3.0	126	92
3.3.1.6	**L3 Corrector (Dewar Window)**	1.4	1.8	198	154
3.3.1.7	**Filters**	0.5	0.7	554	396
3.3.1.8	**Collimation**	2.1	4.4	132	63
3.3.1.9	**Focus**	2.0	4.0	139	69
Total		**8.71**	**11.17**	**31.8**	**24.8**

In Table 1 for a reference wavelength of $\lambda = 5 \times 10^{-5}\ cm$ the conversion between $\langle r^2 \rangle^{1/2}$ and R_0 is given by the formula $R_0 = \frac{277.06}{\langle r^2 \rangle^{1/2}}$. The conversion to FWHM in arcseconds is given by $FWHM = \frac{10.1}{R_0}$. The totals at the bottom of Table 1 are consistent with the assumption that the atmospheric value of R_0 decreases with increasing zenith angle, $\mathbf{z}$, as $(\mathbf{cos(z)})^{\frac{3}{5}}$. The $(\mathbf{cos(z)})^{\frac{3}{5}}$ variation with zenith angle was used as a starting point for the distribution of all component allocations. The baseline optical model was then used to estimate the level of difficulty of achieving each allocation and this evaluation was used to redistribute the image budget allocations. Attempts were made to make the component allocations to vary more slowly with zenith angle than the atmosphere in order to keep the atmosphere as the limiting factor in determining the delivered image quality. The total allocation of 8.71 µm for the telescope image budget at the zenith corresponds to a contribution of 0.32" to the system PSF in accordance with specification 3.1.7. Likewise, 11.17 µm at a zenith angle of 70° corresponds to a contribution of 0.41" as specified in paragraph 3.1.6.

3.3.1.1 Telescope aberrations shall contribute ≤ 6.6 µm RMS to the telescope PSF when the g, r, i, z, y, and w filters are in use.

In this context, telescope aberrations refer to all aberrations which are intrinsic to the optical design, not those which are the result of manufacturing, support or collimation errors. The optical image size budget (SCD 5.2.5) applies over the g, r, and i Sloan filters, over the modified z and y filters, and over the w filter for asteroid detection. A 6.6 µm RMS error is equivalent to an image error of 0.24″.

3.3.1.2 The primary mirror and its support shall contribute ≤ 3.1 µm RMS to the telescope PSF near zenith and ≤ 4.4 µm at a zenith angle of 70°.
This is includes support errors, polishing errors, and coating errors. A potential break-down of these errors is given in PSDC-300-011-02.

3.3.1.3 The secondary mirror and its support shall contribute ≤ 1.4 µm RMS to the telescope PSF near zenith and ≤ 1.7 µm at a zenith angle of 70°.
This is includes support errors, polishing errors, and coating errors. A potential break-down of these errors is given in PSDC-300-011-02.

3.3.1.4 The L1 corrector and its support shall contribute ≤ 2.3 µm RMS to the telescope PSF near zenith and ≤ 3.3 µm at a zenith angle of 70°.
This is includes support, polishing, tilt, despace, and decenter errors. A potential break-down of these errors is given in PSDC-300-011-02.

3.3.1.5 The L2 corrector and its support shall contribute ≤ 2.2 µm RMS to the telescope PSF near zenith and ≤ 3.0 µm at a zenith angle of 70°.
This is includes support, polishing, tilt, despace, and decenter errors. A potential break-down of these errors is given in PSDC-300-011-02.

3.3.1.6 The L3 corrector and its support shall contribute ≤ 1.4 µm RMS to the telescope PSF near zenith and ≤ 1.8 µm at a zenith angle of 70°.
This is includes support, polishing, tilt, despace, and decenter errors. A potential break-down of these errors is given in PSDC-300-011-02.

3.3.1.7 The filters and their support shall contribute ≤ 0.5 µm RMS to the telescope PSF near zenith and ≤ 0.7 µm at a zenith angle of 70°.
This is includes support, polishing, tilt, despace, and decenter errors. A potential break-down of these errors is given in PSDC-300-011-02.

3.3.1.8 The collimation of the telescope optics shall not degrade the telescope PSF by more than 2.1 µm RMS near zenith and ≤ 4.4 µm at a zenith angle of 70°.
Note that since the corrector optics already have decenter and tilt requirements, this refers to the alignment of the primary and secondary optical axes with respect to the optical axis of the Cassegrain Core. This is the collimation allotment seen in Table 1. Tolerancing of the Pan-STARRS baseline optical design shows that this specification can be met by keeping the primary and secondary axes aligned to within 75 µm in translation and control of the tilt of the two axes to an accuracy of ±1”. For a 0.9 m diameter secondary, this tilt requires actuators with a resolution of about 2 µm. Both of these requirements are plausible. The primary difficulty will be to sense the mirror displacement and tilts to a sufficient accuracy.

3.3.1.9 Focus errors of the telescope shall degrade the PSF ≤ 2.0 µm RMS near zenith and ≤ 4.0 µm at a zenith angle of 70°.
Focus updates will be required from the camera wave front sensor on a per exposure basis to ensure this requirement.

3.3.1.10 The optical design for Pan-STARRS shall have a focal surface with a sag of less than 200 µm across the full 1.5° field of view.
Note that this is a specification on the optical design, not on the quality of the rotator, flexures in the mirror cell, or on the position of camera devices in the focal plane. Preventing image blur over the surface of the 50 mm square CCDs requires a minimum focal surface radius of curvature of 30 m. For a telescope focal length of 8 m, a 1.5° FOV spans a radius of 210 mm. An upper limit of a sag of 200 µm is therefore equivalent to a lower limit of 1.1×10^5 mm in the focal surface radius of curvature.

3.3.1.11 The focal surface field distortion shall be ≤ 3% from the mean plate scale.
To meet the SGS requirement 4.2.3 to develop a static sky map, images will be warped in software to fit onto a common reference surface and summed to form the static sky image. The accuracy of this process will be enhanced by keeping the image distortions below 3%.

3.3.1.12 The quality of refractive surfaces (e.g., scratch and dig) shall be 80/50.
The scratch and dig specification on the optics primarily affects the small angle scattering from these surfaces. Almost all of the optical surfaces are large in scale, far from focus (even L3), and will be exposed to normal atmospheric dust. The scratch and dig specifications therefore need only be good enough to guarantee that dust on the surfaces will be the dominant source of small angle scattering. An analysis of this can be found in PSDC-330-002-00 (The Pan-STARRS Filter Set Specification).

3.3.1.13 The entrance pupil of the telescope shall be defined by the outside diameter of the primary mirror and the tip of the secondary baffle.
The outer boundary of the entrance pupil shall be defined by the primary-mirror outside-diameter mask. The inner boundary of the entrance pupil shall be defined by the tip of the secondary baffle.

3.3.1.14 The primary and secondary mirrors will be made out of low expansion glass.
This helps to minimize optical aberrations that result from thermal changes to the telescope optics.

3.3.1.15 The telescope shall have mirror covers that shield both the primary mirror and the Cassegrain corrector optics from dust and minor precipitation.

3.3.1.16 The telescope mirror covers shall be remotely operable and capable of closing from a completely open position within 30 seconds.
The mirror covers shall be remotely operable by the OTIS software.

3.3.1.17 The telescope mirror covers shall have both fully closed and fully open limit switch feedback.

3.3.2 Collimation

Wide field telescopes are very sensitive to errors in the collimation of their optics. This is particularly true for Cassegrain layouts, and the primary and secondary mirrors are the optical elements with the tightest positioning specifications. The precise limits and resolutions on the mirror actuators will only be known after an optical design has been chosen and "toleranced". However, below are given rough estimates of these based on rough preliminary tolerancing of the currently considered optical layouts. Based simply on the SCD choice of a Cassegrain layout with a very wide field of view it is possible to know that the following types of motions will be required in order to place and keep the telescope in proper collimation.

3.3.2.1 The secondary shall be actuated in 5 axes: x-tilt, y-tilt, piston, x-translation, and y-translation.
All of these motions must be remotely controlled by the OTIS to keep the telescope in focus and in collimation at all times.

3.3.2.2 The secondary actuators shall have a resolution ≤2 µm and a range of motion ≥5 mm.
Note that the resolution of these actuators is driven by the need to control the tilt of the secondary to an accuracy of about 1".

3.3.2.3 The primary mirror shall be adjustable in 4 axes: x-tilt, y-tilt, x-translation, and y-translation.
Adjustments of the primary mirror will be necessary during initial collimation of the telescope. Automated adjustments of the primary mirror will need to be made as a function of zenith angle.

3.3.2.4 The tilt and x-translation of the primary mirror shall be either manual or automated.
The x-axis is assumed to be parallel to the altitude axis of the telescope and perpendicular to the optical axis of the telescope.

3.3.2.5 The y-translation of the primary mirror shall be automatically adjustable.
This axis shall be controlled by the OTIS software. It is assumed here and in Figure 1 that this will be done via an interface with the TCS. The y-axis is perpendicular to both the altitude and optical axes of the telescope.

3.3.2.6 The primary mirror tilt actuators shall have a resolution ≤10 µm and allow a range of piston motion ≥ 5 mm.

3.3.2.7 The primary mirror x- and y-translation shall have a resolution ≤25 µm and allow a range of motion ≥1 mm.

Ray tracing of the baseline optical design shows that the primary and secondary axes must be within 75 µm of each other. This collimation requirement drives the resolution of these actuators. The range is driven by the maximum expected sag in the telescope Cassegrain Core.

3.3.2.8 The primary mirror shall reposition to within 100 µm after having been removed and replaced in the telescope.

This specification refers to the accuracy with which the primary mirror will reposition in a single translational axis before realignment procedures are undertaken.

3.3.2.9 The position and tilt of the optical axis of the primary mirror shall be known with respect to a well-defined mechanical fiducial on the mirror.

This position and tilt must be documented by the optician who polishes the primary mirror. One suggested mechanical fiducial would be the bore of the primary mirror center hole.

3.3.2.10 The position of the optical axis of the secondary mirror shall be marked by a dimple on the face of the mirror.

This position must be marked and documented by the optician who polishes the secondary mirror.

3.3.2.11 The primary mirror support shall utilize a pneumatic support system.

3.3.2.12 The air pressure for the primary mirror pneumatic support system shall be monitored.

This monitor shall detect if the pneumatic support pressure drops below a safe threshold. If this occurs, a signal indicating this condition must be available to the OTIS. This specification assumes that the M1 mirror supports are designed such that no damage will be done to either the mirror nor to its supports if air pressure is lost while the telescope is at large zenith angles. If this is not the case, then this signal must trigger an interlock which will protect the mirror in the event of a loss of support system air pressure.

3.3.2.13 The primary mirror support shall incorporate a 12 point astigmatism correction system that attaches to either the primary mirror or the secondary mirror.

3.3.2.14 The astigmatism correction system shall be controllable by the OTIS software.

3.3.2.15 The astigmatism correction system shall be capable of correcting for 0.5 waves of either astigmatism or trefoil errors in the telescope wave front.

3.3.2.16 The primary and secondary support systems shall have support errors that are compatible with the astigmatism correction system.

This specification implies that the primary and secondary support systems must keep the total surface error of the telescope below about 0.2 waves without corrections from this system in order to allow the astigmatism correction system the capability of removing residual astigmatism in the optics.

3.3.3 Telescope Throughput

Section 6.2 details how we are defining the telescope throughput. The Pan-STARRS telescopes are tasked with acquiring temporal coverage of the sky. Because of this, throughput is related to both observing efficiency and telescope reliability. Some issues related to the reliability of the telescope system that will be specified for the full Pan-STARRS array will not be specified for PS-1. Others, relating to fundamental aspects of the telescope geometry are given in this section.

The top level specification 3.1.1 states that the telescope aperture shall be 1.8m. This is effectively a telescope throughput specification.

3.3.3.1 Antireflective coatings shall be applied to all refractive surfaces and shall have reflectance ≤2% over the wavelength range from 400nm to 1100 nm.

The coatings of lenses and windows must be effective over the wavelength range defined by the g, r, i, z, y filters. Antireflective coatings are feasible for this band-pass and reduce ghost images and increase throughput. Ref. SGS 4.4.4 and 4.4.5. Note that the anti-reflective coatings of the filters themselves are dealt with in PSDC-330-002-00.

3.3.3.2 The reflectivity of the mirror coatings shall be ≥80% and the mirror coatings shall be made of either bare aluminum or protected silver.

This requirement refers to the value of $R(\lambda)$ which is defined in section 6.2. The choice between these coatings will be based on the feasibility and cost of protected silver. Durable protected silver on M1 and M2 would increase throughput 20% and has the potential to significantly decrease re-coating costs. With progress reported by the Laurence Livermore NL, the Gemini Project, and others, this appears feasible. Ref. SGS 4.4.4

3.3.3.3 The telescope obscuration shall be ≤37%.

This requirement refers to the value of $\omega(0)$, which is defined in section 6.2 and has an impact on the design of the telescope baffles.

3.3.4 The Filters

The Pan-STARRS filter complement is given in Table 2. The detailed specifications for these filters are given in PSDC-330-002-00 and those specifications will not be repeated here. But, the filter band-passes themselves are shown here because they are useful for the evaluation of the telescope optics. The size of the Pan-STARRS filters probably precludes them from using colored glasses in their manufacture. It is anticipated that they will be constructed as interference coatings on a planar substrate. Drawings of the physical size of the filters can be found in PSTD-020-002-01.

Table 2. The Pan-STARRS Filters

Filter	**Half Maximum Transmission Wavelengths (nm)**		**Bandwidth (nm)**
	Blue Side Cutoff	**Red Side Cutoff**	
g	402	552	150
r	552	691	139
i	691	818	127
z	818	922	104
y	970	1028	58
w	402	818	416

3.3.5 The Filter Mechanism

Figure 1 illustrated that the filter mechanism is one of three subsystems that make up the Lower Cassegrain Core (LCC). The other LCC subsystems are the shutter and the camera. Figure 4 illustrates the layout of subsystems in the LCC. This figure shows the current concept of the LCC support structure, the filter mechanism, the shutter, the camera, the primary mirror, the L3 dewar window corrector, and the system focal plane. The dashed lines in the left detail drawing of this figure show the design envelopes of these subsystems. The dimensions in this drawing serve to illustrate the location of these design envelopes with respect to the optical elements in the current telescope design. The dimensions of the design envelopes shown in this figure are given explicitly in paragraphs 3.3.5.4, 3.3.6.8, and 3.3.7.1 of this document. Note that the details in this figure of the support structure, filter mechanism, and camera shown are subject to change as the design concepts evolve, but the locations of the design envelopes are fixed quantities defined in this document.

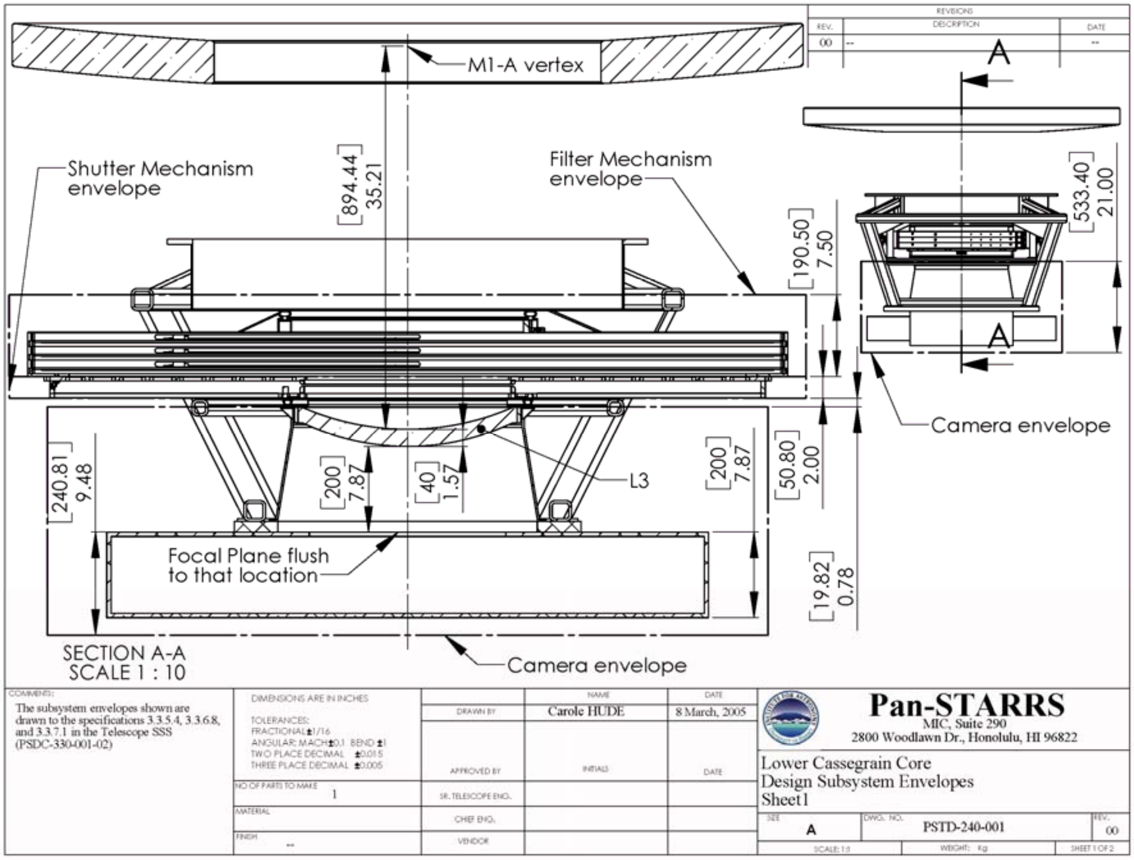

Figure 4. Physical layout of the Lower Cassegrain Core Subsystems

Only one filter is placed in the optical path at a time, i.e., filters are not combined. The filter thicknesses are such that refocusing is not required after a change. The filter is part of the optical design such that the telescope need not form sharp images when a filter is not present.

The top level specification 3.1.17 states that the time interval between the initiation and completion of a filter change shall be less than 45 sec.

3.3.5.1 The filter mechanism shall function during telescope slews and at all rotation angles and altitudes of the telescope.

3.3.5.2 The filter mechanism shall hold a total of 6 filters at one time.

The filter changer capacity shall include the complete project complement to protect the filters from damage and contamination that can come from handling. Ref. SGS 4.4.2 and 4.4.3

3.3.5.3 The filter position repeatability shall be 500 µm 2D RMS

In general, filter transmission non-uniformity, whether intrinsic or due to contamination, in combination with position non-repeatability degrades photometric accuracy. Ref: SGS 4.4.5. However, the filters are so far out of focus in the Pan-STARRS optical layout, that the filter position is not critical and will probably not significantly influence the photometry in the images.

3.3.5.4 The filter mechanism shall fit within the following envelope: 73 x 29.5 x 7.50 in (1855 x 750 x 190 mm)

The dimensions above are given in order of width, depth, and height. Height is the dimension along the optical axis and is the most critical dimension to satisfy. The location of this envelope with respect to the top vertex of the primary mirror is given in Figure 4.

3.3.5.5 The filter mechanism (including filters) shall weigh < 350 lbs (160 kg).

3.3.5.6 The filter mechanism shall place ≤ 60 ft-lbs torque on the instrument rotator at all times.

Rotational imbalance in the filter mechanism places constraints on the instrument rotator torque and power dissipation limits. The specifications on the telescope rotator are given in paragraph 3.3.8.10.

3.3.5.7 The filter mechanism shall have a MTBF of ≥ 19200 cycles.

The MTBF of the filter mechanism is derived in section 6.2 below.

3.3.5.8 The clear aperture in the filter mechanism shall be 480 mm.

This aperture assumes the optical layout specified in the PS-1 Design 2.0. This C.A. must remain consistent with the physical size of the filters as given in PSTD-020-002-01.

3.3.5.9 Filters shall be protected from contamination.

Filter transmission is made non-uniform by particle contamination. The filter changer shall be internally sealed and each filter will be in a sealed environment when the filter is retracted into its housing. A sealed volume containing L2, L3 and the filters shall be formed when the filter changer is assembled with the similarly sealed shutter, lens assembly, and giga-pixel camera. This protects these components from contamination during normal operations.

3.3.5.10 Humidity shall be monitored and controlled within the filter mechanism.

Coatings are changed or degraded by humidity changes. The dewar window will cool radiatively and condensation on the dewar window must be prevented.

3.3.5.11 Filters shall be removable for inspection and cleaning.

It is desirable, but not required that this shall be possible without removing the giga-pixel camera from the telescope.

3.3.5.12 Surfaces in the filter housing and mechanisms shall be designed and treated to minimize stray light.
Illuminated and critical surfaces shall be minimized. Illuminated and critical surface orientation, surface treatment, finish, etc., shall be chosen to mitigate stray light. Possible surface treatments include anodization, flocking, and painting.

3.3.5.13 The filter mechanism shall provide state feedback
It is necessary for the telescope software to be able to query the filter mechanism for the status of all encoders and limit switches in the mechanism.

3.3.5.14 The filter mechanism assembly shall be modular with quick disconnect cables.
This requirement is to facilitate removal of the filter changer assembly.

3.3.5.15 The filter mechanism shall dissipate ≤ 0.2 W of heat into the optical beam.
The calculations on which this specification is based are given in section 6.3. This refers to a time averaged heat dissipation into the gas cavity of the Cassegrain core.

3.3.5.16 The filter mechanism shall have a volumetric leak rate of ≤ 2.6 cm^3/sec.
The Cassegrain instrument package will be continuously backfilled with dry air in order to protect the filters and to inhibit condensation on the dewar window. This leak rate limit is derived in section 6.3. This refers to a leak rate of dry air at nearly ambient pressure.

3.3.5.17 The filter mechanism shall keep stresses on the filters below 1000 psi during operation.
The rationale for this limit is given in section 6.6.

3.3.5.18 The filter mechanism shall keep stresses on the filters below 1000 psi during filter installation.
The rationale for this limit is given in section 6.6.

3.3.6 The Camera Shutter

As stated earlier, the shutter will most likely be implemented as a moving slit whose width and timing are controllable. The shutter shall meet the following specifications for all orientations with respect to gravity.

3.3.6.1 The shutter shall make available a continuous range of exposure durations from 100 ms to 300 s.
The Design Reference Mission (PSDC-230-001-00) does not specify any exposure longer than 120 seconds. But, the scheduling of the telescope will require flexibility for exposure times caused by poor seeing conditions. In addition, calibration source radiance may be low for the narrowest band-passes being considered. The maximum exposure time is chosen to be larger than any anticipated exposures.

3.3.6.2 The accuracy of any exposure duration shall be better than 0.5% of the exposure duration.

This is departure of the mean duration over the field of view from the commanded duration. This requirement is driven by the SCD requirement to achieve 1% photometry in the static sky images.

3.3.6.3 In a single exposure, all points in the focal plane shall experience the same exposure duration to better than 0.5%.

This is the variation of the exposure from the mean at each position in the image plane. This requirement is driven by the SCD requirement to achieve 1% photometry in the static sky images.

3.3.6.4 The shutter shall be ready to begin a subsequent exposure no more than 1.0 second after the completion of a previous exposure.

3.3.6.5 The clear aperture of the shutter shall be 480 mm.

3.3.6.6 The blade position of the shutter mechanism shall be known as a function of time to a 10 msec accuracy.

To assure data quality, it is necessary to monitor the operation of the shutter. Time-tagged reports of the beginning and end of motion of each shutter blade suffice if blade velocity is uniform. Encoding the position of each blade and reporting its location vs. time is more desirable. Other state conditions will depend on the details of the shutter design. An example of such feedback would be limit switches at the extreme positions of the shutter blades.

3.3.6.7 The shutter mechanism shall have a MTBF ≥ 480,000 cycles.

This number is derived in section 6.2 of this document.

3.3.6.8 The shutter assembly shall fit within the following envelope: 73 x 29.5 x 2 in (1855 x 750 x 51 mm)

The dimensions above are given in order of width, depth, and height. Height is the dimension along the optical axis and is the most critical dimension to satisfy. The location of this envelope with respect to the top vertex of the primary mirror is given in Figure 4.

3.3.6.9 The shutter mechanism shall weigh ≤ 70 lbs. (32 kg).

3.3.6.10 The shutter mechanism shall place ≤ 5 ft-lbs torque on the instrument rotator at all times.

A Pan-STARRS sized shutter blade is predicted to weigh less than 0.3 kg (0.66 lb). For two blades at a distance of 600 mm (2 ft) from the optical axis, we have a torque of 1.3 ft-lbs. This specification places constraints on the telescope instrument rotator torque which is given in paragraph 3.3.8.10.

3.3.6.11 The shutter assembly will dissipate ≤ 0.4 W of heat into the optical beam
The calculations on which this are based is given in section 6.3. Note that this is a time average dissipation of heat into the optical cavity of the Cassegrain core.

3.3.6.12 The shutter assembly when mounted in the Cassegrain core shall have a volumetric leak rate of ≤ 2.6 cm^3/sec.
The Cassegrain instrument package will be continuously backfilled with dry air in order to protect the filters and to inhibit condensation on the dewar window. This leak rate limit is derived in section 6.3. This refers to a leak rate of dry air at nearly ambient pressure.

3.3.6.13 The shutter assembly shall be modular with quick disconnect cables.
This requirement is to facilitate the removal of the shutter assembly.

3.3.7 The Camera

This section defines requirements of the camera that are driven by physical aspects of the telescope.

3.3.7.1 The camera shall fit within the following envelope: 66 x 46 x 21 in (1676 x 1168 x 533 mm).
The dimensions are given in order of width, depth, and height. The optical axis is parallel to the height dimension. The location of this envelope with respect to the top vertex of the primary mirror is given in Figure 4.

3.3.7.2 The camera weight shall be ≤ 520 lbs (236 kg).

3.3.7.3 The camera shall place ≤ 5 ft-lbs of out-of-balance torque on the instrument rotator at all times.
This specification interacts with the torque specification on the instrument rotator (paragraph 3.3.8.10).

3.3.7.4 The camera mounting shall allow a 90° rotation of the camera with respect to the telescope optical axis.
It is acceptable for the camera to be removed and reinstalled on its mounting flange for this rotation to be accomplished.

3.3.7.5 Coatings and glasses used in the camera dewar window shall be made of non-radioactive materials.

3.3.8 Pointing and Tracking

The pointing and tracking of the telescope is controlled by the telescope mount, the drives and the software controls of the drives (both the higher level controls in OTIS and the lower level PID loop controls). These items can be thought of as the outer loop of the image stabilization system. Their role is to reduce image motion to the pixel level with a bandwidth of a few Hz. Smaller amplitude, higher frequency image motion is removed by shifting the image on the OTAs.

Accelerations and velocities of the telescope drives are not specified here. The step and slew specifications in paragraphs 3.1.14 through 3.1.16 and the settling time required by the telescope structure and the mirror mounts will define these quantities. However, in section 6.4 we consider approximate values for these quantities that are implied by the step and slew specifications.

3.3.8.1 All mirror components shall be protected from seismic force damage with accelerations < 0.3g.

Shock absorbers, springs and/or energy absorbing bumpers shall be employed limit stresses on susceptible components to tolerable levels. Mauna Kea is considered a zone 4 seismic site in the Uniform Building Code (UBC), which is the most severe risk seismic category. Haleakala is considered a zone 2B seismic site (http://hvo.wr.usgs.gov/earthquakes/hazards/). Descriptions of the seismic zone categories can be found at www.cement.org/masonry/seismic.pdf and http://cem.utah.gov/pdf/vsp.pdf. A seismic zone 4 has a 10% chance of ground accelerations exceeding 0.3g in a 50 year period. A seismic zone 2B has a 10% chance of ground accelerations exceeding 0.15g in a 50 year period.

3.3.8.2 The telescope pointing accuracy shall be <10 arcseconds 2-D RMS

This is an operational efficiency requirement which directly affects the system value of the parameter t_{closed} discuss in section 6.2.

3.3.8.3 The telescope altitude and azimuth encoders shall have 0.01″ resolution or better.

The dynamic range of the encoders should be consistent with this specification and the maximum slew velocities implied by specification 3.1.14.

3.3.8.4 Open-loop tracking error shall be ≤ 100 mas 2-D RMS for 1 minute of time.

This requirement is set to assure that telescope tracking error is small compared to the atmospheric image motions. If this is true, then the tracking will have no impact on the telescope PSF and it does not need to be included in the telescope image budget (Table 1). The RMS one-dimensional atmospheric image motions are given by

$$\delta\theta = 0.043 \times D^{-1/6} \times R_0^{-5/6} \text{ arcsec}$$

where both D, the telescope diameter, and R_0, the seeing Fried length, are expressed in meters. For a 1.8 m diameter mirror and mean seeing of 0.6″, we have $\delta\theta = 0.17''$ RMS. If the telescope tracking errors are below 0.07″ RMS, then the tracking errors increase the atmospheric motions by less than an 8%. To convert this to a 2-D number we multiply by $\sqrt{2}$.

3.3.8.5 The wind-induced tracking error shall be 70 mas 2-D RMS or less
This is to be measured with the axis encoders with a torque equivalent to the design wind load applied. The design wind load is given in 3.3.10.4

3.3.8.6 The telescope shall be able to track between zenith angles of 10 and 70 degrees for periods >5 minutes without interruption.
This flows down directly from SCD requirement 5.2.11. This requirement influences requirements on the rotator limits (3.3.8.9) because of the upper limit on the zenith angles that the telescope is required to track to.

3.3.8.7 The mechanical limits on the altitude axis shall be beyond a zenith distance of 75 degrees.
This is required to allow limit switches and safety shock absorbers room to act.

3.3.8.8 The azimuth tracking limits shall be ± 220 degrees with an azimuth cable wrap null point at 100 degrees measured from north toward east.
The null point location is a function of observatory latitude and is set by minimizing times when the azimuth must be unwrapped to accommodate the azimuth cable wrap limits.

3.3.8.9 The instrument rotator limits shall be > ± 60 degrees.
It is not planned to move the instrument rotator beyond these limits. The intent of this restriction is to alleviate the need for a cable wrap on the instrument rotator.

3.3.8.10 The instrument rotator shall support an out-of-balance torque load ≥ 70 ft-lbs (95 N-m).
This specification refers to the rotational torque on the rotator and will interact with specifications for the maximum out-of-balance torques that can be generated by the filter mechanism (paragraph 3.3.5.6), by the shutter (paragraph 3.3.6.10), by the camera (paragraph 3.3.7.3), and any estimates of out-of-balance torques generated by the instrument cable drape.

3.3.8.11 The instrument rotator shall support a load of 1433 lbs (650 kg) with a center of mass 15” (0.381 m) from its mounting plate.
This is the estimated weight and center of mass for the Lower Cassegrain Core instrument package.

3.3.8.12 The telescope mirror cell shall support a load of 606 lbs (275 kg) with a center of mass 5.9” (150 mm) from the top of the mirror cell.
This is the estimated weight and center of mass for the Upper Cassegrain Core instrument package. This weight includes an estimate of the weight of an Atmospheric Dispersion Corrector (ADC).

3.3.8.13 The telescope axes shall have brakes to prevent unwanted motions of the telescope and enclosure.
This specification includes altitude, azimuth, and instrument rotator axes. The brakes shall require power to disengage, but should also incorporate some means of manual over-ride. The specification for the manual over-rides, the interaction of these over-rides with a safety interlock, and for locking pins is given in section 3.5.

3.3.8.14 The telescope guiding bandwidth shall be ≥1 Hz.
The giga-pixel camera sends the common mode error from measurements of guide stars to the telescope control system. It is assumed that these measurements will be low-pass filtered to the bandwidth of the axis servo systems. The bandwidth of the axis servo systems is in large part determined by specification 3.1.16.

3.3.9 The Instrument Calibration Facility

The calibration system provides a means of illuminating the entrance pupil of the optical system so that pixel to pixel variations in sensitivity can be determined. Control over spatial, angular, and spectral band-pass is important.

3.3.9.1 Spatial uniformity over the entrance pupil shall be ±10% or better on scales larger than 10 cm (TBR).

3.3.9.2 Angular uniformity shall be ±10% or better over the 3° field of view (TBR).

3.3.9.3 Spectral uniformity shall be ±10% or better over each of g, r, i, z, y filter band-passes (TBR).

3.3.9.4 Radiance shall be adequate to 50% saturate pixels in 30 seconds (TBR).

3.3.9.5 Autonomous operation shall not be required of the calibration facility.
This non-requirement is specific to the PS-1 prototype.

3.3.10 The Telescope Enclosure

The telescope enclosure protects the telescope and giga-pixel camera from adverse weather, supports their operation, and provides a safe work environment while allowing the telescope a view of the sky when conditions are favorable. It includes handling equipment and pathways adequate to service large system components, e.g., the primary and secondary mirror assemblies, the giga-pixel camera, the filter mechanism, and the instrument shutter.

3.3.10.1 The enclosure shall be capable of tracking with the telescope without vignetting its field of view.

3.3.10.2 The enclosure shall be able to slew at the maximum required telescope rates without mechanical interference with the telescope.
This maximum rate is set by the specification listed in 3.1.13.

3.3.10.3 The enclosure shall be capable of protecting the telescope against wind gusts as high as 100 mph (45 m sec^{-1}).
This is a survival specification, not an operational specification.

3.3.10.4 The telescope shall be capable of operating in sustained winds of 20 mph (9 m sec^{-1}).
The Comprehensive Atmospheric Prediction System (CAPS) was designed and deployed on Haleakala by the U.S. Air Force AEOS facility in 1998. Since that time the CAPS seasonal wind charts (http://pan-starrs.ifa.hawaii.edu/project/people/waterson/HaleakalaClimate/KCE_Task1_wind_Temp_Rh.pdf) for Haleakala show that the summit wind speeds are less than 20 mph over 80% of the time. For observations only towards the west, the percentage of time below 20 mph is above 90%.

3.3.10.5 The enclosure shall be capable of protecting the telescope against 3 in hr^{-1} rainfall and against snow loads of 20 lb ft^{-2} (1 kPa).

3.3.10.6 The telescope enclosure shall require ≤ 45 kW of power.
This figure includes power used in the telescope support building which is expected to require 23 kW of power for the on site computers and support building lights and heating. Note that the document PSDC-300-018-01 discusses Pan-STARRS power requirements in the PS-1 enclosure.

3.3.10.7 The enclosure shutter shall have a watch-dog timer to close and automatically put the observatory in hibernation.
If not reset regularly by the enclosure control computer, the shutter shall contain hardware that will close it automatically. The shutter must be remotely operable so as to facilitate autonomous operation. The hibernation state is defined in Section 3.2.3

3.3.10.8 The enclosure shutter shall be able to close within 5 minutes.
This is a maximum time limit. The shutter must be able to close within this time under all circumstances.

3.3.10.9 The enclosure shutter vents, and telescope mirror covers shall have a fail-safe mechanism to protect against power failures.
The enclosure must have a way of sensing power failures and sufficient UPS power to close the telescope mirror covers, the enclosure shutter, and the enclosure vents.

3.3.10.10 The enclosure shutter shall have a clear opening ≥ 2.5 m.
Installation of the telescope may be performed with the aid of an exterior crane through the shutter opening. The shutter opening shall accommodate mirror handling for recoating and instrument handling with adequate clearances. The shutter clearance must accommodate following errors of the enclosure and misalignment.

3.3.10.11 The enclosure shutter shall have air dams.
"Air dams" are barriers near the enclosure shutter entrance which prevent air cooled from the skin of the enclosure from falling into the enclosure. The purpose of these dams are to mitigate image degradation (seeing) caused by the presence of thermal mass and radiators near the telescope's light path.

3.3.10.12 The enclosure shall have automatically controlled venting of outside air into the observing (telescope) level of the enclosure.
The enclosure venting will need to be controlled by OTIS.

3.3.10.13 The enclosure shall have thermal barriers between the observing and equipment levels of the enclosure that allow no more than 200 W of heat leakage into the observing level.
Heat leakage into the observing floor must be kept to a minimum to minimize the "dome" seeing.

3.3.10.14 The enclosure shall be able to keep the telescope to within 2° C of the expected night time temperatures during the day.
The difficulty of meeting this requirement depends on the amount of outside air infiltration that the enclosure permits, the maximum day-to-night temperature differentials expected at the site, and the amount of air-conditioning power available in the telescope enclosure. Allowing larger temperature differentials than this will significantly deteriorate the seeing during the start of a night. The average temperature on Haleakala is 7° C. From a five year average (1998-2003) of data, the highest monthly average temperature was 20° C and the lowest monthly average was -5° C.

3.3.10.15 The external surfaces of the telescope enclosure shall be white.
Note that if paint is used, titanium oxide paint will be acceptable owing to the requirement for the air dam on the shutter (3.3.10.11).

3.3.10.16 The enclosure shall have space for the calibration facility.
The design of the calibration facility will dictate the specifics of this requirement.

3.3.10.17 The enclosure walls shall be opaque.
The acquisition of calibration data will occur primarily during daylight hours. For this reason every practical effort must be made to limit the amount of light into the dome. Doors and vents must seal as well as possible and the skin of the observatory cannot be translucent. How well this is accomplished will have a significant impact on the design of the calibration facility.

3.3.10.18 The state of all enclosure doors or hatches which can be damaged by moving parts of the enclosure or telescope must be monitored by a safety interlock.

3.3.10.19 The enclosure shall have safety interlocks which prevent damage to the telescope and personnel if a failure in the dome mechanism should occur.
The telescope shall be protected against failures in the enclosure azimuth rotation mechanism. The inverse is also true, the same mechanism should protect the enclosure against failures in the telescope azimuth drive.

3.3.10.20 Close Operations Support
In close proximity to the telescope and giga-pixel camera, i.e., within the telescope chamber, the following items are required for their operation and maintenance. Note that the expected location of equipment inside the Pan-STARRS enclosure is given in the document PSDC-300-018-01.

3.3.10.20.1 Fixed track, lifting equipment and hatches or openings, etc., shall be provided for the servicing of the telescope optics subassemblies, giga-pixel camera, shutter, and filter changer.

A jib crane is to be provided on the enclosure service balcony that is capable of lifting approximately 800 kg. Access to the jib crane shall be sufficient to allow removal of the giga-pixel camera and its cart (approximately 400 kg) from the observing level to the ground.

3.3.10.20.2 A written procedure shall be provided for the removal and installation of the primary and secondary mirrors, the corrector lenses, the shutter mechanism, the filter mechanism, the rotator, and the camera.

3.3.10.20.3 Telescope Pier: The telescope pier shall provide a stiff support for the telescope and will be vibration isolated from the rest of the telescope enclosure.

3.3.10.20.4 Mounting for the camera power supply, an HP rack 7" high and 27" deep weighing approximately 250 lbs., shall be provided less than 15' from the camera.

3.3.10.20.5 A separate power phase shall be provided for the camera electronics.

3.3.10.20.6 A copper ground connection shall be provided for the camera electronics near the base of the pier.

This connection must be electrically tied to the rebar in the pier and thrust block for instrument and telescope grounding. This connection should exit the pier near the cable wrap. This connection should terminate in some type of lug nuts which allow easy connection of large copper ground straps.

3.3.10.20.7 Glycol/water chiller lines shall be provided for cooling the camera He compressor, the camera controller electronics, and the SkyProbe camera controllers.

The required cooling power, flow rates, and locations of these items are detailed in PSDC-300-018-01.

3.3.10.20.8 The water flow and temperature of the facility chiller lines shall be monitored.

3.3.10.20.9 Space and a way to install the following equipment shall be provided on or in very close proximity to the observing floor:

1. A 30 l/sec vacuum pump (camera dewar pumping station)

2. A CTI 9600 compressor (for the camera cooling)

3. A UPS for the camera controllers.

4. 6 Dry N_2 tanks (DOT-3AA2400 or 3AA2015, for backfilling the camera and purging the Cassegrain Core).

Note that the expected location of Pan-STARRS equipment inside the PS-1 enclosure is detailed in PSDC-300-018-01.

3.3.11 The Environment Monitors

In the Pan-STARRS SCD there are four levels of environmental monitoring. There is an external "Metrology Station", which is mostly responsible for monitoring conditions outside the dome. There are "enclosure environment sensors", which focus mostly on conditions inside the dome. There are "telescope environment sensors", which focus on conditions of the hardware inside the dome. And there are "instrument sensors", which report conditions inside the instrumentation. Temperatures and pressures inside the camera dewar are the simplest example of the last level of sensors. The metrology station will be discussed in the Pan-STARRS Observing Site Plan and the camera sensors are discussed in the camera SSS.

3.3.11.1 Enclosure environment monitors

3.3.11.1.1 Web cameras shall be provided throughout the enclosure to monitor all moving parts.

This is important as a redundant monitor of all moving parts inside the dome e.g. mirror covers, enclosure shutter, and telescope altitude axis *and should also include at least one monitor outside of dome as an inspection of the dome rotation itself.* This also helps to address safety issues.

3.3.11.1.2 The dust density of particulates with diameters between 0.5 and 10 μm shall be measured inside the dome to an accuracy of 10% or better in a 1 minute time interval at dust levels between 0.1 μg/m^3 and 100 μg/m^3.

This is required to assure the safety of the mirrors on the telescope. Note that 1 $\mu g/m^3$ is approximately equivalent to $2x10^4$ particles/ft^3 if the particles are 1 µm in diameter with a density of 2.5 gm/cm^3.

3.3.11.1.3 The air temperature in the enclosure shall be measured to a resolution of 0.5° C and over a range of -15°C to +30°C.

3.3.11.1.4 The dew point in the dome shall be measured to an accuracy of ± 1° C.

3.3.11.2 Telescope environment monitors

3.3.11.2.1 All mirror and truss temperature sensors shall have a temperature resolution <0.2° C and a range of -10° C to +25° C.

3.3.11.2.2 The primary mirror shall have sensors measuring radial temperature differences on the back side of the glass.

3.3.11.2.3 The primary mirror shall have sensors measuring axial temperature differences across the glass.

3.3.11.2.4 The secondary mirror shall have sensors measuring radial temperature differences on the back of the glass.

3.3.11.2.5 The secondary mirror shall have sensors measuring axial temperature differences across the glass.

3.3.11.2.6 The temperature of each of the secondary spider supports shall be monitored.

3.3.11.2.7 The temperature of each of the main truss supports shall be monitored.

3.4 System interface requirements.

Almost all of the external interfaces for the telescope and telescope enclosure are control interfaces with the observatory control software, OTIS. In particular, the software interfaces between the OTIS and the TCS and DCS are the most prominent external interfaces. Almost all of the internal interfaces are mechanical interfaces. The one exception to this would be the mechanical interface between the camera and the Cassegrain Core, which would be the only external mechanical interface. This division is the direct result of defining OTIS as its own subsystem and the TCS/DCS as vendor supplied software.

3.4.1 Interface identification and diagrams.

Figure 1 in section 1.2 shows the telescope control interfaces as red lines. The arrows on these lines show the flow of control signals. In the same manner, Figure 5 shows the enclosure control interfaces. Once again, the control lines with open arrows are defined elsewhere. In this case they are described in Figure 1.

Table 3 is a summary of the control interfaces shown in both of these figures and Table 4 is a summary of the mechanical interfaces.

The only mechanical external interface to the telescope subsystem is the mechanical interface to the camera. This is shown in Figure 1 by the blue line marked "CAMERA MI". This document does not explicitly label the mechanical interfaces to items like the enclosure air conditioning or the shutter drives because these interfaces will be wholly internal to the manufacture of the enclosure itself. There is an implicit understanding here that the form of these interfaces must not interfere with the performance of the telescope and the enclosure nor interfere with the functionality of the calibration facility.

Table 3. The Telescope and Enclosure Control Interfaces

Interface	Data/Commands		Data Flow
	Source	Destination	
Enclosure Interfaces			
AC	DCS	Building Air Conditioning	Bi-directional
LIGHTS	DCS	Building Lights	Uni-directional
CALIB	OTIS	Calibration Facility	Bi-directional
ENCL DR	DCS	Enclosure Drives	Bi-directional
ENCL SHUTTER	DCS	Enclosure Shutter Drives	Bi-directioal
VENTS	DCS	Enclosure Vents	Bi-directional
INTERLOCKS	Safety Interlocks	TCS	Uni-directional
ENCL MON	Environ. Monitors	OTIS	Uni-directional
Telescope Interfaces			
ALT	TCS	Altitude Drives	Bi-directional
AZ	TCS	Azimuth Drives	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	OTIS	Filter Mechanism	Bi-directional
CAM SHUTTER	DHC	Camera Shutter	Bi-directional
TEL TEMPS	Tel. Temp. Sensors	TCS	Uni-directional
TEL ENV	Tel. Env. Sensors	OTIS	Bi-directional
ADC	ADC	OTIS	Bi-directional

Table 4. Telescope and Enclosure Mechanical Interfaces

Interface	Mating Parts	
	A	B
Enclosure Interfaces		
FORK BASE MI	Telescope Fork	Telescope Pier
Telescope Interfaces		
M1 SUPPORT	Primary Mirror	M1 Mirror Cell
M1MC MI	M1 Mirror Cell	Telescope Fork
AZ MI	Azimuth Drive System	Telescope 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
B2 MI	Baffle 2	Truss
B1 MI	Baffle 1	Upper Cassegrain Core
UCC MI	Upper Cassegrain Core	M1 Mirror Cell
L1 MI	L1 Corrector Lens	Upper Cassegrain Core
L2 MI	L2 Corrector Lens	Upper Cassegrain Core
LCC MI	Lower Cassegrain Core	Instrument Rotator
FILTER MECH MI	Filter Mechanism	Lower Cassegrain Core
SHUTTER MI	Shutter Mechanism	Filter Mechanism
ROT MI	Instrument Rotator	M1 Mirror Cell
CAMERA MI	Camera	Lower Cassegrain Core
FORK MI	Pier	Fork Base

There are several requirements in the sections above which will directly impact the design of the enclosure and its mechanical interfaces. The requirements in Section 3.3.10.20 Close Operations Support deal with the mirror handling and with the general requirement for the enclosure doors and lifting fixtures to support the removal of the camera, filter mechanism, shutter, and the various pieces of the telescope optics. Requirement 3.3.10.20.6 calls for the installation of proper grounding which will affect the construction of the pier itself. Requirement 3.3.10.10 refers to the need for the shutter enclosure itself to be wide enough to support the installation of the telescope.

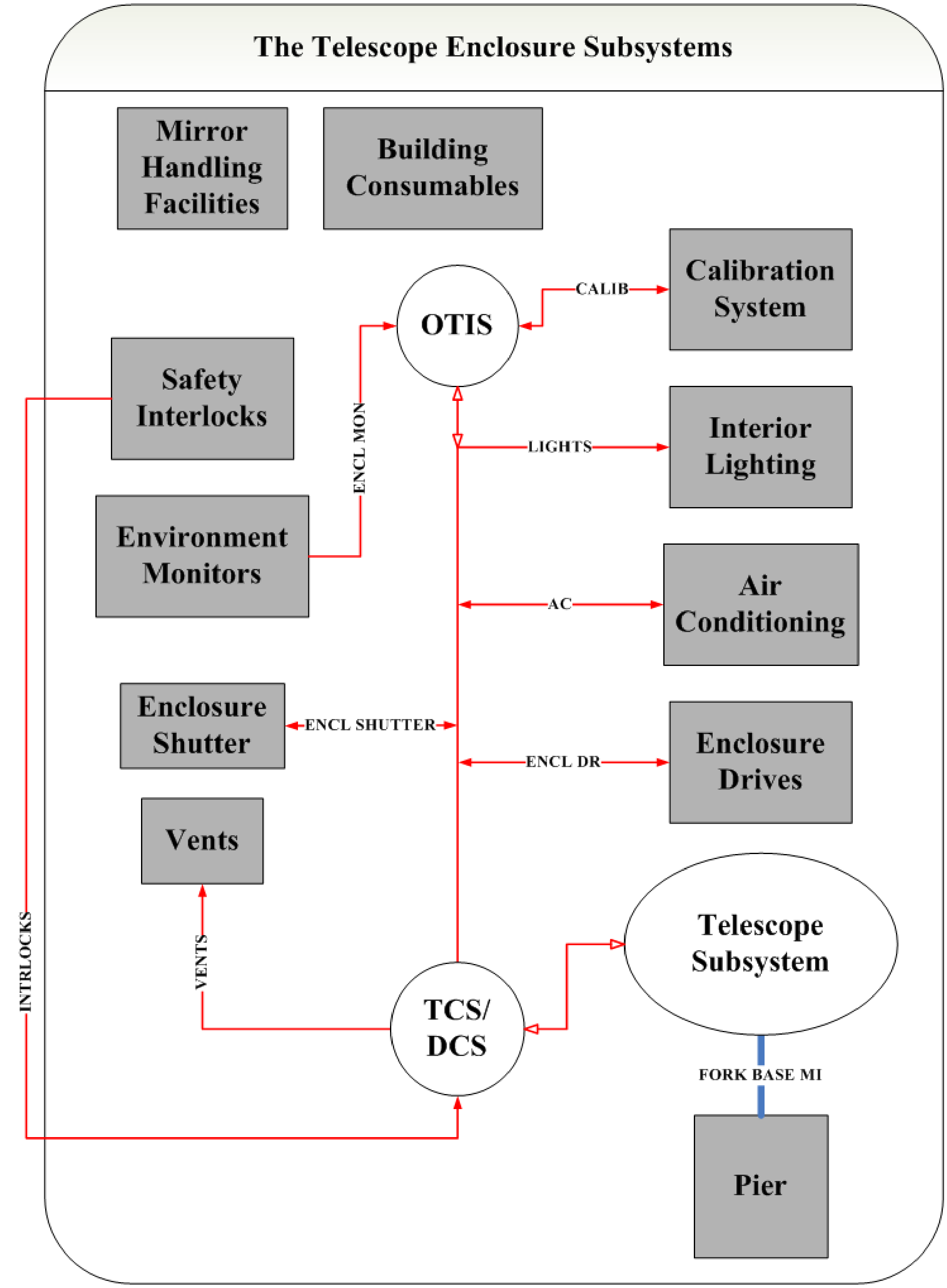

Figure 5. The Enclosure Control Interfaces

3.4.2 External interface requirements

3.4.2.1 The enclosure air conditioning shall be remotely controllable.

In particular, OTIS must be able to both read and set the set-point of the building air conditioning. If the air-conditioning has an internal temperature monitor, OTIS must be able to read this monitor.

3.4.2.2 The enclosure lights shall be remotely controllable.

All lights on the observing level of the enclosure must be capable of being commanded by OTIS. The remote commands should take precedent over all manual switches.

3.4.2.3 The calibration facility shall be remotely controllable.

This does not include the set up of the calibration facility each time it is used, which may require on-site attendance.

3.4.2.4 The enclosure drives shall be remotely controllable.

It is acceptable for the enclosure to be slaved off of the telescope itself. In other words, a "co-rotating" dome is acceptable. We do not require the telescope to move independently from the dome in its azimuth motions.

3.4.2.5 The enclosure shutter shall be remotely controllable.

3.4.2.6 The enclosure vents shall be remotely controllable.

3.4.2.7 All interlock systems shall have the ability to interrupt the observatory control software and communicate their state to it when queried.

Note that it is not desirable for the observatory software to be able to control any safety interlocks.

3.4.2.8 The environmental monitors in the enclosure shall communicate their readings when queried by the observatory control software.

3.4.2.9 The altitude and azimuth axes shall be remotely controllable with position, limit switch, and motor current feedback.

3.4.2.10 All actuators in the primary and secondary mirror cells shall be remotely controllable with position and limit switch feedback.

3.4.2.11 The primary mirror covers shall be remotely controllable with limit switch feedback.

3.4.2.12 The instrument rotator shall be remotely controllable with position and limit switch feedback.

3.4.2.13 All actuators in the filter mechanism shall be remotely controllable with position, limit switch, temperature, and humidity feedback.

Note that the filter mechanism must both position the filters as well as maintain their environment. This requires temperature and humidity sensors inside the filter mechanism which can be queried by the observatory software. The limit switches on the filter mechanism will also include any switches which are needed to monitor the status of doors or access panels to the interior of the mechanism.

3.4.2.14 The camera shutter shall be remotely controllable with position and limit switch feedback.

3.4.3 System internal interface requirements

Figure 1 in section 1.2 and Figure 5 in section 3.4.1 show internal (mechanical) interfaces as blue lines. Table 4 is a summary of these interfaces which should serve to identify these interfaces for the purpose of communications between the project and vendors. For many of these interfaces there are no special requirements beyond the obvious need to have consistency between mating parts. The exceptions to this are given below.

The Pan-STARRS project plans to provide the Lower and Upper Cassegrain Core structures. A telescope vendor is likely to provide the M1 mirror cell and instrument rotator to which these two structures mount. Therefore, the UCC MI and the LCC MI are two important mechanical interfaces that must be carefully defined by joint communication between the telescope vendor and the Pan-STARRS telescope office.

3.4.3.1 The L1 and L2 mechanical interfaces shall minimize thermal stresses on the corrector optics over the temperature range -10 to +30° C.

3.4.3.2 The L1 and L2 mechanical interfaces shall minimize support stress on the corrector optics between 10 and 70° zenith angles.

These stresses need to be consistent with the image budget given for the L1 and L2 corrector optics in section 3.3.1.

3.4.3.3 The L1 and L2 mechanical interfaces shall maintain the spacing and decentering requirements on the optics given in section 3.3.1.

3.4.3.4 The rotator shall maintain the position of the camera focal plane to < ±5 µm during a single exposure.

For any optical system the Rayleigh criterion gives a position accuracy for the system focal plane of $\Delta z = \pm 2 \lambda F^2$, where F is the system's F-number and λ is a characteristic wavelength of use. For $\lambda = 0.5$ µm and $F = 4.44$ we have $\Delta z \leq \pm 19.7$ µm. But this error is shared with the camera optics. In a single 30 second exposure, motions perpendicular to the telescope's optical axis must be kept well below the telescope PSF. At the zenith this is expected to be approximately 0.72", which is equivalent to a FWHM diameter of 27.9 µm. Note that this is not a specification on the total rotator run-out, but rather on the expected run-out during the course of a single 30 second exposure.

3.5 Personnel safety requirements

Safety to workers around the telescope must be provided. It is assumed here that normal practices of building safety codes (on stairways, ceiling heights, doorway clearances, and railings) will apply to the telescope enclosure. These will not be detailed here. Safety to the telescope itself must also be considered, but these issues have been covered in the sections above. Examples of instrument safety requirements are 3.3.8.13 (brakes on telescope axes), 3.3.10.9 (shutter and mirror covers in power failures), 3.3.10.18 (enclosure door and hatches), and 3.3.10.19 (azimuth drive safety).

3.5.1 Locking pins shall be provided for the altitude axis and the instrument rotator mechanisms.

Locking pins prevent motion of the altitude telescope axis and the instrument rotator during maintenance or service activities and protect personnel and equipment. A means of preventing axis motion shall be provided in the case of any unbalanced condition. The restraint system capacities shall exceed the largest unbalanced condition encountered during maintenance. They shall be labeled with their capacity.

3.5.2 Manual over-rides of telescope axes brakes shall be monitored by a safety interlock system.

The telescope brakes are to prevent unwanted motion of the telescope in case of power failures. The manual over-ride to these brakes must be present to allow manual motion of the telescope in emergencies. The telescope interlock needs to protect against unintended use of these manual over-rides.

3.5.3 All pinch points in the enclosure shall be labeled with lockout warnings.

3.5.4 Emergency stop switches shall be present on the observing level and on any floors with co-rotating parts to prevent telescope or enclosure motion.

These emergency stops should over-ride remote commands to the telescope and the enclosure mechanisms they are designed to stop.

3.6 Security and privacy requirements

Public access to the telescope enclosure must be restricted. Doors, locks, and stairways must be built with this in mind.

3.7 Design and construction constraints

The design and construction constraints on the telescope and enclosure are related to the fact that the PS-1 telescope is being constructed within the confines of a National Park and in a State Conservation District.

3.7.1 Protection of Native Plants and Insects

Haleakalā National Park has experienced the introduction of destructive non-native species that compete with and have in some cases displaced native plants and insects. These introductions threaten the ecological balance at the site, and in cooperation with Haleakala National Park, IfA requires any contractor to take the following measures at Haleakalā Observatories to prevent construction or repair activities from introducing new species:

3.7.1.1 Any equipment, supplies, and containers with construction materials that originate from elsewhere, i.e., the other islands or the mainland, must be checked for infestation by unwanted species by a qualified biologist or agricultural inspector prior to being transported from Kahului.

Specimens of non-native species found in these inspections are to be offered to the state for curation, and those not wanted are to be destroyed. All construction vehicles must be steam cleaned before they are transported through the National Park. The contractor shall provide certification attesting to compliance with this paragraph for inspection and steam cleaning. Contractors shall also notify IfA a week prior to their initial entry into Haleakalā National Park, so that arrangements can be made with the Park Service or other provider of inspection services. After the initial entry, coordination shall be directly between the inspectors and the contractor.

3.7.1.2 Importation of fill material to the site is prohibited, unless such fill (e.g., sand) is sterilized to remove seeds, larvae, insects, and other biota that could survive at the site and propagate.

3.7.1.3 All material obtained from excavation is to remain on Haleakalā.

3.7.1.4 Surplus excavated cinders, soil, etc., is to be offered to other agencies located at the summit or the National Parks Service.

3.7.1.5 Contractors are required to participate in IfA pre-construction briefings to inform workers of the damage that can be done by unwanted introductions.

3.7.1.6 Satisfactory fulfillment of this requirement would be evidenced by a signed declaration from each worker who drives a construction vehicle into the site.

3.7.1.7 Parking of heavy equipment and storage of construction materials outside the immediate confines of Haleakalā Observatories property is prohibited.

3.7.1.8 Contractors are required to remove construction trash frequently, particularly materials that could serve as a food source that would increase the population of mice and rats that prey on native species.

3.7.2 Protection of `Ua`u (Dark-rumped Petrel)

The endangered `Ua`u, or Dark-rumped Petrel, occupies burrows on the upper slopes of Haleakalā from February to October. The burrows are located in cinder and are active year after year, since the birds return to the site of their birth. Petrels are night flying birds, leaving their burrows to search for food during nesting and fledgling seasons. The nearest burrows are located on the south slopes below Mees Solar Observatory and on the north slopes below the Maui Space Surveillance Complex. The following seven requirements are in place to ensure that the `Ua`u habitat will be protected during any construction activities.

3.7.2.1 During the months when birds are present on Haleakala, care must be exercised to ensure that the birds will not be disturbed.
3.7.2.2 Therefore, vibration and noise from heavy construction equipment or activities must not impact the normal life cycle of resident birds. If heavy construction equipment will be necessary at the site, consultation with IfA and avifaunal experts will be required to determine feasibility.

3.7.2.3 Haleakalā Observatories personnel will notify HNP of any `Ua`u mortalities. Contractor personnel will report mortalities to IfA immediately.

3.7.2.4 Contractors will be given current maps of locations of `Ua`u burrows to assist with `Ua`u conservation.
HNP biologists are continuously finding and mapping new `Ua`u burrows, and these maps will made available to the Haleakalā Observatories for planning purposes.

3.7.2.5 Construction of fences will be avoided, if possible, to avoid `Ua`u mortality from collisions.

3.7.2.6 To avoid attracting `Ua`u, contractors will make every effort not to use broadband lighting.
Colored lighting such as red, blue, or orange should be considered.

3.7.2.7 Lighting for construction hazards or night work must be approved by IfA prior to installation.
All lighting must be shielded from above, so that night flying birds will not be disoriented by upward projecting lights that are mistaken for natural sources of navigable lighting.

3.7.2.8 Workers at the site must be informed of vibration, noise, and lighting hazards to endangered species, and must be informed that their activities are to be confined to the construction site to minimize risk to birds in adjacent areas.

3.7.3 Pollution Control

Haleakalā Observatories is located in a cinder cone in a State Conservation District. Construction at the site requires special care to maintain the unpolluted environment.

3.7.3.1 No hazardous waste is to be released at the site.
3.7.3.2 Surplus or used paint, oil, solvents, cleaning chemical, etc., must be removed from the area and disposed of by an EPA- approved Transport Storage Disposal Facility.

3.7.3.3 Accidental spills of any hazardous material during the execution of a contractor's project at the site must be reported immediately to the on-site IfA supervisor.
Spill containment will be supervised by UH personnel at the site.

3.7.3.4 Spill remediation methods must be approved by the University of Hawaii's Environmental Health and Safety Office (EHSO) prior to clean up, and all costs incurred for clean-up will be assigned to the contractor.
In the event of a reportable release, the construction contractor will be liable for any federal or state imposed non-compliance penalties.

3.7.3.5 Washing and curing water used for aggregate processing, concrete curing, clean up, etc., cannot be released into the soil at the site.
A recovery process is required by the contractor to capture wastewaters.

3.7.4 Dust Control

It is of particular importance to maintain a dust free environment at Haleakalā Observatories. Telescope mirrors, lenses, and sensors can be quickly damaged by wind born dust. Haleakalā Observatories is located at 10,000 feet, and is often exposed to winds in excess of 30 mph. Before, during, and after winter storms, winds can exceed 50 mph. The natural substrate at the site is a mixture of fine volcanic sand and cinders. Fugitive dust from the finer material can be released when the substrate is disturbed.

3.7.4.1 Contractors will adhere strictly to the requirement that dust be controlled at all times, including non-working hours, weekends, and holidays.
Sprinkling or similar methods will be required to keep disturbed finer material from becoming airborne.

3.7.4.2 Dust control must be accomplished by equipment that the Contractor keeps on site and sprinkling or similar activities must result in less than 10 pounds of fugitive dust released into the atmosphere per 24-hour period, as measured by standard collection methods.

3.7.4.3 No oil or chemical treating shall ever be used at the site for dust control.

3.7.4.4 Dust resulting from surface preparation of surfaces to be painted by sanding, power tools, or scraping and brushing shall be controlled by the Contractor by use of catchments and filtering systems/devices to prevent damage to the telescope mirrors, lenses and sensors.

3.7.5 Waste management

Construction or refurbishing of existing facilities will result in quantities of solid waste, and remnants of food and packaging that construction crews may bring for consumption at the site.

3.7.5.1 Only materials that are not EPA "Listed" or "Characteristic" wastes can be managed as solid waste at the site.

3.7.5.2 Solid waste cannot be stockpiled or dumped at the site or on the slope below the Haleakalā Observatories facilities.

3.7.5.3 Solid waste and debris must be secured such that strong winds cannot disperse materials.

This is particularly important during weekends, holidays, and other non-working hours.

3.7.5.4 No food is to be left on the ground or in Haleakalā Observatories solid waste storage areas to prevent attraction of rats and other pests.

3.7.6 Protection of Historic and Cultural Resources

For the kanaka maoli, the lava, cinders, dust, rocks and boulders are all sacred to Pele, the goddess of the volcano. In fact, Pele means lava in Hawaiian. Workers at Haleakalā Observatories need to be culturally sensitive to the fact that they are in a place still considered sacred by Native Hawaiians. As the responsible agency, UH IfA is committed to preserving the cultural resources at the site and has sought advice from the native Hawaiian community on Maui concerning the best methods to use to achieve that objective. One outcome of those consultations and the cultural resource evaluations of Haleakalā Observatories is that the IfA has adopted rules for the long-term preservation of archaeological and cultural resources for all facilities, past, present, and future.

3.7.6.1 Any construction within Haleakalā Observatories requiring a permit from the Department of Land and Natural Resources shall require the consultation and monitoring of a Cultural Specialist.

The Cultural Specialist will be engaged at the earliest stages of the planning process, monitor the construction process, and consult with and advise the on-site Project Manager with regard to any cultural or spiritual correction. For the purposes of this section, a Cultural Specialist must be a kanaka maoli, preferably a kupuna (elder), and a kahu (clergyman) as well, and one who has personal knowledge of the spiritual and cultural significance and protocol of Haleakalā.

3.8 Packaging requirements

3.8.1 The mirror shipping crates must be compatible in envelope, weight, and shock resistance with shipment over U.S. roads.

3.8.2 All crates for shipment of the optics must include sufficient weather resistance to withstand rain and snow for several days without exposing the optics to moisture.

3.8.3 All crates for shipment of the filters must be humidity controlled.

3.8.4 Parts for the enclosure must be compatible in envelope and weight with shipment over U.S. roads.

4 Qualification Provisions

Note that in the following table the term "Test" generally refers to on-site testing unless otherwise noted.

Table 5. Qualification Matrix

Paragraph Number	Requirement	Verification Method
Top Level Requirements		
3.1.1	The telescope aperture shall be 1.8 m in diameter	Inspection
3.1.2	The telescope operational altitude range shall be 10° to 70° zenith angle.	Test
3.1.3	The half-angle of the telescope field of view shall be 1.5°	Test
3.1.4	The telescope focal length shall be 8.0m	Test
3.1.5	The PS-1 complement of filters shall be the *g,r,i,z,y and w* filters.	Inspection
3.1.6	The telescope shall deliver a PSF ≤ 0.41″ FWHM at a zenith angle of 70° for the full complement of filters	Test
3.1.7	The telescope shall deliver a PSF ≤ 0.32″ FWHM at a zenith angle of 0° for the full complement of filters.	Test
3.1.8	The PS-1 telescope shall utilize an altitude-over-azimuth mount.	Inspection
3.1.9	The sum of systematic contributions to the photometric error in PS-1 data is to be less than 0.025 magnitudes.	Analysis
3.1.10	The PS-1 stray light management shall include a fully baffled focal plane, contamination control and other measures to mitigate the impact of stray light.	Analysis
3.1.11	The PS-1 state shall be reported and logged.	Inspection
3.1.12	PS-1 telescope shall support maintenance and service.	Inspection
3.1.13	The altitude and azimuth axes of the PS-1 telescope shall have maximum velocities ≥ 1.0°/second and ≥ 2.0°/sec, respectively.	Test
3.1.14	The PS-1 telescope axes shall be capable of slewing 3.0° and settling to the nominal open loop tracking errors in a 5 second time interval.	Test
3.1.15	For intermediate step angles (from 0.002 to 0.01 degrees) the PS-1 telescope shall be capable of slewing and settling to the nominal open loop tracking errors in a 2 second time interval.	Test
3.1.16	For small step angles (from 0.00003 to 0.002 degrees) the PS-1 telescope shall be capable of slewing and settling to the nominal open loop tracking errors in a 1 second time interval.	Test

Paragraph Number	Requirement	Verification Method
3.1.17	The time between the initiation and completion of a filter change shall be less than 45 sec.	Test
3.1.18	The telescope mirror cell design shall be compatible with the PS-1 primary mirror blank.	Inspection
3.1.19	The telescope secondary support structure shall be compatible with the PS-1 secondary mirror blank.	Inspection
Required States and Modes		
3.2.1	Observing	Inspection
3.2.2	Calibrating	Inspection
3.2.3	Hibernating	Inspection
3.2.4	Protected	Inspection
3.2.5	Servicing	Inspection
3.2.6	Off	Inspection
3.2.7	Failure	Inspection
Image Quality		
3.3.1.1	Telescope aberrations shall contribute ≤ 6.6 μm RMS to the telescope PSF when the g, r, i, z, y, and w filters are in use.	Analysis
3.3.1.2	The primary mirror and its support shall contribute ≤ 3.1 μm RMS to the telescope PSF near zenith and ≤ 4.4 μm at a zenith angle of 70°.	Test
3.3.1.3	The secondary mirror and its support shall contribute ≤ 1.4 μm RMS to the telescope PSF near zenith and ≤ 1.7 μm at a zenith angle of 70°.	Test
3.3.1.4	The L1 corrector and its support shall contribute ≤ 2.3 μm RMS to the telescope PSF near zenith and ≤ 3.3 μm at a zenith angle of 70°.	Test
3.3.1.5	The L2 corrector and its support shall contribute ≤ 2.2 μm RMS to the telescope PSF near zenith and ≤ 3.0 μm at a zenith angle of 70°.	Test
3.3.1.6	The L3 corrector and its support shall contribute ≤ 1.4 μm RMS to the telescope PSF near zenith and ≤ 1.8 μm at a zenith angle of 70°.	Test
3.3.1.7	The filters and their support shall contribute ≤ 0.5 μm RMS to the telescope PSF near zenith and ≤ 0.7 μm at a zenith angle of 70°.	Test
3.3.1.8	The collimation of the telescope optics shall not degrade the telescope PSF by more than 2.1 μm RMS near zenith and ≤ 4.4 μm at a zenith angle of 70°.	Test
3.3.1.9	Focus errors of the telescope shall degrade the PSF ≤ 2.0 μm RMS near zenith and ≤ 4.0 μm at a zenith angle of 70°.	Test
3.3.1.10	The optical design for Pan-STARRS shall have a focal surface with a sag of less than 200 μm across the full 1.5°	Test

Paragraph Number	Requirement	Verification Method
	field of view.	
3.3.1.11	The focal surface field distortion shall be ≤ 3% from the mean plate scale.	Test
3.3.1.12	The quality of refractive surfaces (e.g., scratch and dig) shall be 80/50.	Test
3.3.1.13	The entrance pupil of the telescope shall be defined by the outside diameter of the primary mirror and the tip of the secondary baffle.	Test
3.3.1.14	The primary and secondary mirrors will be made out of low expansion glass.	Test
3.3.1.15	The telescope shall have mirror covers that shield both the primary mirror and the Cassegrain corrector optics from dust and minor precipitation.	Inspection
3.3.1.16	The telescope mirror covers shall be remotely operable and capable of closing from a completely open position within 30 seconds.	Test
3.3.1.17	The telescope mirror covers shall have both fully closed and fully open limit switch feedback.	Test
Collimation		
3.3.2.1	The secondary shall be actuated in 5 axes: x-tilt, y-tilt, piston, x-translation, and y-translation.	Inspection
3.3.2.2	The secondary actuators shall have a resolution ≤2 μm and a range of motion ≥5 mm.	Test
3.3.2.3	The primary mirror shall be adjustable in 4 axes: x-tilt, y-tilt, x-translation, and y-translation.	Inspection
3.3.2.4	The tilt and x-translation of the primary mirror shall be either manual or automated.	Inspection
3.3.2.5	The y-translation of the primary mirror shall be automatically adjustable.	Inspection
3.3.2.6	The primary mirror tilt actuators shall have a resolution ≤10 μm and allow a range of piston motion ≥ 5 mm.	Test
3.3.2.7	The primary mirror x- and y-translation shall have a resolution ≤25 μm and allow a range of motion ≥1 mm.	Test
3.3.2.8	The primary mirror shall reposition to within 100 μm after having been removed and replaced in the telescope.	Analysis
3.3.2.9	The position and tilt of the optical axis of the primary mirror shall be known with respect to a well-defined mechanical fiducial on the mirror.	Test
3.3.2.10	The position of the optical axis of the secondary mirror shall be marked by a dimple on the face of the mirror.	Inspection
3.3.2.11	The primary mirror support shall utilize a pneumatic support system.	Inspection

Paragraph Number	Requirement	Verification Method
3.3.2.12	The air pressure for the primary mirror pneumatic support system shall be monitored.	Inspection
3.3.2.13	The primary mirror support shall incorporate a 12 point astigmatism correction system that attaches to either the primary mirror or the secondary mirror.	Inspection
3.3.2.14	The astigmatism correction system shall be controllable by the OTIS software.	Test
3.3.2.15	The astigmatism correction system shall be capable of correcting for 0.5 waves of either astigmatism or trefoil errors in the telescope wave front.	Analysis
3.3.2.16	The primary and secondary support systems shall have support errors that are compatible with the astigmatism correction system.	Analysis
Telescope Throughput		
3.3.3.1	Antireflective coatings shall be applied to all refractive surfaces and shall have reflectance ≤2% over the wavelength range from 400nm to 1100 nm	Test
3.3.3.2	The reflectivity of the mirror coatings shall be ≥80% and the mirror coatings shall be made of either bare aluminum or protected silver.	Test
3.3.3.3	The telescope obscuration shall be ≤37%.	Analysis
The Filters		
3.3.4	The filter specifications are given in PSDC-300-006-00	
The Filter Mechanism		
3.3.5.1	The filter mechanism shall function during telescope slews and at all rotation angles and altitudes of the telescope.	Test
3.3.5.2	The filter mechanism shall hold a total of 6 filters at one time.	Inspection
3.3.5.3	The filter position repeatability shall be 500 µm 2D RMS	Inspection
3.3.5.4	The filter mechanism shall fit within the following envelope: 73 x 29.5 x 7.50 in (1855 x 750 x 190 mm)	Test
3.3.5.5	The filter mechanism (including filters) shall weigh < 350 lbs (160 kg).	
3.3.5.6	The filter mechanism shall place ≤ 60 ft-lbs torque on the instrument rotator at all times.	Test
3.3.5.7	The filter mechanism shall have a MTBF of ≥ 19200 cycles.	Analysis
3.3.5.8	The clear aperture in the filter mechanism shall be 480 mm.	Inspection
3.3.5.9	Filters shall be protected from contamination.	Inspection
3.3.5.10	Humidity shall be monitored and controlled within the filter mechanism.	Test
3.3.5.11	Filters shall be removable for inspection and cleaning.	Inspection

Paragraph Number	Requirement	Verification Method
3.3.5.12	Surfaces in the filter housing and mechanisms shall be designed and treated to minimize stray light.	Inspection
3.3.5.13	The filter mechanism shall provide state feedback	Test
3.3.5.14	The filter mechanism assembly shall be modular with quick disconnect cables.	Inspection
The Camera Shutter		
3.3.6.1	The shutter shall make available a continuous range of exposure durations from 100 ms to 300 s.	Test
3.3.6.2	The accuracy of any exposure duration shall be better than 0.5% of the exposure duration.	Test
3.3.6.3	In a single exposure, all points in the focal plane shall experience the same exposure duration to better than 0.5%.	Test
3.3.6.4	The shutter shall be ready to begin a subsequent exposure no more than 1.0 second after the completion of a previous exposure.	Test
3.3.6.5	The clear aperture of the shutter shall be 480 mm.	Inspection
3.3.6.6	The blade position of the shutter mechanism shall be known as a function of time to a 10 msec accuracy.	Test
3.3.6.7	The shutter mechanism shall have a MTBF ≥ 480,000 cycles.	Analysis
3.3.6.8	The shutter assembly shall fit within the following envelope: 73 x 29.5 x 2 in (1855 x 750 x 51 mm)	Inspection
3.3.6.9	The shutter mechanism shall weigh ≤ 70 lbs. (32 kg).	Test
3.3.6.10	The shutter mechanism shall place ≤ 5 ft-lbs torque on the instrument rotator at all times.	Test
3.3.6.11	The shutter assembly will dissipate ≤ 0.4 W of heat into the optical beam	Test
3.3.6.12	The shutter assembly when mounted in the Cassegrain core shall have a volumetric leak rate of ≤ 2.6 cm^3/sec.	Test
3.3.6.13	The shutter assembly shall be modular with quick disconnect cables.	Inspection
The Camera		
3.3.7.1	The camera shall fit within the following envelope: 66 x 46 x 21 in (1676 x 1168 x 533 mm).	Test
3.3.7.2	The camera weight shall be ≤ 520 lbs (236 kg).	Test
3.3.7.3	The camera shall place ≤ 5 ft-lbs of out-of-balance torque on the instrument rotator at all times.	Test
3.3.7.4	The camera mounting shall allow a 90° rotation of the camera with respect to the telescope optical axis.	Inspection
Pointing and Tracking		
3.3.8.1	All mirror components shall be protected from seismic force damage with accelerations < 0.3g.	Analysis

Paragraph Number	Requirement	Verification Method
3.3.8.2	The telescope pointing accuracy shall be <10 arcseconds 2-D RMS	Test
3.3.8.3	The telescope altitude and azimuth encoders shall have 0.01″ resolution	Test
3.3.8.4	Open-loop tracking error shall be ≤ 100 mas 2-D RMS for 1 minute of time.	Test
3.3.8.5	The wind-induced tracking error shall be 70 mas 2-D RMS or less	Test
3.3.8.6	The telescope shall be able to track between zenith angles of 10 and 70 degrees for periods >5 minutes without interruption.	Test
3.3.8.7	The mechanical limits on the altitude axis shall be beyond a zenith distance of 75 degrees.	Test
3.3.8.8	The azimuth tracking limits shall be ± 220 degrees with an azimuth cable wrap null point at 100 degrees measured from north toward east.	Test
3.3.8.9	The instrument rotator limits shall be > ± 60 degrees.	Test
3.3.8.10	The instrument rotator shall support an out-of-balance torque load ≥ 70 ft-lbs (95 N-m).	Test
3.3.8.11	The instrument rotator shall support a load of 1433 lbs (650 kg) with a center of mass 15" (0.381 m) from its mounting plate.	Analysis
3.3.8.12	The telescope mirror cell shall support a load of 606 lbs (275 kg) with a center of mass 5.9" (150 mm) from the top of the mirror cell.	Analysis
3.3.8.13	The telescope axes shall have brakes to prevent unwanted motions of the telescope and enclosure.	Inspection
3.3.8.14	The telescope guiding bandwidth shall be ≥1 Hz.	Test
The Instrument Calibration Facility		
3.3.9.1	Spatial uniformity over the entrance pupil shall be ±10% or better on scales larger than 10 cm (TBR).	Test
3.3.9.2	Angular uniformity shall be ±10% or better over the 3° field of view (TBR).	Test
3.3.9.3	Spectral uniformity shall be ±10% or better over each of g, r, i, z, y filter band-passes (TBR).	Test
3.3.9.4	Radiance shall be adequate to 50% saturate pixels in 30 seconds (TBR).	Test
3.3.9.5	Autonomous operation shall not be required of the calibration facility.	-
The Telescope Enclosure		
3.3.10.1	The enclosure shall be capable of tracking with the telescope without vignetting its field of view.	Test

Paragraph Number	Requirement	Verification Method
3.3.10.2	The enclosure shall be able to slew at the maximum required telescope rates without mechanical interference with the telescope.	Test
3.3.10.3	The enclosure shall be capable of protecting the telescope against wind gusts as high as 100 mph (45 m sec^{-1}).	Analysis
3.3.10.4	The telescope shall be capable of operating in sustained winds of 20 mph (9 m sec^{-1}).	Test
3.3.10.5	The enclosure shall be capable of protecting the telescope against 3 in hr^{-1} rainfall and against snow loads of 20 lb ft^{-2} (1 kPa)	Analysis
3.3.10.6	The telescope enclosure shall require ≤ 45 kW of power.	Analysis
3.3.10.7	The enclosure shutter shall have a watch-dog timer to close and automatically put the observatory in hibernation.	Test
3.3.10.8	The enclosure shutter shall be able to close within 5 minutes.	Test
3.3.10.9	The enclosure shutter vents, and telescope mirror covers shall have a fail-safe mechanism to protect against power failures.	Test
3.3.10.10	The enclosure shutter shall have a clear opening ≥ 2.5 m.	Inspection
3.3.10.11	The enclosure shutter shall have air dams.	Inspection
3.3.10.12	The enclosure shall have automatically controlled venting of outside air into the observing (telescope) level of the enclosure.	Test
3.3.10.13	The enclosure shall have thermal barriers between the observing and equipment levels of the enclosure that allow no more than 200 W of heat leakage into the observing level.	Analysis
3.3.10.14	The enclosure shall be able to keep the telescope to within 2° C of the expected night time temperatures during the day.	Test
3.3.10.15	The external surfaces of the telescope enclosure shall be white.	Inspection
3.3.10.16	The enclosure shall have space for the calibration facility.	Inspection
3.3.10.17	The enclosure walls shall be opaque.	Inspection
3.3.10.18	The state of all enclosure doors or hatches which can be damaged by moving parts of the enclosure or telescope must be monitored by a safety interlock.	Inspection
3.3.10.19	The enclosure shall have safety interlocks which prevent damage to the telescope and personnel if a failure in the dome mechanism should occur.	Inspection
3.3.10.20.1	Fixed track, lifting equipment and hatches or openings, etc., shall be provided for the servicing of the telescope optics subassemblies, giga-pixel camera, shutter, and filter	Inspection

Paragraph Number	Requirement	Verification Method
	changer.	
3.3.10.20.2	A written procedure shall be provided for the removal and installation of the primary and secondary mirrors, the corrector lenses, the shutter mechanism, the filter mechanism, the rotator, and the camera.	Inspection
3.3.10.20.3	Telescope Pier: The telescope pier shall provide a stiff support for the telescope and will be vibration isolated from the rest of the telescope enclosure.	Analysis
3.3.10.20.4	Mounting for the camera power supply, an HP rack 7" high and 27" deep weighing approximately 250 lbs., shall be provided less than 15' from the camera.	Inspection
3.3.10.20.5	A separate power phase shall be provided for the camera electronics.	Inspection
3.3.10.20.6	A copper ground connection shall be provided for the camera electronics near the base of the pier.	Inspection
3.3.10.20.7	Glycol/water chiller lines shall be provided for cooling the camera He compressor, the camera controller electronics, and the SkyProbe camera controllers.	Inspection
3.3.10.20.8	The water flow and temperature of the facility chiller lines shall be monitored.	Inspection
3.3.10.20.9	Space and a way to install the following equipment shall be provided on or in very close proximity to the observing floor:	Inspection
The Environment Monitors		
3.3.11.1.1	Web cameras shall be provided throughout the enclosure to monitor all moving parts.	Inspection
3.3.11.1.2	The dust density of particulates with diameters between 0.5 and 10 μm shall be measured inside the dome to an accuracy of 10% or better in a 1 minute time interval at dust levels between 0.1 μg/m^3 and 100 μg/m^3.	Inspection
3.3.11.1.3	The air temperature in the enclosure shall be measured to a resolution of 0.5° C and over a range of -15°C to +30°C.	Test
3.3.11.1.4	The dew point in the dome shall be measured to an accuracy of ± 1° C.	Test
3.3.11.2.1	All mirror and truss temperature sensors shall have a temperature resolution <0.2° C and a range of -10° C to +25° C.	Analysis
3.3.11.2.2	The primary mirror shall have sensors measuring radial temperature differences on the back side of the glass.	Inspection
3.3.11.2.3	The primary mirror shall have sensors measuring axial temperature differences across the glass.	Inspection
3.3.11.2.4	The secondary mirror shall have sensors measuring radial	Inspection

Paragraph Number	Requirement	Verification Method
	temperature differences on the back of the glass.	
3.3.11.2.5	The secondary mirror shall have sensors measuring axial temperature differences across the glass.	Inspection
3.3.11.2.6	The temperature of each of the secondary spider supports shall be monitored.	Inspection
3.3.11.2.7	The temperature of each of the main truss supports shall be monitored	Inspection
External interface requirements		
3.4.2.1	The enclosure air conditioning shall be remotely controllable.	Test
3.4.2.2	The enclosure lights shall be remotely controllable.	Test
3.4.2.3	The calibration facility shall be remotely controllable.	Test
3.4.2.4	The enclosure drives shall be remotely controllable.	Test
3.4.2.5	The enclosure shutter shall be remotely controllable.	Test
3.4.2.6	The enclosure vents shall be remotely controllable.	Test
3.4.2.7	All interlock systems shall have the ability to interrupt the observatory control software and communicate their state to it when queried.	Test
3.4.2.8	The environmental monitors in the enclosure shall communicate their readings when queried by the observatory control software.	Test
3.4.2.9	The altitude and azimuth axes shall be remotely controllable with position, limit switch, and motor current feedback.	Test
3.4.2.10	All actuators in the primary and secondary mirror cells shall be remotely controllable with position and limit switch feedback.	Test
3.4.2.11	The primary mirror covers shall be remotely controllable with limit switch feedback.	Test
3.4.2.12	The instrument rotator shall be remotely controllable with position and limit switch feedback.	Test
3.4.2.13	All actuators in the filter mechanism shall be remotely controllable with position, limit switch, temperature, and humidity feedback.	Test
3.4.2.14	The camera shutter shall be remotely controllable with position and limit switch feedback.	Test
System internal interface requirements		
3.4.3.1	The L1 and L2 mechanical interfaces shall minimize thermal stresses on the corrector optics over the temperature range -10 to +30° C.	Analysis
3.4.3.2	The L1 and L2 mechanical interfaces shall minimize support stress on the corrector optics between 10 and 70° zenith angles.	Analysis

Paragraph Number	Requirement	Verification Method
3.4.3.3	The L1 and L2 mechanical interfaces shall maintain the spacing and decentering requirements on the optics given in section 3.3.1.	Test
3.4.3.4	The rotator shall maintain the position of the camera focal plane to < ±5 μm during a single exposure.	Test
Personnel safety requirements		
3.5.1	Locking pins shall be provided for the altitude axis and the instrument rotator mechanisms.	Inspection
3.5.2	Manual over-rides of telescope axes brakes shall be monitored by a safety interlock system.	Test
3.5.3	All pinch points in the enclosure shall be labeled with lockout warnings.	Inspection
3.5.4	Emergency stop switches shall be present on the observing level and on any floors with co-rotating parts to prevent telescope or enclosure motion.	Test
Packaging requirements		
3.8.1	The mirror shipping crates must be compatible in envelope, weight, and shock resistance with shipment over U.S. roads.	Measure
3.8.2	All crates for shipment of the optics must include sufficient weather resistance to withstand rain and snow for several days without exposing the optics to moisture.	Test
3.8.3	All crates for shipment of the filters must be humidity controlled.	Test
3.8.4	Parts for the enclosure must be compatible in envelope and weight with shipment over U.S. roads.	Inspection

5 Requirements Traceability

Table 6. Requirements Trace Matrix

Subsystem Requirements		System/Subsystem Requirement	
Paragraph Number	**Caption**	**Paragraph Number**	**Caption**
Required States and Modes			
3.2.1	Observing	3.1.6	The telescope shall deliver a PSF ≤ 0.41″ FWHM at a zenith angle of 70° for the full complement of filters (PSF quality)
3.2.2	Calibrating	3.1.9	The sum of systematic contributions to the photometric error in PS-1 data is to be less than 0.025 magnitudes.
3.2.3	Hibernating	3.1.12	PS-1 telescope shall support maintenance and service.
3.2.4	Protected	3.1.12	Maintenance & Service
3.2.5	Servicing	3.1.12	Maintenance & Service
3.2.6	Off	3.1.12	Maintenance & Service
3.2.7	Failure	3.1.12	Maintenance & Service
Image Quality			
3.3.1.1	Telescope aberrations shall contribute ≤ 6.6 µm RMS to the telescope PSF when the g, r, i, z, y, and w filters are in use.	3.1.6	PSF quality
3.3.1.2	The primary mirror and its support shall contribute ≤ 3.1 µm RMS to the telescope PSF near zenith and ≤ 4.4 µm at a zenith angle of 70°.	3.1.6	PSF quality
3.3.1.3	The secondary mirror and its support shall contribute ≤ 1.4 µm RMS to the telescope PSF near zenith and ≤ 1.7 µm at a zenith angle of 70°.	3.1.6	PSF quality
3.3.1.4	The L1 corrector and its support shall contribute ≤ 2.3 µm RMS to the telescope PSF near zenith and ≤ 3.3 µm at a zenith angle of 70°.	3.1.6	PSF quality
3.3.1.5	The L2 corrector and its support shall	3.1.6	PSF quality

Subsystem Requirements		System/Subsystem Requirement	
Paragraph Number	**Caption**	**Paragraph Number**	**Caption**
	contribute ≤ 2.2 μm RMS to the telescope PSF near zenith and ≤ 3.0 μm at a zenith angle of 70°.		
3.3.1.6	The L3 corrector and its support shall contribute ≤ 1.4 μm RMS to the telescope PSF near zenith and ≤ 1.8 μm at a zenith angle of 70°.	3.1.6	PSF quality
3.3.1.7	The filters and their support shall contribute ≤ 0.5 μm RMS to the telescope PSF near zenith and ≤ 0.7 μm at a zenith angle of 70°.	3.1.6	PSF quality
3.3.1.8	The collimation of the telescope optics shall not degrade the telescope PSF by more than 2.1 μm RMS near zenith and ≤ 4.4 μm at a zenith angle of 70°.	3.1.7	PSF quality
3.3.1.9	Focus errors of the telescope shall degrade the PSF ≤ 2.0 μm RMS near zenith and ≤ 4.0 μm at a zenith angle of 70°.	3.1.7	PSF quality
3.3.1.10	The optical design for Pan-STARRS shall have a focal surface with a sag of less than 200 μm across the full 1.5° field of view.	3.1.7	PSF quality
3.3.1.11	The focal surface field distortion shall be ≤ 3% from the mean plate scale.	3.1.7	PSF quality
3.3.1.12	The quality of refractive surfaces (e.g., scratch and dig) shall be 80/50.	3.1.9	Manage stray light
3.3.1.13	The entrance pupil of the telescope shall be defined by the outside diameter of the primary mirror and the tip of the secondary baffle.	3.1.7	PSF quality
3.3.1.14	The primary and secondary mirrors will be made out of low expansion glass.	3.1.7	PSF quality
Collimation			
3.3.2.1	The secondary shall be actuated in 5 axes: x-tilt, y-tilt, piston, x-translation, and y-translation.	3.1.7	PSF quality
3.3.2.2	The secondary actuators shall have a resolution ≤2 μm and a range of motion ≥5 mm.	3.1.7	PSF quality
3.3.2.3	The primary mirror shall be adjustable in 4 axes: x-tilt, y-tilt, x-translation, and	3.1.7	PSF quality

Subsystem Requirements		System/Subsystem Requirement	
Paragraph Number	Caption	Paragraph Number	Caption
	y-translation.		
3.3.2.4	The tilt and x-translation of the primary mirror shall be either manual or automated.	3.1.7	PSF quality
3.3.2.5	The y-translation of the primary mirror shall be automatically adjustable.	3.1.7	PSF quality
3.3.2.6	The primary mirror tilt actuators shall have a resolution ≤10 µm and allow a range of piston motion ≥ 5 mm.	3.1.7	PSF quality
3.3.2.7	The primary mirror x- and y-translation shall have a resolution ≤25 µm and allow a range of motion ≥1 mm.	3.1.7	PSF quality
3.3.2.8	The primary mirror shall reposition to within 100 µm after having been removed and replaced in the telescope.	3.1.7	PSF quality
3.3.2.9	The position and tilt of the optical axis of the primary mirror shall be known with respect to a well-defined mechanical fiducial on the mirror.	3.1.7	PSF quality
3.3.2.10	The position of the optical axis of the secondary mirror shall be marked by a dimple on the face of the mirror.	3.1.7	PSF quality
3.3.2.11	The primary mirror support shall utilize a pneumatic support system.	3.1.7	PSF quality
3.3.2.12	The air pressure for the primary mirror pneumatic support system shall be monitored.	3.1.7	PSF quality
3.3.2.13	The primary mirror support shall incorporate a 12 point astigmatism correction system that attaches to either the primary mirror or the secondary mirror.	3.1.7	PSF quality
3.3.2.14	The astigmatism correction system shall be controllable by the OTIS software.	3.1.7	PSF quality
3.3.2.15	The astigmatism correction system shall be capable of correcting for 0.5 waves of either astigmatism or trefoil errors in the telescope wave front.	3.1.7	PSF quality
3.3.2.16	The primary and secondary support systems shall have support errors that are compatible with the astigmatism	3.1.7	PSF quality

Subsystem Requirements		System/Subsystem Requirement	
Paragraph Number	**Caption**	**Paragraph Number**	**Caption**
	correction system.		
Telescope Throughput			
3.3.3.1	Antireflective coatings shall be applied to all refractive surfaces and shall have reflectance ≤2% over the wavelength range from 400nm to 1100 nm	3.1.9	Manage stray light
3.3.3.2	The reflectivity of the mirror coatings shall be ≥80% and the mirror coatings shall be made of either bare aluminum or protected silver.	6.2	Telescope throughput
3.3.3.3	The telescope obscuration shall be ≤37%.	6.2	Telescope throughput
The Filter Mechanism			
3.3.5.1	The filter mechanism shall function during telescope slews and at all rotation angles and altitudes of the telescope.	3.1.17	Filter change time
3.3.5.2	The filter mechanism shall hold a total of 6 filters at one time.	3.1.17	Filter change time
3.3.5.3	The filter position repeatability shall be 500 µm 2D RMS	3.1.9	Photometric precision
3.3.5.4	The filter mechanism shall fit within the following envelope: 73 x 29.5 x 7.50 in (1855 x 750 x 190 mm)	3.1.8	Altitude-azimuth mount
3.3.5.5	The filter mechanism (including filters) shall weigh < 350 lbs (160 kg).	3.1.8	Altitude-azimuth mount
3.3.5.6	The filter mechanism shall place ≤ 60 ft-lbs torque on the instrument rotator at all times.	3.1.8	Altitude-azimuth mount
3.3.5.7	The filter mechanism shall have a MTBF of ≥ 19200 cycles.	3.1.17	Filter change time
3.3.5.8	The clear aperture in the filter mechanism shall be 480 mm.	3.1.7	PSF quality
3.3.5.9	Filters shall be protected from contamination.	3.1.9	Photometric precision
3.3.5.10	Humidity shall be monitored and controlled within the filter mechanism.	3.1.9	Photometric precision
3.3.5.11	Filters shall be removable for inspection and cleaning.	3.1.12	Maintenance and service support
3.3.5.12	Surfaces in the filter housing and mechanisms shall be designed and	3.1.9	Manage stray light

Subsystem Requirements		System/Subsystem Requirement	
Paragraph Number	**Caption**	**Paragraph Number**	**Caption**
	treated to minimize stray light.		
3.3.5.13	The filter mechanism shall provide state feedback	3.1.11	State reporting and logging
3.3.5.14	The filter mechanism assembly shall be modular with quick disconnect cables.	3.1.12	Maintenance and service support
The Camera Shutter			
3.3.6.1	The shutter shall make available a continuous range of exposure durations from 100 ms to 300 s.	6.2	Telescope throughput
3.3.6.2	The accuracy of any exposure duration shall be better than 0.5% of the exposure duration.	3.1.9	Photometric precision
3.3.6.3	In a single exposure, all points in the focal plane shall experience the same exposure duration to better than 0.5%.	3.1.9	Photometric precision
3.3.6.4	The shutter shall be ready to begin a subsequent exposure no more than 1.0 second after the completion of a previous exposure.	3.1.9	Photometric precision
3.3.6.5	The clear aperture of the shutter shall be 480 mm.	3.1.7	PSF quality
3.3.6.6	The blade position of the shutter mechanism shall be known as a function of time to a 10 msec accuracy.	3.1.11	State reporting and logging
3.3.6.7	The shutter mechanism shall have a MTBF $\geq$ 480,000 cycles.	6.2	Telescope Throughput
3.3.6.8	The shutter assembly shall fit within the following envelope: 73 x 29.5 x 2 in (1855 x 750 x 51 mm)	3.1.8	Altitude-azimuth mount
3.3.6.9	The shutter mechanism shall weigh $\leq$ 70 lbs. (32 kg).	3.1.8	Altitude-azimuth mount
3.3.6.10	The shutter mechanism shall place $\leq$ 5 ft-lbs torque on the instrument rotator at all times.	3.1.8	Altitude-azimuth mount
3.3.6.11	The shutter assembly will dissipate $\leq$ 0.4 W of heat into the optical beam	3.1.7	PSF quality
3.3.6.12	The shutter assembly when mounted in the Cassegrain core shall have a volumetric leak rate of $\leq 2.6\ cm^3/sec$.	3.1.7	PSF quality
3.3.6.13	The shutter assembly shall be modular	3.1.12	Maintenance and

Subsystem Requirements		System/Subsystem Requirement	
Paragraph Number	**Caption**	**Paragraph Number**	**Caption**
	with quick disconnect cables.		service support
	The Camera		
3.3.7.1	The camera shall fit within the following envelope: 66 x 46 x 21 in (1676 x 1168 x 533 mm).	3.1.12	Maintenance and service support
3.3.7.2	The camera weight shall be ≤ 520 lbs (236 kg).	3.1.12	Maintenance and service support
3.3.7.3	The camera shall place ≤ 5 ft-lbs of out-of-balance torque on the instrument rotator at all times.	3.1.12	Maintenance and service support
3.3.7.4	The camera mounting shall allow a 90° rotation of the camera with respect to the telescope optical axis.	3.1.9	Photometric precision
	Pointing and Tracking		
3.3.8.1	All mirror components shall be protected from seismic force damage with accelerations < 0.3g.	3.1.12	PS-1 telescope shall support maintenance and service.
3.3.8.2	The telescope pointing accuracy shall be <10 arcseconds 2-D RMS	3.1.9	Photometric precision
3.3.8.3	The telescope altitude and azimuth encoders shall have 0.01″ resolution	3.1.7	PSF quality
3.3.8.4	Open-loop tracking error shall be ≤ 100 mas 2-D RMS for 1 minute of time.	3.1.7	PSF quality
3.3.8.5	The wind-induced tracking error shall be 70 mas 2-D RMS or less	3.1.7	PSF quality
3.3.8.6	The telescope shall be able to track between zenith angles of 10 and 70 degrees for periods >5 minutes without interruption.	3.1.7	PSF quality
3.3.8.7	The mechanical limits on the altitude axis shall be beyond a zenith distance of 75 degrees.	3.1.2	Operation altitude range
3.3.8.8	The azimuth tracking limits shall be ± 220 degrees with an azimuth cable wrap null point at 100 degrees measured from north toward east.	6.2	Telescope Throughput
3.3.8.9	The instrument rotator limits shall be > ± 60 degrees.	6.2	Telescope Throughput
3.3.8.10	The instrument rotator shall support an out-of-balance torque load ≥ 70 ft-lbs	3.1.12	Maintenance and service support

Subsystem Requirements		System/Subsystem Requirement	
Paragraph Number	**Caption**	**Paragraph Number**	**Caption**
	(95 N-m).		
3.3.8.11	The instrument rotator shall support a load of 1433 lbs (650 kg) with a center of mass 15" (0.381 m) from its mounting plate.	3.1.12	Maintenance and service support
3.3.8.12	The telescope mirror cell shall support a load of 606 lbs (275 kg) with a center of mass 5.9" (150 mm) from the top of the mirror cell.	3.1.12	Maintenance and service support
3.3.8.13	The telescope axes shall have brakes to prevent unwanted motions of the telescope and enclosure.	3.1.12	Maintenance and service support
3.3.8.14	The telescope guiding bandwidth shall be ≥1 Hz.	3.1.7	PSF quality
The Instrument Calibration Facility			
3.3.9.1	Spatial uniformity over the entrance pupil shall be ±10% or better on scales larger than 10 cm (TBR).	3.1.9	Photometric precision
3.3.9.2	Angular uniformity shall be ±10% or better over the 3° field of view (TBR).	3.1.9	Photometric precision
3.3.9.3	Spectral uniformity shall be ±10% or better over each of g, r, i, z, y filter band-passes (TBR).	3.1.9	Photometric precision
3.3.9.4	Radiance shall be adequate to 50% saturate pixels in 30 seconds (TBR).	6.2	Telescope Throughput
3.3.9.5	Autonomous operation shall not be required of the calibration facility.		
The Telescope Enclosure			
3.3.10.1	The enclosure shall be capable of tracking with the telescope without vignetting its field of view.	6.2	Telescope Throughput
3.3.10.2	The enclosure shall be able to slew at the maximum required telescope rates without mechanical interference with the telescope.	3.1.14	Slewing and settling time
3.3.10.3	The enclosure shall be capable of tracking with the telescope without vignetting its field of view.	3.1.9	Photometric precision

Subsystem Requirements		System/Subsystem Requirement	
Paragraph Number	**Caption**	**Paragraph Number**	**Caption**
3.3.10.4	The telescope shall be capable of operating in sustained winds of 20 mph (9 m sec^{-1}).	3.1.14	Slewing and settling time
3.3.10.5	The enclosure shall have safety interlocks which prevent damage to the telescope and personnel if a failure in the dome mechanism should occur.	3.1.12	Maintenance and service support
3.3.10.6	The telescope enclosure shall require ≤ 45 kW of power.	3.1.12	Maintenance and service support
3.3.10.7	The enclosure shutter shall have a watch-dog timer to close and automatically put the observatory in hibernation.	3.1.12	Maintenance and service support
3.3.10.8	The enclosure shutter shall be able to close within 5 minutes.	3.1.12	Maintenance and service support
3.3.10.9	The enclosure shutter vents, and telescope mirror covers shall have a fail-safe mechanism to protect against power failures.	3.1.12	Maintenance and service support
3.3.10.10	The enclosure shutter shall have a clear opening ≥ 2.5 m.	3.1.7	PSF quality
3.3.10.11	The enclosure shutter shall have air dams.	3.1.7	PSF quality
3.3.10.12	The enclosure shall have automatically controlled venting of outside air into the observing (telescope) level of the enclosure.	3.1.7	PSF quality
3.3.10.13	The enclosure shall have thermal barriers between the observing and equipment levels of the enclosure that allow no more than 200 W of heat leakage into the observing level.	3.1.7	PSF quality
3.3.10.14	The enclosure shall be able to keep the telescope to within 2° C of the expected night time temperatures during the day.	3.1.7	PSF quality
3.3.10.15	The external surfaces of the telescope enclosure shall be white.	3.1.7	PSF quality
3.3.10.16	The enclosure shall have space for the calibration facility.	3.1.9	Photometric precision
3.3.10.17	The enclosure walls shall be opaque.	3.1.9	Photometric precision
3.3.10.18	The state of all enclosure doors or hatches which can be damaged by	3.1.12	Maintenance and service support

Subsystem Requirements		System/Subsystem Requirement	
Paragraph Number	**Caption**	**Paragraph Number**	**Caption**
	moving parts of the enclosure or telescope must be monitored by a safety interlock.		
3.3.10.19	The enclosure shall have safety interlocks which prevent damage to the telescope and personnel if a failure in the dome mechanism should occur.	3.1.12	Maintenance and service support
3.3.10.20.1	Fixed track, lifting equipment and hatches or openings, etc., shall be provided for the servicing of the telescope optics subassemblies, giga-pixel camera, shutter, and filter changer.	3.1.12	Maintenance and service support
3.3.10.20.2	A written procedure shall be provided for the removal and installation of the primary and secondary mirrors, the corrector lenses, the shutter mechanism, the filter mechanism, the rotator, and the camera.	3.1.12	Maintenance and service support
3.3.10.20.3	Telescope Pier: The telescope pier shall provide a stiff support for the telescope and will be vibration isolated from the rest of the telescope enclosure.	3.1.7	PSF quality
3.3.10.20.4	Mounting for the camera power supply, an HP rack 7" high and 27" deep weighing approximately 250 lbs., shall be provided less than 15' from the camera.	3.1.12	Maintenance and service support
3.3.10.20.5	A separate power phase shall be provided for the camera electronics.	3.1.12	Maintenance and service support
3.3.10.20.6	A copper ground connection shall be provided for the camera electronics near the base of the pier.	3.1.12	Maintenance and service support
3.3.10.20.7	Glycol/water chiller lines shall be provided for cooling the camera He compressor, the camera controller electronics, and the SkyProbe camera controllers.	3.1.7	PSF quality
3.3.10.20.8	The water flow and temperature of the facility chiller lines shall be monitored.	3.1.11	State reporting and logging
3.3.10.20.9	Space and a way to install the following	3.1.12	Maintenance and

Subsystem Requirements		System/Subsystem Requirement	
Paragraph Number	**Caption**	**Paragraph Number**	**Caption**
	equipment shall be provided on or in very close proximity to the observing floor:		service support
The Environment Monitors			
3.3.11.1.1	Web cameras shall be provided throughout the enclosure to monitor all moving parts.	3.1.11	State reporting and logging
3.3.11.1.2	The dust density of particulates with diameters between 0.5 and 10 μm shall be measured inside the dome to an accuracy of 10% or better in a 1 minute time interval at dust levels between 0.1 $\mu g/m^3$ and 100 $\mu g/m^3$.	3.1.7	PSF quality
3.3.11.1.3	The air temperature in the enclosure shall be measured to a resolution of 0.5° C and over a range of -15°C to +30°C.	3.1.11	State reporting and logging
3.3.11.1.4	The dew point in the dome shall be measured to an accuracy of ± 1° C.	3.1.11	State reporting and logging
3.3.11.2.1	All mirror and truss temperature sensors shall have a temperature resolution <0.2° C and a range of	3.1.11	State reporting and logging
3.3.11.2.2	The primary mirror shall have sensors measuring radial temperature differences on the back side of the glass.	3.1.11	State reporting and logging
3.3.11.2.3	The primary mirror shall have sensors measuring axial temperature differences across the glass.	3.1.11	State reporting and logging
3.3.11.2.4	The secondary mirror shall have sensors measuring radial temperature differences on the back of the glass.	3.1.11	State reporting and logging
3.3.11.2.5	The secondary mirror shall have sensors measuring axial temperature differences across the glass.	3.1.11	State reporting and logging
3.3.11.2.6	The temperature of each of the secondary spider supports shall be monitored.	3.1.11	State reporting and logging
3.3.11.2.7	The temperature of each of the main truss supports shall be monitored	3.1.11	State reporting and logging
External interface requirements			

Subsystem Requirements		System/Subsystem Requirement	
Paragraph Number	**Caption**	**Paragraph Number**	**Caption**
3.4.2.1	The enclosure air conditioning shall be remotely controllable.	3.1.12	Maintenance and service support
3.4.2.2	The enclosure lights shall be remotely controllable.	3.1.12	Maintenance and service support
3.4.2.3	The calibration facility shall be remotely controllable.	3.1.12	Maintenance and service support
3.4.2.4	The enclosure drives shall be remotely controllable.	3.1.12	Maintenance and service support
3.4.2.5	The enclosure shutter shall be remotely controllable.	3.1.12	Maintenance and service support
3.4.2.6	The enclosure vents shall be remotely controllable.	3.1.12	Maintenance and service support
3.4.2.7	All interlock systems shall have the ability to interrupt the observatory control software and communicate their state to it when queried.	3.1.12	Maintenance and service support
3.4.2.8	The environmental monitors in the enclosure shall communicate their readings when queried by the observatory control software.	3.1.12	Maintenance and service support
3.4.2.9	The altitude and azimuth axes shall be remotely controllable with position, limit switch, and motor current feedback.	3.1.12	Maintenance and service support
3.4.2.10	All actuators in the primary and secondary mirror cells shall be remotely controllable with position and limit switch feedback.	3.1.12	Maintenance and service support
3.4.2.11	The primary mirror covers shall be remotely controllable with limit switch feedback.	3.1.12	Maintenance and service support
3.4.2.12	The instrument rotator shall be remotely controllable with position and limit switch feedback.	3.1.12	Maintenance and service support
3.4.2.13	All actuators in the filter mechanism shall be remotely controllable with position, limit switch, temperature, and humidity feedback.	3.1.12	Maintenance and service support
3.4.2.14	The camera shutter shall be remotely controllable with position and limit switch feedback.	3.1.12	Maintenance and service support

Subsystem Requirements		System/Subsystem Requirement	
Paragraph Number	**Caption**	**Paragraph Number**	**Caption**
System internal interface requirements			
3.4.3.1	The L1 and L2 mechanical interfaces shall minimize thermal stresses on the corrector optics over the temperature range -10 to +30° C.	3.1.7	PSF quality
3.4.3.2	The L1 and L2 mechanical interfaces shall minimize support stress on the corrector optics between 10 and 70° zenith angles.	3.1.7	PSF quality
3.4.3.3	The L1 and L2 mechanical interfaces shall maintain the spacing and decentering requirements on the optics given in section 3.3.1.	3.1.7	PSF quality
3.4.3.4	The rotator shall maintain the position of the camera focal plane to $< \pm 5$ μm during a single exposure.	3.1.7	PSF quality
Personnel safety requirements			
3.5.1	Locking pins shall be provided for the altitude axis and the instrument rotator mechanisms.	3.1.12	Maintenance and service support
3.5.2	Manual over-rides of telescope axes brakes shall be monitored by a safety interlock system.	3.1.12	Maintenance and service support
3.5.3	All pinch points in the enclosure shall be labeled with lockout warnings.	3.1.12	Maintenance and service support
3.5.4	Emergency stop switches shall be present on the observing level and on any floors with co-rotating parts to prevent telescope or enclosure motion.	3.1.12	Maintenance and service support
Packaging requirements			
3.8.1	The mirror shipping crates must be compatible in envelope, weight, and shock resistance with shipment over U.S. roads.	3.1.12	Maintenance and service support
3.8.2	All crates for shipment of the optics must include sufficient weather resistance to withstand rain and snow for several days without exposing the optics to moisture.	3.1.12	Maintenance and service support
3.8.3	All crates for shipment of the filters must be humidity controlled.	3.1.12	Maintenance and service support
3.8.4	Parts for the enclosure must be	3.1.12	Maintenance and

Subsystem Requirements		System/Subsystem Requirement	
Paragraph Number	**Caption**	**Paragraph Number**	**Caption**
	compatible in envelope and weight with shipment over U.S. roads.		service support

6 Notes

6.1 Ghosting

For the PS-1 telescope there will not be a requirement on the ghost images because the impacts of the ghosts on the image analysis is a complex issue and is not well known. The current optical layouts show that stellar ghosts shall have image diameters on the focal plane > 2 mm. With diameters larger than 2 mm, the surface brightness of the ghost images are reduced by geometric spreading from the initial stellar image by a factor of $\left(\frac{d_{ghost}}{d_{PSF}}\right)^2$ where d_{PSF} is the diameter of the stellar PSF and d_{ghost} is the diameter of the ghost image. For 0.6" seeing and a plate scale of 38.8 μm arcsec^{-1}, $d_{PSF} \approx 1.2'' = 0.047$ mm and the surface brightness of a 2 mm diameter ghost image should be a factor of 1800 lower than that of the stellar image which produced it. In addition to this, it is not unreasonable to assume that anti-reflection coatings will reduce the ghost image surface brightness by an additional factor of 2000. This requires anti-reflection coatings of only 2.2%, which should be achievable for these optics. The combination of geometry and limits on surface reflectivity should result in a total surface brightness reduction of $>10^6$ (approximately 15 magnitudes). For a sky brightness of 21 magnitudes arcsec^{-1}, this means that only stars brighter than 6th magnitude will produce ghost images with surface brightness comparable to the normal sky background. One of the benefits of the prototype will be the assessment of the impact of ghost images on the system. Ghosting will be considered with all of the optical designs and monitored carefully in the analysis of the images. By not making this a system requirement for PS-1 we are not allowing it to be a cost driver for the prototype.

6.2 Telescope Throughput

The telescope throughput, $\xi(\lambda)$, is characterized by the following equation

$$\xi = \frac{\eta_{clear}}{2\pi} \frac{t_{open}}{\left(t_{closed} + t_{open}\right)} \int_{-\infty}^{\infty} \int_{0}^{2\pi} \int_{0}^{\theta_{\max}} d\lambda d\varphi d\theta (1-\omega(\theta,\varphi)) T_L(\lambda)^6 F(\lambda) R(\lambda)^2$$

where η_{clear} is the fraction of useable observing time the telescope is in operation, t_{open} is the typical exposure time, t_{closed} is the time required for the telescope to read out the camera, slew, settle, change filters, and open the shutter, $\omega(\theta,\varphi)$ is the telescope vignetting, $\theta_{\max}$ is the maximum half-angle which defines the telescope's field of view (FOV), φ is the azimuthal angular coordinate in the telescope's FOV, λ is wavelength, $T_L(\lambda)$ is the transmission of a single surface on a corrector element lens, $F(\lambda)$ is the filter transmission, and $R(\lambda)$ is the reflectivity of mirrors in the telescope. Note that with this definition, the telescope étendue, ε', is given by $\varepsilon' = \xi A$, where A is the telescope aperture area. This is a modified version of the system étendue, ε, given in the SCD. If the whole system were being considered here, the detector response would also be included in this equation. It is assumed in this equation that F incorporates the surface losses and the bulk transmission of the filter and that the bulk transmission through the corrector lenses is 100%. The telescope obscuration is given by $\omega(0)$. It is often assumed that $\omega(\theta,\varphi) = \omega(0)$, but for wide-field telescopes this is a poor approximation. For the Pan-STARRS optical layout a good approximation is $\omega(\theta,\varphi) = \omega(\theta)$. For the Pan-STARRS band-passes another good approximation is $R(\lambda) = R$.

To maximize the system étendue it is necessary to maximize the telescope throughput. Each of the requirements in this section has an impact on defining the terms in this equation. A lower acceptable limit on ξ can be computed by averaging over the integrals and making assumptions about acceptable values for the component terms. If an obscuration of 40%, filter transmissions of 85%, mirror reflectivities of 85%, reflection losses of 2%, an exposure time of 30 s, a read out and slew time of 15 seconds, and an observing availability, η_{clear}, of 90% is assumed, then $\xi \approx 0.20$. This will be considered a lower limit for the telescope throughput for the full Pan-STARRS array, but will only be considered as a goal for the PS1 telescope.

The term η_{clear} is essentially a telescope system reliability factor. This term can be thought of as consisting of terms due to the telescope reliability, the filter mechanism reliability, and the shutter reliability. The probability of failure for the telescope system is $\boldsymbol{1-\eta_{clear}}$. If the probability of failure of any of these mechanism is equal, then any one of them must have a reliability of about $\boldsymbol{\eta_{clear}^{\frac{1}{3}} \approx 0.97}$. In practice, however, the shutter and filter mechanisms will be in operation both during clear and cloudy nights as well as during significant parts of the day owing to the need to acquire calibration data. Therefore, the reliability of both the shutter mechanism and the filter will have to be considerably higher than that of the telescope itself. If the shutter and filter mechanisms can be made to have a reliability of 99.5%, then the telescope reliability needs to be 91%. For PS1 we will not be specifying a telescope reliability, but we will specify reliabilities for both the shutter and filter mechanisms.

For the shutter, a reliability of 0.995 is equivalent to 0.005 failures per night. Assuming 10 hour nights with 15 seconds per cycle, we have 2,400 cycles/night and a MTBF of 2,400/.005=480,000 cycles. This is equivalent to about 1 failure per year if the weather reduces the amount of time on the sky to 55%.

For the filter, there will be far fewer cycles per night. If we assume that there is a filter change approximately every 25 exposures, then there are only 96 cycles/night. A reliability of 0.995 is then equivalent to a MTBF of 96/0.005=19,200 cycles.

The ratio $\frac{t_{open}}{t_{open}+t_{closed}}$ is an observing efficiency factor. Owing to the fact that the Pan-STARRS project will be making very short (10 second) exposures for much of its lifetime, this factor is determined in large part by the speed that the telescope can be repositioned. This factor, therefore, strongly influences the step and settle specifications of both PS1 and PS4.

6.3 Heat transfer calculations and the gas leak rate in the Cassegrain Core

The amount of heat that is transferred from a metal surface to the air is given by

$$\dot{Q} = hA\Delta T_{surf}$$

where ΔT_{surf} is the temperature difference between the ambient air and the surface, A is the surface area in contact with the air, and h is the heat transfer coefficient between the air and the surface. The heat transfer coefficient is given by

$$h = \frac{k}{L} N_u$$

where $k = 0.025$ W/m-C is the air conductivity, L is the length of the surface in contact with the air, and N_u is the Nussult Number, given by

$$N_u = 0.664 \left(P_r\right)^{\frac{1}{3}} \sqrt{R_e}$$

where $P_r = \frac{\nu}{\kappa_d}$ is the Prandtl Number and $R_e = \frac{\rho V L}{\mu}$ is the Reynolds Number. The density of dry air is given by $\rho = 1.168\ \text{kg/m}^3$. The viscosity of air is given by $\mu = 0.017\ \text{cP} = 1.7 \times 10^{-4}\ \text{gm/cm-sec}$ and the kinematic viscosity is given by $\nu = \frac{\mu}{\rho} = 0.146\ \text{cm}^2/\text{sec}$. The thermal diffusivity of dry air is given by $\kappa_d = \frac{k}{\rho c} = 0.214\ \text{cm}^2/\text{sec}$ where $c = 1.0$ kJ/kg-C is dry air's specific heat. And V is the velocity of the air over the surface. For dry air, the Prandtl Number is given by $P_r = 0.682$. The value of the Reynolds Number will depend upon our assumptions about the airflow over the plate. We will deal with this issue later.

The presence of the siloxane in the Atmospheric Dispersion Corrector (ADC) that is being considered for the Pan-STARRS optics represents a significant limitation on the heat that will be allowed to be input into the Cassegrain core. The temperature coefficient of the siloxane is $\frac{dn}{dt} =$ -3.9 x 10^{-4} C^{-1}. The optical pathlength through the siloxane is $\tau = nl$ where n is the index of refraction of the siloxane and l is the physical pathlength through it. If ΔT_{lens} is a characteristic temperature difference across the lens radius and if the physical pathlength through the siloxane is $l = 5+5 = 10$ mm, the optical path difference across the lens becomes $\Delta\tau = l\Delta T_{lens}\frac{dn}{dt}$. Ray tracing through the telescope optics indicates that we need to keep $\Delta\tau \leq \frac{\lambda}{6} \approx 1 \text{ x } 10^{-7}$ m (RMS). For $\Delta T_{lens} \leq \frac{\Delta\tau}{l\frac{dn}{dt}} \approx$ 0.026 C. This is an RMS number, but a peak-to-valley variation would still correspond to $\Delta T_{lens} \leq$ 0.08 C. We therefore require that the heat input from the filter and shutter mechanisms be small enough that it will not drive temperature variations in the Cassegrain core of this magnitude.

If we assume that the actuators are along the sides of this cavity and that they are the only heat source, then only the side panels will likely be heated by the actuators and they will tend to drive a radial variation in the gas temperature in the Cassegrain core. But, if $\Delta t = \frac{R_{lens}}{V}$ is the time that it takes for a gas cell to travel from the perimeter of the lens to the lens center, then the Cassegrain core will tend to heat up uniformly with minimal temperature gradients if

$$\frac{dT_{gas}}{dt} < \frac{\Delta T_{lens} V}{R_{lens}}$$

where $\frac{dT_{gas}}{dt}$ is the rate of change of the gas temperature.

The temporal change in the internal energy of the gas in the Cassegrain core is given by

$$\dot{Q}_{in} - \dot{Q}_{out} = \rho c V_{cc}\frac{dT_{gas}}{dt}$$

where V_{cc} is the volume of gas inside the Cassegrain core. If we assume that heat conduction out of the Cassegrain core is minimal ($\dot{Q}_{out} \approx 0$) and if we require all heating to be uniform across the lens, then we have

$$\dot{Q}_{in} < \rho c V_{cc}\frac{\Delta T_{lens} V}{R_{lens}}$$

The filter mechanism has an envelope of dimensions 1.86 x 0.75 x 0.19 m (paragraph 3.3.5.4) and a volume of 0.27 m^3. The shutter has an envelope of 1.86 x 0.75 x 0.05 m (paragraph 3.3.6.8) and a volume of 0.07 m^3. The combined volume of the Cassegrain core is therefore on the order of $V_{cc} =$ 0.5 m^3.

The air velocity, $\boldsymbol{V}$, inside the Cassegrain core will be dependent primarily on the leak rate of gas out of this cavity. This will not be true if the seals on the Cassegrain core seams are truly gas tight. Under those circumstances convection will determine$\boldsymbol{V}$, but the current concepts call for loose seals and a substantial leak rate.

If we assume that the filter mechanism is a rectangular box with metal joint seems on all of its corners and a circular seam on the top and bottom surfaces that is the size of the filter ($\boldsymbol{R}_{lens} = 300\text{ mm}$), then it is easy to show that there are approximately 1000 linear inches of seams in this structure. If we additionally assume that these seams have gaps which are on the order of a machine tool surface roughness (~0.001"), then $\boldsymbol{A}_{leak} \approx 1\text{ in}^2$ is the cumulative area of leakage in this structure. The shutter will have approximately the same amount of leak area, so we estimate the total leakage in the Cassegrain core to be $\boldsymbol{A}_{leak} \approx 2\text{ in}^2 = 1.3\text{x}10^1\text{ cm}^2$ for a well-made structure without gas-tight seals.

The mass flux through the seams, $\dot{\boldsymbol{m}}$, is related to the volumetric leak rate by the equation $\dot{\boldsymbol{m}} = \boldsymbol{\rho}\dot{\boldsymbol{V}}_{leak}$, where $\dot{\boldsymbol{V}}_{leak}$ has the units of cm^3/sec. The mass flux is also related to the bulk velocity of the gas in the cavity by the equation $\dot{\boldsymbol{m}} = \boldsymbol{\rho}\boldsymbol{A}_{leak}\boldsymbol{V}$. Combining these two equations gives

$$\boldsymbol{V} = \frac{\dot{\boldsymbol{V}}_{leak}}{\boldsymbol{A}_{leak}}$$

We wish to keep the leak rate, $\dot{\boldsymbol{V}}_{leak}$, low enough to be able to supply the chamber with gas from a single gas cylinder for a period of about 2 week2. A typical dry air gas cylinder has 220 ft^3 = 6.23 x 10^6 cm^3 of gas. If we assume a time period of 14 days = 1.2x10^6 sec, then we can afford a leak rate of $\dot{\boldsymbol{V}}_{leak} = 5.2\text{ cm}^3\text{/sec}$. Combining this with our estimate of $\boldsymbol{A}_{leak}$ we find an expected bulk gas velocity of $\boldsymbol{V} = 0.4\text{ cm/sec}$.

We can now return to our calculation of thermal heat limits in the filter and shutter mechanisms. Given an estimate of $\boldsymbol{V}$ we can now use the equation for $\dot{\boldsymbol{Q}}_{in}$ given above to find that

$$\dot{\boldsymbol{Q}}_{in} < 0.62\text{ W}$$

If a typical surface length of warm plate in these mechanisms is $\boldsymbol{L} = 1\text{ m}$, then this and our estimate of $\boldsymbol{V}$ above allow us to calculate a Reynolds number for the expected heat transfer between the Cassegrain core structure and the gas inside it. Doing this we find $\boldsymbol{R}_e = 275$ which leads to $\boldsymbol{N}_u = 9.7$ and $\boldsymbol{h} = 0.24\text{ W/m}^2\text{-C}$ for a plate of 1 m length.

For the case where the sides of the filter mechanism are the only warm surfaces contributing to the heat flux into the Cassegrain core we have $\boldsymbol{A} = 1.86\text{ x }0.19\text{ x }2 = 0.71\text{ m}^2$. Using this value for the area, solving for $\Delta\boldsymbol{T}_{surf}$ using our starting equation for $\dot{\boldsymbol{Q}}$, and assuming the power limit given above leads to an estimate for the maximum surface temperature that can be allowed for the filter mechanism walls. We find $\Delta T_{surf} < 3.7\text{ C}$.

6.4 Motor drive acceleration and maximum velocities

The basic requirements on the telescope drives come from the maximum velocity specifications given in paragraph 3.1.13 and from the step and settle specifications given in paragraphs 3.1.14 through 3.1.16. But it is useful to consider what approximate accelerations are implied by these specifications.

Paragraph 3.1.14 requires the telescope to slew 3.0° and settle to nominal open loop tracking errors in 5 seconds. If the settle time of the telescope for a move of this size is 1 second, then only 4 seconds are available for the telescope move.

If the telescope has a trapezoidal velocity profile with an equal and constant acceleration and deceleration, then D, the distance moved by the telescope, is related to a, the telescope acceleration, and v_m, the maximum telescope velocity, by the equation

$$D = v_m \left(\frac{v_m}{a} + t_2 \right)$$

where t_2 is the amount of time the telescope travels at the maximum velocity. The move for a given distance with minimum acceleration will happen with $t_2 = 0$. The total time that this move takes will be given by

$$T_m = \frac{2D}{v_m}$$

And the total step and settle time will be $T = T_m + T_s$ where T_s is the time it takes the telescope to settle to its open loop tracking specification after it has reached its target destination. If we assume a step and settle of 3° in 5 seconds, then Table 7 shows the minimum drive accelerations and the maximum velocities required to attain these minimum accelerations when different settle times are assumed.

Table 7. Telescope Drive Accelerations and Maximum Velocities

Assumed Telescope Settle Time, T_s (sec)	Minimum Telescope Drive Acceleration, $a=v_m^2/D$ (°/sec^2)	Required Telescope Drive Maximum Velocity, $v_m=2D/T_m$ (°/sec)
0	0.48	1.2
1	0.75	1.5
2	1.32	2.0

If higher accelerations are acceptable, then the condition $t_2 = 0$ can be dropped. Under these circumstances we have

$$t_2 = \frac{2D}{v_m} - T_m \quad \text{and} \quad a = \frac{2v_m}{T_m - t_2}$$

If we assume that $v_m = 1^\circ/\mathbf{sec}$, $D = 3^\circ$, and $T_m = 4$ sec, then $t_2 = 2$ sec and $a = 1^\circ/\mathbf{sec}^2$. This move profile has a settle time and total move time identical to the second row in Table 7. These two cases illustrate the trade-off between higher acceleration rates and lower maximum velocities. Likewise, if we assume conditions similar to the last row in Table 7, $v_m = 2^\circ/\mathbf{sec}$, $D = 3^\circ$, and $T_m = 2.5$ sec, then $t_2 = 0.5$ sec and $a = 2^\circ/\mathbf{sec}^2$. In this case $T_s = 2.5$ sec and the trade off is between acceleration rate and settle time. From this it can be seen that acceleration rates increase rapidly as the settle time increases past 2 seconds.

6.5 On-sky step and settle characteristics as a function of zenith angle

The step and settle times specified in paragraphs 3.1.14, 3.1.15, and 3.1.16 refer to the motions of each telescope axis. For an alt-az telescope, the on-sky motions of the telescope do not follow the axis motions when the telescope is near zenith. In particular, as the telescope approaches the zenith, to move a fixed angular on-sky distance the azimuth axis motions increase roughly as $\frac{1}{\cos(90 - z)}$, where z is the telescope zenith angle. Since this is a singularity at $z = 0$, alt-az telescopes cannot track through a region near the zenith because the maximum velocity required of the azimuth axis becomes impossible to sustain. For this same reason, the step and settle characteristics of the telescope are also dependent on the zenith angle.

The region about the zenith in which the telescope cannot track is often called the “keyhole”. Our telescope is specified by paragraph 3.1.2 to have a “keyhole” of less than 10°. The telescope and enclosure shall be capable of tracking up to the keyhole limit, but it will not be capable of meeting the 3.0° step and settle specifications at zenith angles this small. The fundamental limitation is not caused by the speed of the telescope, but by the speed of the enclosure. With the maximum velocities specified in paragraph 3.1.13, the step and settle times for an on-the-sky move of 3.0° as a function of zenith angle will follow those given in Table 8.

Table 8. PS-1 Step and Settle Times as a Function of Zenith Angle

Zenith Angle (degrees)	**Time to Step 3.0° and Settle (seconds)***
70-40	5
30	5.75
20	7.5
10	12

*Assuming a maximum azimuth velocity of 2°/sec

6.6 Filter mechanism mechanical stress calculations

The filter mechanism must keep the filters safe during operations and during installation of the filters into the mechanism. Glass breaks primarily in tension rather than compression. Typical glass tensile strengths are around 7000 psi. Note that this is not a theoretical strength, but rather a typical limit to safe handling based on manufacturer stress testing of ground glass samples. Polished glasses will often have a tensile strength a factor of two higher than this. A safety factor of 7 gives a limit of 1000 psi for the stress placed on the filter glass.

We assume in the following analysis that the filters can be mounted in such a way that no point contacts are made between the filter glass and its carriage. Potting of the filter in a frame is a typical way to avoid such point contacts.

We can approximate the surface area of the filter glass by assuming a circular filter of 500 mm diameter and a filter thickness of 10 mm. Such a circular filter will have a circumference of about 62" and an edge area of $\boldsymbol{A_e} = 15700\ \text{mm}^2 = 24.3\ \text{in}^2$. Assuming fused silica, such a filter will weigh about 11 lbs. and have a mass of about 5 kg. If we assume that a mechanical shock to the filter will be evenly distributed over a quarter of its circumference we have a shock stress of $\boldsymbol{\sigma_{ss}} = \frac{\boldsymbol{4ma}}{\boldsymbol{A_e}}$. We assume an upper limit of $\boldsymbol{\sigma_{ss}} = 1000\ \text{psi} = 6.9 \times 10^6\ \text{Pa}$, which is equivalent to an upper limit of the acceleration on the glass of $\boldsymbol{a} < \frac{\boldsymbol{\sigma_{ss} A_e}}{\boldsymbol{4m}} = \frac{6.9 \times 10^6\ \text{N/m}^2 \times 1.57 \times 10^{-2}\ \text{m}^2}{4 \times 5\ \text{kg}} = 5.4 \times 10^3\ \text{m/sec}^2$.

To meet the filter change-out time specification, the filters will have to travel at a velocity of approximately $\text{v} = 50\ \text{mm/sec} = \boldsymbol{at}$, where $\boldsymbol{a}$ is the acceleration the filter sees at the end of its travel and $\boldsymbol{t}$ is the time it takes for the filter to stop. If the filter mechanism brings the filters from this velocity to a stop in a distance of 3 mm, then $\boldsymbol{x} = 3\ \text{mm} = \frac{\boldsymbol{1}}{\boldsymbol{2}}\boldsymbol{at^2}$ and $\boldsymbol{a} = \frac{\boldsymbol{6}}{\boldsymbol{t^2}}$. Assuming the velocity of the filter mechanism above gives $\boldsymbol{a} = \frac{\boldsymbol{50}}{\boldsymbol{t}} = \frac{\boldsymbol{6}}{\boldsymbol{t^2}}$, and we have a stopping time of $\boldsymbol{t} = \frac{\boldsymbol{6}}{\boldsymbol{50}} = 0.12\ \text{sec}$ and an acceleration of $\boldsymbol{a} = \frac{\boldsymbol{50}}{\boldsymbol{0.12}} = 416\ \text{mm/sec}^2$. This is clearly negligible compared to the stresses that the glass can support. Even if the mechanism were to stop in $1/10^{th}$ the distance (0.3 mm), the acceleration is still only 4160 mm/sec^2, which is a factor of 1300 below the shock stress limit suggested above.

This shows that as long as the filter mechanism does not allow free-fall motions of the glass, even if the filter carriage was to collide with a hard stop, the glass is in no danger from the slow velocities that it will experience in the filter mechanism.

Thermal stresses on the filters from CTE mismatches between the glass and its mount are of far greater concern than mechanical shocks. Studies on the lens mount designs (PSDC-300-019-00) suggest that these stresses will be manageable for the filters.