U N I V E R S I T Y O F H A W A I ‘ I A T M Ā N O A

Institute for Astronomy

Pan-STARRS Project Management System

PS2/PS4 Telescope Vendor Specifications

Prepared For	**:Pan-STARRS Project Management Office**
Prepared By	**:Gates, Morgan, Burgett, Giebink**
	:PanSTARRS Technical Staff
Document No.	**:PSDC-350-004-01**
Document Date	**:24 August 2010**

DISTRIBUTION STATEMENT

Approved for Public Release – Distribution is Unlimited

2680 Woodlawn Drive, Honolulu, Hawaii 96822
An Equal Opportunity/Affirmative Action Institution

Revision History

Version/Revision	Date	Comments
00	9 August 2010	Creation of initial document
01	23 Aug 2010	Added software requirements

Table of Contents

1 SCOPE OF DOCUMENT 1

2 REFERENCED DOCUMENTS 1

3 INTRODUCTION 3

3.1 System Overview 3

3.2 Document Overview 7

4 REQUIREMENTS 8

4.1 Environmental Requirements 8
4.1.1 The telescope shall operate at 4267 meters (14000ft) elevation. 8
4.1.2 PS4 will observe in winds averaging 10m/s (22 mph) or less with gusts not to exceed 15m/s (34 mph) 8
4.1.3 The environmental temperatures will be between 5° and -10°C during observations 8
4.1.4 All mirror components shall be operable after the application of seismic forces with accelerations < 0.3g. 8
4.1.5 Observations will be performed in relative humidity of 80% or less 9

4.2 System Requirements 10
4.2.1 The telescope volume shall be contained within the dimensions given in PSTD-780-001 10
4.2.2 The PMA volume shall be contained within the dimensions given in PSTD-540-001 11
4.2.3 The telescope aperture shall be 1.8 m in diameter 11
4.2.4 The telescope operational altitude range shall be 10° to 70° zenith angle. 11
4.2.5 The half-angle of the telescope field of view shall be 1.5° 11
4.2.6 The telescope focal length shall be 8.0m 11
4.2.7 The PS4 telescope shall utilize an altitude-over-azimuth mount. 11
4.2.8 The PS4 stray light management shall include a fully baffled focal plane, contamination control and other measures to mitigate the impact of stray light. 14

4.2.9 The PS4 state and errors shall be reported and logged. 14
4.2.10 The telescope shall be remotely operable. 14
4.2.11 The Telescope Control Computer (TCC) shall be remotely bootable from an “off”, “protected” or “hibernating” state (see paragraph 4.2.25). 14
4.2.12 The telescope and TCC shall recover from a power outage without personnel on-site. 14
4.2.13 PS4 telescope shall support maintenance and service. 14
4.2.14 All lubricants used within the telescope shall be low temperature compatible and the lubricants within purchased components shall be replaced with low temperature compatible lubricants during construction. 14
4.2.15 All heat sources on, in or near the telescope shall be contained in air tight, temperature controlled enclosures. 14
4.2.16 The altitude and azimuth axes of the PS4 telescope shall have maximum velocities ≥ 1.0°/second and ≥ 2.0°/sec, respectively. 15
4.2.17 The PS4 telescope axes shall be capable of slewing 3.0° and settling to the nominal open loop tracking errors in a 5 second time interval. 15
4.2.18 For intermediate step angles (from 0.002 to 0.01 degrees) the PS4 telescope shall be capable of slewing and settling to the nominal open loop tracking errors in a 2 second time interval. 15
4.2.19 For small step angles (from 0.00003 to 0.002 degrees) the PS4 telescope shall be capable of slewing and settling to the nominal open loop tracking errors in a 1 second time interval. 15
4.2.20 The telescope mirror cell design shall be compatible with the PS4 primary mirror blank. 15
4.2.21 The M1 Support shall be compatible with the location of the primary mirror support pads given in PSTD-020-001. 16
4.2.22 The telescope secondary support structure shall be compatible with the PS4 secondary mirror blank. 20
4.2.23 The telescope fork assembly shall allow a minimum clearance of 21” (550mm) between the bottom of the instrument package and the top of the fork when the telescope is at zenith. 20
4.2.24 The telescope fork assembly shall provide a swing clearance ≥ 6” (150mm) with a solid fork bottom. 20
4.2.25 The telescope structure and mirror supports shall maintain the registration of the secondary mirror to the values in Table 4 without adjustment of its actuators 22
4.2.26 The secondary spider supports shall be insulated or made of low CTE material. 22

4.3 Required States and Modes 22
4.3.1 Observing Mode 22
4.3.2 Calibrating State 23
4.3.3 Hibernating State 23
4.3.4 Protected State 23
4.3.5 Servicing Mode 23
4.3.6 Off State 23
4.3.7 Failure State 23

4.4 Software Requirements 24
4.4.1 The Vendor shall supply low level telescope software that will interface to the Project-supplied SW. 24
4.4.2 The Vendor shall provide a SW interface allowing control of the telescope subsystems with minimum latencies by the Project-supplied SW. 24
4.4.3 The Vendor-supplied interface(s) should provide the capability for the Project to add a minimum of eight (8) new data sources 24
4.4.4 The Vendor shall provide interface control descriptions (ICDs) between Vendor-supplied and Project-supplied SW. 24
4.4.5 The Vendor-supplied SW shall provide the capability to control velocity, acceleration, and position of all telescope axes for celestial tracking. 24
4.4.6 The Vendor-supplied SW shall provide the capability for Project-supplied SW to control velocity, acceleration, and position of all telescope axes in real time. 24

4.4.7 The Vendor-supplied SW shall provide the capability for Project-supplied SW to read and control all control loop parameters and diagnostics. 24
4.4.8 Vendor-supplied SW shall use velocity commanded control with position feedback as opposed to position/time command control. 24
4.4.9 The Vendor-supplied SW shall include any software needed for PID tuning of each servo axis. 25
4.4.10 The Vendor-supplied SW shall include software that is required to move each axis under computer control. 25
4.4.11 The Vendor-supplied SW shall include the capability to monitor all of the raw encoder counts, motor currents, and pressure and temperature sensor data. 25
4.4.12 The Vendor-supplied interface(s) shall support Linux-based Project-supplied SW. 25

4.5 System Capability Requirements 25
4.5.1 Image Quality 25
4.5.1.1 The support of the primary mirror shall contribute ≤ 0.025 µm RMS surface errors to the primary surface near zenith and ≤ 0.060 µm RMS surface errors at a zenith angle of 70°. 25
4.5.1.2 The support of the secondary mirror shall contribute ≤ 0.050 µm RMS surface errors to the secondary surface near zenith and ≤ 0.070 µm RMS surface errors at a zenith angle of 70°. 26
4.5.1.3 The entrance pupil of the telescope shall be defined by the outside diameter of the primary mirror and the tip of the secondary baffle. 26
4.5.2 Collimation 26
4.5.2.1 The secondary shall be actuated in 5 axes: x-tilt, y-tilt, piston, x-translation, and y-translation. 26
4.5.2.2 The secondary mirror actuators shall have a resolution ≤2 µm and a range of motion ≥5 mm. 26
4.5.2.3 The primary mirror shall be adjustable in 4 axes: x-tilt, y-tilt, x-translation, and y-translation. 26
4.5.2.4 The tilt and x-translation of the primary mirror shall be either manual or automated. 27
4.5.2.5 The y-translation of the primary mirror shall be automatically adjustable. 27
4.5.2.6 The primary mirror tilt actuators shall have a precision ≤10 µm and allow a range of piston motion ≥ 5 mm. 27
4.5.2.7 The primary mirror x- and y-translation shall have a precision ≤25 µm and allow a range of motion ≥1 mm. 27
4.5.2.8 The primary mirror shall reposition to within 100 µm after having been removed and replaced in the telescope. 27
4.5.2.9 The telescope primary mirror cell shall have a fiducial surface whose axial distance from the M2 actuator mounting surface is known to within ±150 µm. 27
4.5.2.10 It is recommended that the telescope shall utilize a pneumatic support system for the primary mirror. 27
4.5.2.11 The air pressure and humidity for the primary mirror pneumatic support system shall be monitored. 28
4.5.2.12 The primary mirror support shall incorporate a 12 point astigmatism correction system that attaches to the primary mirror. 28
4.5.2.13 The astigmatism correction system shall be controllable by the Project-supplied software software. 28
4.5.2.14 The astigmatism correction system shall be capable of correcting for a range of 2.0 waves of either astigmatism or trefoil errors in the telescope wave front to a precision of 0.05 waves. 28
4.5.2.15 The primary and secondary support systems shall have support errors that are compatible with the astigmatism correction system. 28
4.5.2.16 The telescope telemetry of the primary and secondary mirror's position shall be independent of the mirror actuators. 28
4.5.2.17 The resolution of the primary mirror position measurement shall be ≤2 µm in translation and ≤0.5" in tip/tilt relative to the PMA 28
4.5.2.18 The resolution of the secondary mirror position measurement shall be ≤2 µm in translation and ≤1.0" in tip/tilt relative to the M2 mounting interface 28

4.5.3 Telescope Throughput 28
4.5.3.1 The obscuration from telescope secondary vanes and cone baffle supports shall be ≤1% at the edge of the telescope's field of view. 29
4.5.3.2 The telescope drives, motors, amplifiers, encoders, bearings, compressors, actuators, and mirror supports shall have a cumulative MTBF of ≥ 450 hrs. 29
4.5.3.3 Repair of a telescope failure between the service intervals given below in Table 6 shall not require more than 8 hours, assuming adequate spare parts are stocked at the observatory. 29
4.5.4 Pointing and Tracking 30
4.5.4.1 The telescope pointing accuracy shall be ≤5 arcseconds 2-D RMS 30
4.5.4.2 The telescope pointing precision shall be ≤2 arcsec 2-D RMS over a week's time. 31
4.5.4.3 The telescope altitude and azimuth encoders shall have 0.01″ resolution or better. 31
4.5.4.4 Open-loop tracking error shall be ≤ 110 mas 2-D RMS for 1 minute of time. 31
4.5.4.5 The wind-induced tracking error shall be ≤ 130 mas 2-D RMS near the operational zenith limit and shall be ≤ 230 mas at a zenith angle of 70°. 31
4.5.4.6 The telescope shall be able to track between zenith angles of 10 and 70 degrees for periods up to 5 minutes without interruption. 31
4.5.4.7 The mechanical limits on the altitude axis shall be beyond a zenith distance of 75 degrees. 32
4.5.4.8 The azimuth tracking limits shall be ± 220 degrees with an azimuth cable wrap null point at 100 degrees measured from north toward east. 32
4.5.4.9 The instrument rotator operational limits shall be ≥ ± 96 degrees. 32
4.5.4.10 The instrument rotator slew speed shall be ≥ 2.3°/sec. 32
4.5.4.11 The instrument rotator shall support an out-of-balance torque load up to 50 ft-lbs (68 N-m). 32
4.5.4.12 The instrument rotator shall support a load of 1660 lbs (753 kg) with a center of mass 17" (0.432 m) from its mounting face (datum A on the ICD). 33
4.5.4.13 The telescope mirror cell shall support a load of 606 lbs (275 kg) with a center of mass 10.7" (271 mm) from the UCC mounting face (datum A on the ICD). 33
4.5.4.14 The telescope guiding bandwidth shall be ≥1 Hz. 33

4.6 The Telescope Temperature Monitors 33
4.6.1 All mirror and truss temperature sensors shall have a temperature accuracy of <0.3°C, resolution <0.02° C over a range of -10° C to +25° C. 33
4.6.2 The primary mirror shall have a total of 8 sensors measuring radial temperature differences on the back side of the glass every 90° around its circumference. 33
4.6.3 The secondary mirror shall have a total of 4 sensors measuring temperatures on the back of the glass every 90° around its circumference. 34
4.6.4 The secondary support cage shall have 2 sensors measuring the temperature of the support cage. 34
4.6.5 The temperature of each of the secondary spider supports shall be monitored. 34
4.6.6 The temperature of each of the main truss supports shall be monitored. 34
4.6.7 The temperature of each leg of the LCC shall be monitored. 34

4.7 System interface requirements. 34
4.7.1 Interface identification and diagrams. 34
4.7.2 External interface requirements 38
4.7.2.1 The altitude and azimuth axes shall be remotely controllable with position, limit switch, and motor current feedback. 38
4.7.2.2 All actuators in the primary and secondary mirror cells shall be remotely controllable with position and limit switch feedback. 38
4.7.2.3 The instrument rotator shall be remotely controllable with position and limit switch, and motor current feedback. 38
4.7.3 System internal interface requirements 38
4.7.3.1 The instrument rotator shall maintain the position of the camera focal plane to ≤40µm over its full range of motion and altitude operational range of motion. 38
4.7.3.2 The instrument rotator shall maintain the parallelism of the LCC mounting surface to the telescope X-Y Plane to ≤6 µm over its full range of motion and altitude operational range of motion. 38

4.7.3.3 The Lower Cassegrain Core 38
4.7.3.3.1 The bottom of PMA shall be less than 6.4" (163 mm) below the LCC mounting surface 39
4.7.3.3.2 The LCC mounting surface is located 17.746" [450.76 mm] below the M1 vertex 39
4.7.3.3.3 The inner diameter of the rotating part of the Instrument Rotator shall be larger than 42.322" [1075 mm] 39
4.7.3.4 The Upper Cassegrain Core 42
4.7.3.4.1 The UCC mounting surface is located 1.182" [30 mm] above the LCC mounting plane. 42
4.7.3.4.2 The inner diameter of the fixed race of the Instrument Rotator shall be larger than 38.750" [984 mm]. 42
4.7.3.5 Baffles and Stray Light Mitigation 44
4.7.3.5.1 Baffle Tolerances 44
4.7.3.5.2 The area of the PMA around M1 must be coated with a finish that has reflectivity <2% from 400nm to 1100nm 44
4.7.3.5.3 Baffle finishes shall have reflectivity <2% from 400nm to 1100nm 44
4.7.3.5.4 The Truss Mask shall be adjustable radially by 1.0cm 45
4.7.3.5.5 A tool shall be provided to register the Cone Baffle to the telescope 45
4.7.3.5.6 M1 baffle shall conform to PSTD-660-001. 48
4.7.3.6 Mirror Covers 48
4.7.3.6.1 The telescope shall have mirror covers that shield both the primary mirror and the Cassegrain corrector optics from dust and minor precipitation. 48
4.7.3.6.2 The telescope mirror covers shall be remotely operable and capable of closing from a completely open position within 30 seconds. 48
4.7.3.6.3 The mirror covers shall be remotely operable by the Project-supplied software software. 48
4.7.3.6.4 The telescope mirror covers shall have both fully closed and fully open limit switch feedback. 48
4.7.3.6.5 The telescope mirror covers shall have a fail-safe mechanism to protect against power failures. 48
4.7.3.7 The minimum bend radius for cable and service management system shall not be less than 170mm (6.69"). 48
4.7.3.8 Instrument Cable Wrap 48
4.7.3.8.1 The Cable Wrap shall permit the Instrument Rotator to move relative to the PMA over its full range of motion. 49
4.7.3.8.2 The Cable Wrap shall not obstruct the installation and removal of the Camera, LCC, UCC, or Filter Mechanism 49
4.7.3.8.3 The Cable Wrap shall contain and guide all cables and utilities required for the Filter Mechanism, Camera Shutter, LCC and GPC. 50
4.7.3.8.4 The Cable Wrap shall be compatible with the instrument rotator torque capacity. 50
4.7.3.9 Telescope Cable Drape 50
4.7.3.9.1 The Cable Drape shall permit free motion of the altitude axis between 80° and -5° from zenith. 50
4.7.3.9.2 The Cable Drape shall permit the PS4 yoke to move relative to the dome in azimuth. 50
4.7.3.9.3 The Cable Drape shall contain and guide all cables and utilities required for the PMA, M2, Center Section, Truss, Spider Vanes, Filter Mechanism, Camera Shutter, LCC and GPC. 50
4.7.3.10 The Telescope Cable Wrap shall contain and guide all cables and utilities required for the Altitude Axis, PMA, M2, Center Section, Truss, Spider Vanes, Filter Mechanism, Camera Shutter, LCC and GPC 50

4.8 Personnel safety requirements 50
4.8.1 Response to an open Interlock shall result in controlled stop of all telescope axes and application of all axis-brakes 51
4.8.2 The telescope altitude axis shall have pinned locations at 0° and 75° zenith angle for service. 51
4.8.3 The state of locking pins shall be remotely sensed to prevent the enabling of their respective axes when the pin is engaged. 51
4.8.4 The telescope axes shall have brakes to prevent unwanted motions of the telescope and enclosure. 51

4.8.5 Manual over-rides of telescope axes brakes shall be monitored by a safety interlock system. 51

4.9 Packaging requirements 51

4.9.1 Parts for the telescope must be compatible in envelope and weight with shipment over U.S. roads. 51

5 TELESCOPE COORDINATES 51

6 COMPLIANCE MATRIX 52

7 NOTES 63

7.1 Telescope Image Budget Summary 63

7.2 Telescope Throughput 65

7.3 Motor drive acceleration and maximum velocities 67

8 ACRONYMS 69

List of Figures

Figure 1. Telescope Subsystem Block Diagram. 6

Figure 2. Typical mean wind speeds on Mauna Kea, top is CFHT site data bottom is UKIRT site data. 9

Figure 3 Diurnal temperature variation on the summit of Mauma Kea 10

Figure 4. PS4 Telescope Envelope 12

Figure 5. PMA Envelope 13

Figure 6. The mechanical layout of the primary mirror (PSTD-020-001 sheet 1). 17

Figure 7. The M1 support pad locations (PSTD-020-001 sheet 2). 18

Figure 8. The location of the M1 lateral supports (PSTD-020-001, sheet 3). 19

Figure 9. The PS1 Secondary Mirror Blank Dimensions 21

Figure 10. The Enclosure Control Interfaces 37

Figure 11. Physical layout of the Lower Cassegrain Core Subsystems (PSTD-240-001) 40

Figure 12 LCC Interface Control Document 41

Figure 13. Upper Cassegrain Core ICD 43
Figure 14 PS4 Baffle Design 46
Figure 15 Physical Layout of the M1 Baffle 47

List of Tables

Table 1. PSDC Documents 1
Table 2. PSTD Documents 2
Table 3. External Documents 2
Table 4. Mirror Registration Stability 22
Table 5. Minimum Telemetry Data Rates 25
Table 6. Telescope Service Schedule 29
Table 7. The Telescope and Enclosure Control Interfaces 35
Table 8. Telescope and Enclosure Mechanical Interfaces 35
Table 9. Baffle Tolerances 44
Table 10. Instrument Cable Wrap Project Provided Cables 49
Table 11. Telescope Cable Drape Project Provided Cables 50
Table 12. Telescope System Compliance Matrix 52
Table 13. Telescope Image Budget 64
Table 14. Telescope Drive Accelerations and Maximum Velocities 67
Table 15. Pan-STARRS Acronym List 69

1 Scope of Document

This document describes the specifications for the Pan-STARRS telescopes for use in the 4 telescope array that is designated by the project as PS4. PS4 is to be housed in a common enclosure at the summit of Mauna Kea on the island of Hawaii. Despite having a different location (the summit of Haleakala), the specifications for PS2 are identical with those for PS4.

2 Referenced Documents

Table 1. PSDC Documents

Pan-STARRS ID	Title	Authors
PSDC-230-001	Science Goals Statement	Chambers
PSDC-250-002	The System Concept Definition	Burgett et al
PSDC-300-018	Power, Cooling, and Cable Wraps in the PS1 Telescope	
PSDC-300-024	The PS1 Lens Mount Designs	
PSDC-300-027	The PS4 Telescope Image Budget Allocations	Morgan
PSDC-330-001	The System/Subsystem Specification for the Pan-STARRS PS1 Telescope Subsystem	Morgan and Siegmund
PSDC-330-004	The Baseline Optical Design for PS-1	Morgan
PSDC-330-009	The PS-1 Corrector Lens Specifications	Morgan

Table 2. PSTD Documents

Pan-STARRS ID	Title
PSTD-020-001	PS1 Primary Mirror Blank
PSTD-020-003	PS1 Secondary Mirror, Ribbed Meniscus Mirror Blank
PSTD-240-001	CC Rotator, Design Subsystem Envelopes
PSTD-360-002	PS4 Integrated Sky Probe ICD
PSTD-540-001	PS4 PMA Envelope
PSTD-600-002	PS4 Upper Cassegrain Core ICD
PSTD-620-030	PS4 Lower Cassegrain Core ICD
PSTD-660-001	PS4 M1 Baffle ICD
PSTD-700-001	PS4 Filter Mechanism ICD
PSTD-730-000	PS4 Giga Pixel Camera ICD
PSTD-780-001	PS4 Telescope Envelope

Table 3. External Documents

Source Reference	Title	Authors
M3 Doc. Ref. No. - Concept. Design	Conceptual Facility Design & budget Estimate Common Enclosure, Mauna Kea, Hawaii	M3
NOADC-M-4.0.ZMX	The Zemax Optical Layout	The Project
Da Silva and Businger, 2006	Climatological Analysis of Meteorological Observations at the Summit of Mauna Kea	Da Silva and Businger, Univ. of Lisbon Physics, July 2006.
ASME Y14.5.1M-1994	Mathematical Definitions of Dimensioning and Tolerancing.	

3 Introduction

The University of Hawaii, Institute for Astronomy (IfA) is constructing a ground-based telescope system for the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) Project. A description of the Pan-STARRS Project can be found at http://pan-starrs.ifa.hawaii.edu/. The Pan-STARRS Project has already constructed a prototype telescope called PS1 that is located at the summit of Haleakala on the island of Maui. The specifications for this telescope and for all of its associated instrumentation were given in the document PSDC-330-001. The top level requirements for Pan-STARRS are found in PSDC-250-002.

The Pan-STARRS project will supply the cameras, filter mechanisms, shutters, and auxiliary instrumentation such as the Sky Probes. These specifications will supply the mechanical interfaces to this instrumentation.

Our experience with the construction of PS1 leads us to the conclusion that it is efficient for the Project office to continue to take responsibility for the fabrication and delivery of the telescope optics. The specifications shown here reflect that. Other than the mechanical interfaces to the optics, the specifications for the optics themselves are not provided here. That does not mean that vendors should be unaware of the telescope's optical design. A description of the optical design of the telescope can be found in PSDC-330-004 and in PSDC-330-009.

3.1 System Overview

Each telescope in the PS4 array consists of a 1.8m telescope with a $7\ \deg^2$ field of view (FOV). Behind each PS4 telescope will be mounted a 1 billion pixel (giga-pixel) CCD camera with low noise ($\sigma_r \leq 6\ e^-$) and rapid read-out (~7 seconds), an automated filter changing mechanism and a wide-field shutter. During normal survey operations, all four telescopes will point towards nearly the same point in the sky and take simultaneous images of the same FOV through the same filter band-pass. The pipeline software for PS4 will combine these four images into a single co-added image with detector gaps and artifacts removed. The combined image will then be used to form a difference image with a static sky image acquired from previous observations. Temporal changes in the night sky will then be detected and catalogued in real time from the difference image. The project is supplying the Image Processing Pipeline (IPP) that will combine and difference the sky images in real time. The Project will also provide software that will coordinate the observations of all four telescopes and schedule their observations based on the project science goals and weather. However, it is expected that the telescope vendor will supply low level telescope control software that will interface to the Project-supplied software. Below in Figure 1 the vendor-supplied Telescope Control System is denoted by TCS. The Dome Control System (DCS) will be supplied by the enclosure vendor and is not part of the telescope specification. Interface control documents between Project-supplied and vendor-supplied software are subject to negotiation between the telescope vendor and the project office.

Figure 1 is a block diagram that serves to illustrate the basic conceptual design for each telescope in the PS4 array. 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 PS4 telescopes are to be conventional Cassegrain layouts with a 3 element corrector on an alt-az mount in a dome with an enclosure shutter. Note that with the PS4 common enclosure concept, the dome is not co-rotational with the telescopes. In Figure 1 L1 and L2 denote the first two corrector lenses. 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.

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 Pan-STARRS project will provide the Lower and Upper Cassegrain Core structures that support the corrector lenses and the instrumentation. The telescope vendor is expected to provide the M1 mirror cell and instrument rotator to which these two structures mount. Therefore, this document defines the following important mechanical interfaces:

- The LCC to Instrument Rotator Mechanical Interface (LCC MI in Figure 1).
- The UCC to M1 mirror cell Mechanical Interface (UCC MI in Figure 1).
- The M1 mirror to M1 mirror cell Mechanical Interface (M1 Support in Figure 1).
- The M2 mirror to M2 mirror cell Mechanical Interface (M2 Support in Figure 1).
- The M1 baffle to UCC Mechanical Interface (B1 MI in Figure 1).

The telescope baffle system will be a 5-element Sloan-like design (denoted by B0-B4 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 with vendor-supplied software, but the remainder of these sensors shall be monitored with Project-supplied software.

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 4.7 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 components responsible for the high-level automatic control of the observatory. The DHC is part of the camera control software. The TCS and the DCS represent low-level programs that control both the telescope and enclosure hardware. The TCS software will be supplied by the telescope vendor. Almost all user intervention to the vendor-supplied software will be done with Project-supplied software with possible exceptions to this during maintenance, servicing, and engineering efforts.

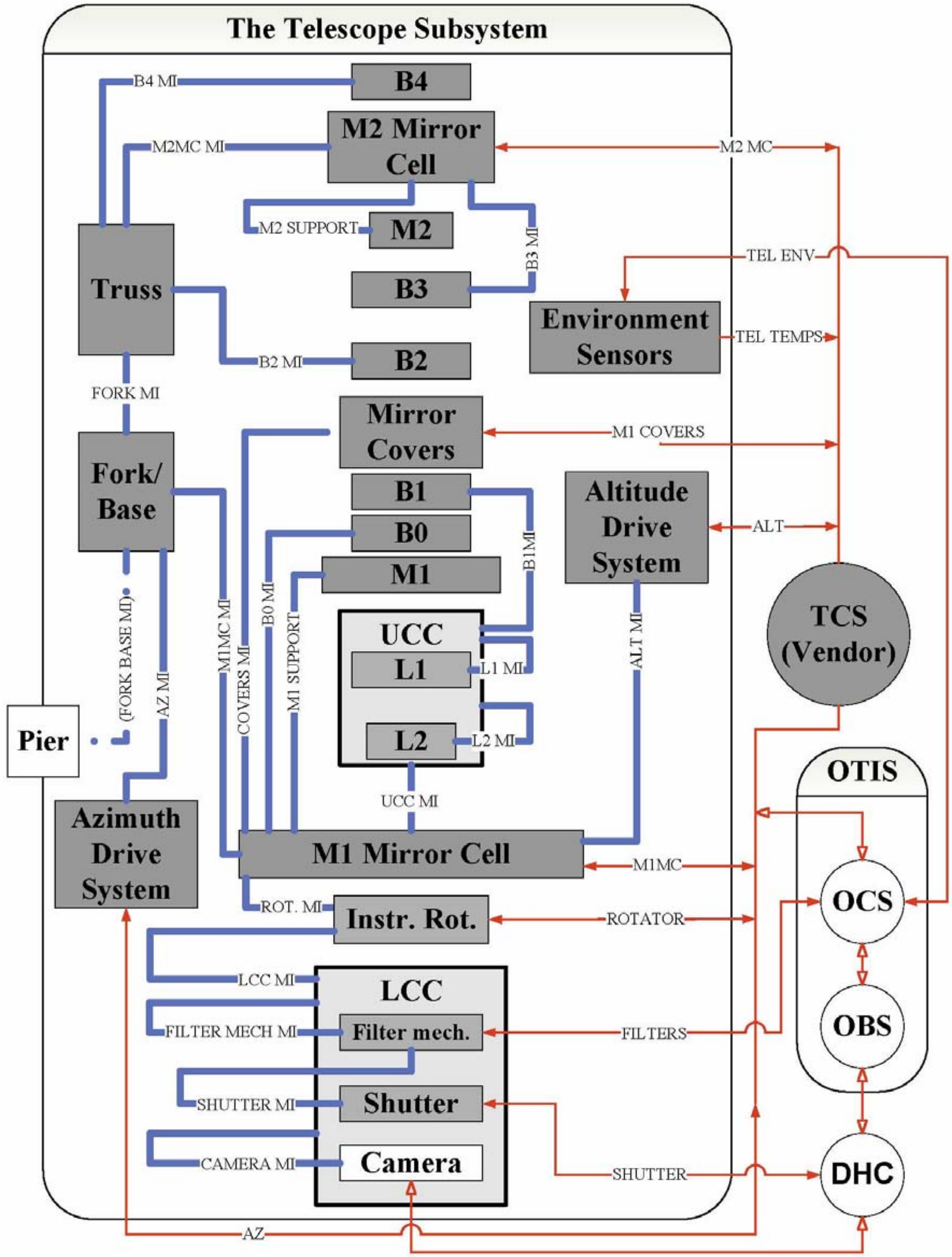


Figure 1. Telescope Subsystem Block Diagram.

The support space for the PS4 telescope will not 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 dedicated Pan-STARRS coating facility. Instead, the mirrors will be taken to other facilities 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 for the handling of the mirrors and Cassegrain Core components. The telescope vendor shall provide the handling carts or lifting fixtures for the installation of the primary and secondary mirror cells onto the telescope.

3.2 Document Overview

The Pan-STARRS System/Subsystem Specification (SSS, PSDC-330-001) contains a complete specification of the Pan-STARRS system designed to meet the top-level specifications and operational requirements contained in the System Concept Definition (SCD, PSDC-250-002). The requirements flow begun in the Science Goals Statement (SGS, PSDC-230-001) 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 and its mirror support systems. This document will not specify the camera itself, the software that runs the telescope, the filter changing mechanism, the camera shutter mechanism, nor the support spaces that will be in close proximity to the telescope enclosure.

These requirements serve as requirements to vendors who will be bidding and building components for the project.

4 Requirements

The requirements summary given here flow down and are derived in large part from the top-level telescope requirements and the conceptual design given in the PS4 SCD.

4.1 Environmental Requirements

Observations will be performed only while weather is permitting. The requirements of this document shall be met over all operational (observation) environmental requirements specified below.

4.1.1 The telescope shall operate at 4267 meters (14000ft) elevation.

Care must be taken to ensure reliable operation at the installation elevation of Mauna Kea. Cooling capacities for electronics, in particular, must be de-rated to function properly in the thin air environment. Careful selection of computer hard drives is required to operate at this elevation.

4.1.2 PS4 will observe in winds averaging 10m/s (22 mph) or less with gusts not to exceed 15m/s (34 mph)

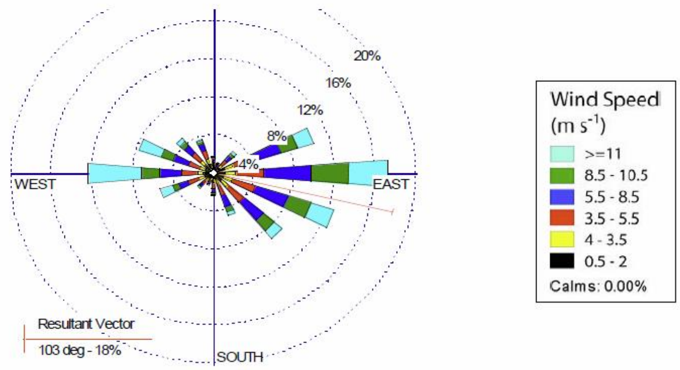
Reduced image quality is permitted by wind loading as defined in paragraph 4.5.4.5. This limit was derived based on historical records of mean wind speeds on the summit of Mauna Kea. These records indicate that wind speeds are at or below this level ~85% of the time on the summit (based on Figure 20 of Da Silva and Businger, 2006). This figure is reproduced below in Figure 2. The gust limit is based on the rough rule of thumb that maximum wind gusts are typically 1.5 times the mean wind speed.

4.1.3 The environmental temperatures will be between 5° and -10°C during observations

The summit of Mauna Kea has an average temperature of 0° C, a diurnal variation of 5° C. These variations are described below in Figure 3. Typical dusk to mid-day temperature differentials are 4° C.

4.1.4 All mirror components shall be operable after the application of seismic forces 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.



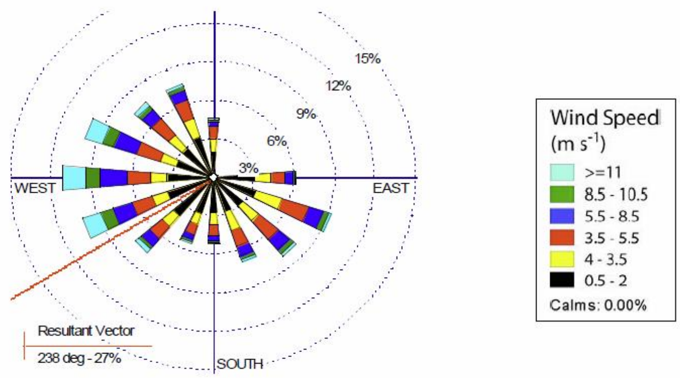


Figure 2. Typical mean wind speeds on Mauna Kea, top is CFHT site data bottom is UKIRT site data.

4.1.5 Observations will be performed in relative humidity of 80% or less

The Mauna Kea summit has a relative humidity that is low (36%) and nearly constant throughout the year. Observations will be suspended if the relative humidity exceeds 80%.

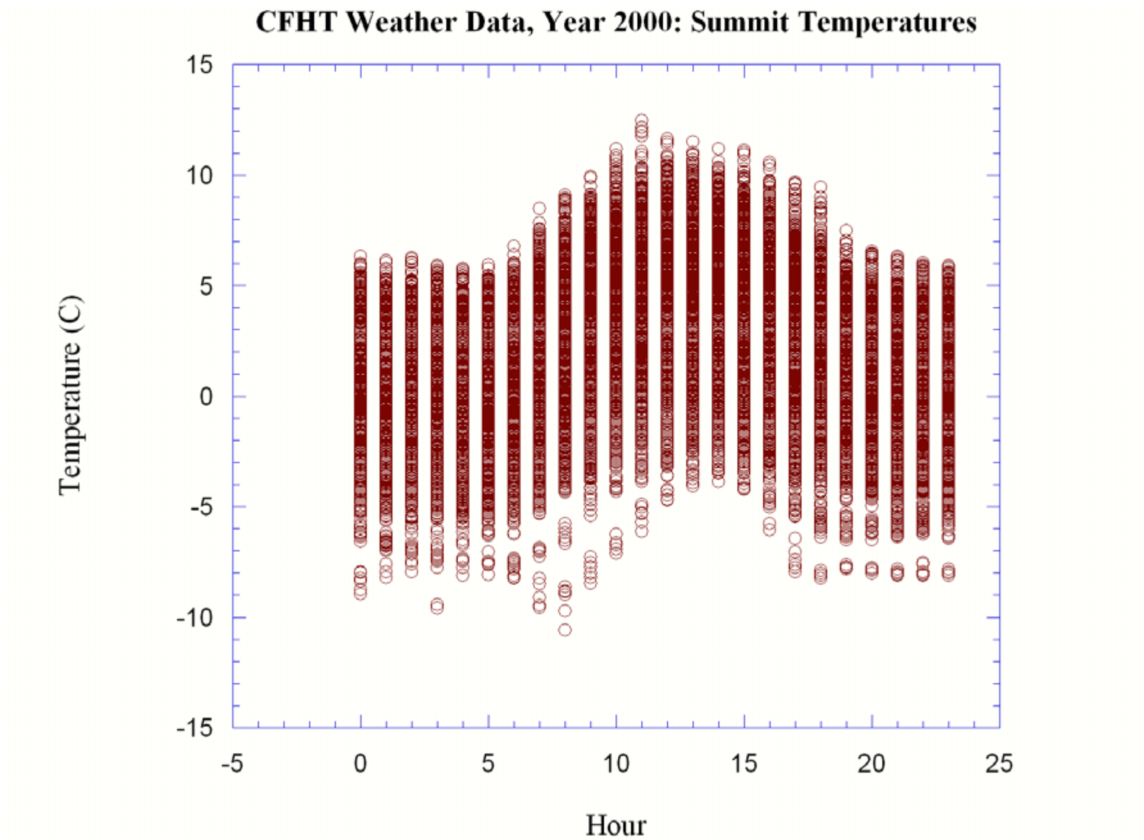


Figure 3 Diurnal temperature variation on the summit of Mauma Kea

4.2 System Requirements

The PS4 top level requirements are derived in part from the SCD top level requirements with the modifications mentioned above. The reasoning behind these requirements is that given in the SCD unless specially noted here. Some top level requirements given in the SSS are not reproduced here owing to the fact that they are not strictly the responsibility of the vendor. However, it is important for the vendor to be aware of these requirements so that they make efforts to avoid impairing the Projects ability to meet them. One example of such a requirement is that the PS4 telescopes will be used to achieve high precision photometry. Another example of a non-vendor requirement is that both the secondary and primary mirrors will be fabricated out of low-expansion type glass. Here the vendor must be aware of this requirement for the design of the mirror supports.

4.2.1 The telescope volume shall be contained within the dimensions given in PSTD-780-001

A copy of the volume requirements drawing for the PS4 telescopes is shown in Figure 4. The constraints are derived not only from the close packed geometry for the common enclosure, but also for the space available in the PS2 dome. The SR3000 and R2500 dimensions show in the drawing define the maximum swept volume for the telescope. Note

1 is a reference for the integration into the dome and the allowable clearances between the telescope and the dome.

Note 3 is a product of the space available in the PS2 Dome to allow clearance between the Primary Mirror Assembly (PMA) and the dome for installation. The thinner the yoke of PS4 the longer the PMA can be.

4.2.2 The PMA volume shall be contained within the dimensions given in PSTD-540-001

A copy of the volume requirements drawing for the PS4 telescopes is shown in Figure 5. The constraints of the PS2 dome define the length and width of the PMA. The overall length can be made longer, if the yoke dimension is thinner. The width is defined as maximum width to pass through the columns supporting the dome. The overall height of the PMA is To Be Determined (TBD) and constrained by the vendor's design spacing between the floor of the yoke and the bottom of the center section with the PMA on the service cart.

4.2.3 The telescope aperture shall be 1.8 m in diameter

This is not a vendor requirement and is stated here for information purposes.

4.2.4 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.

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

This is not a vendor requirement and is stated here for information purposes.

4.2.6 The telescope focal length shall be 8.0m

This is not a vendor requirement and is stated here for information purposes.

4.2.7 The PS4 telescope shall utilize an altitude-over-azimuth mount.

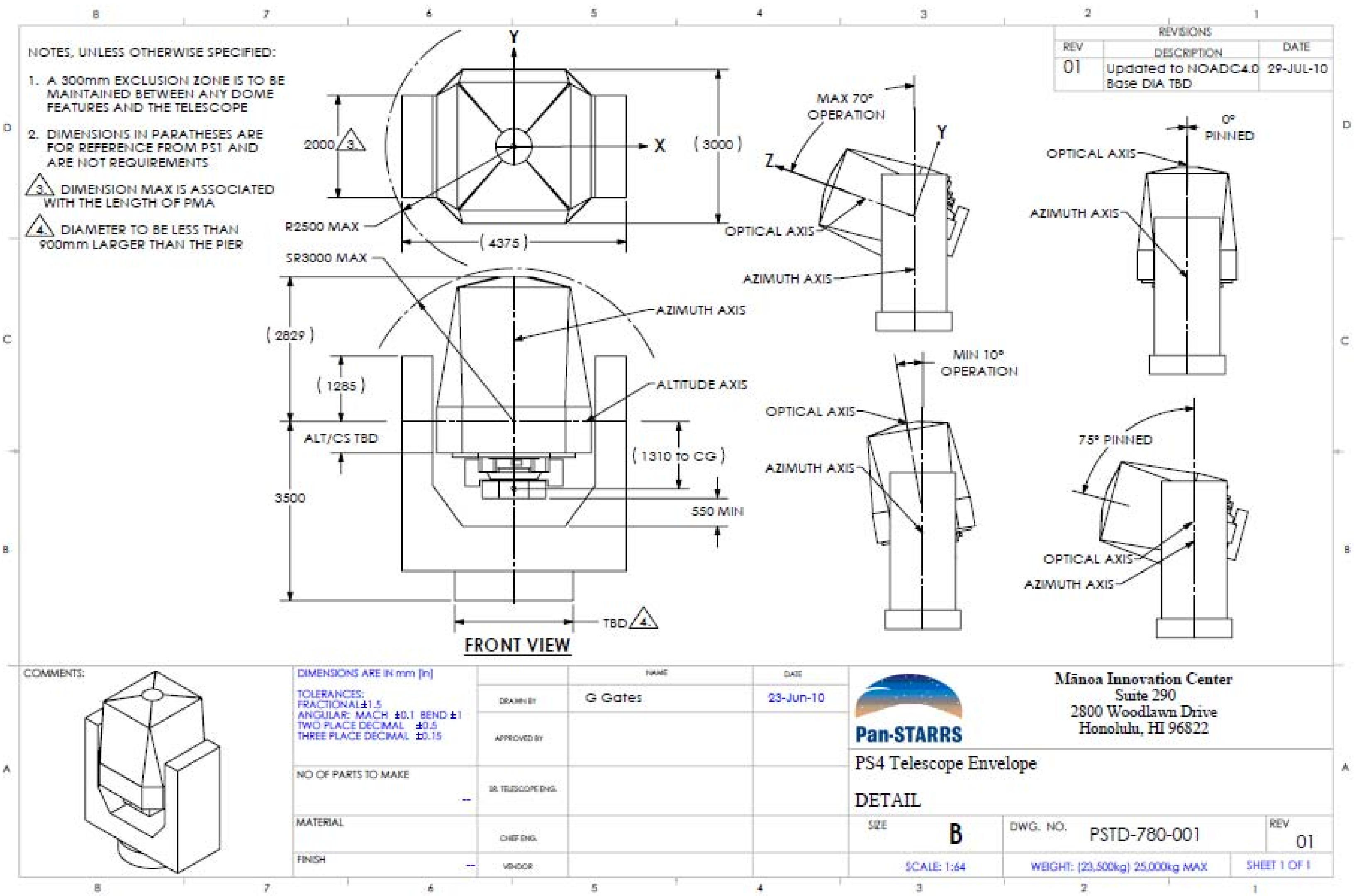


Figure 4. PS4 Telescope Envelope

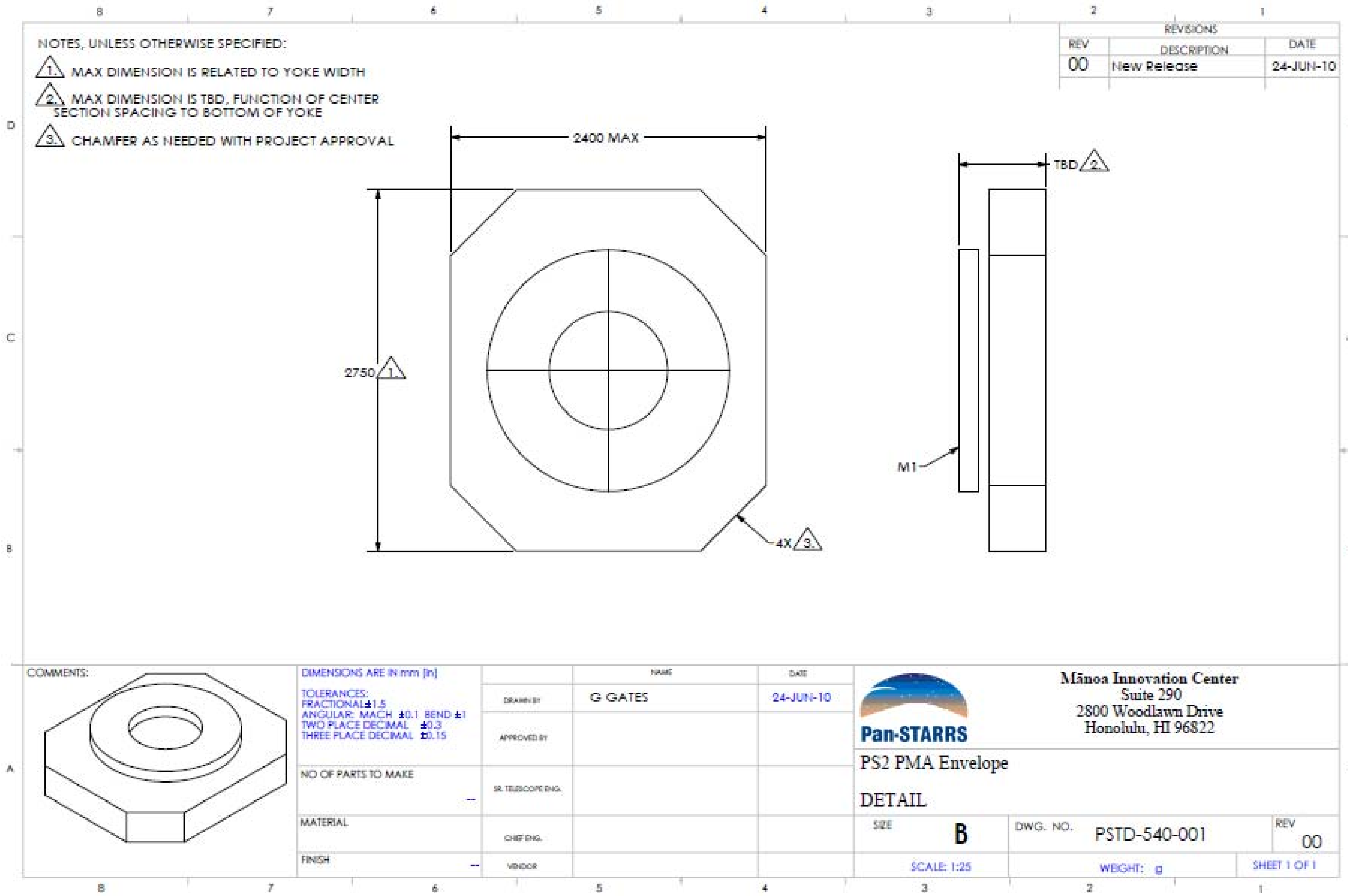


Figure 5. PMA Envelope

4.2.8 The PS4 stray light management shall include a fully baffled focal plane, contamination control and other measures to mitigate the impact of stray light.

Details of the baffles are given below in section 4.7.3.5. Note that while the construction and details of the telescope baffles are the responsibility of the vendor, the baffle concept is supplied by the Project.

4.2.9 The PS4 state and errors shall be reported and logged.

The meanings of the messages logged are to be clear to the specific state being reported and not subject to interpretation.

4.2.10 The telescope shall be remotely operable.

Provisions will be provided to eliminate on-site operator interaction with the telescope to clear system faults.

4.2.11 The Telescope Control Computer (TCC) shall be remotely bootable from an "off", "protected" or "hibernating" state (see paragraph 4.2.25).

4.2.12 The telescope and TCC shall recover from a power outage without personnel on-site.

4.2.13 PS4 telescope shall support maintenance and service.

Close attention will be paid to the location and access to components housed within the telescope structure. Reasonable access will be provided in the design to reach, test and replace any item that may require service. Disassembly of telescope sub-systems to gain access to serviceable items is strongly discouraged as a design approach.

4.2.14 All lubricants used within the telescope shall be low temperature compatible and the lubricants within purchased components shall be replaced with low temperature compatible lubricants during construction.

4.2.15 All heat sources on, in or near the telescope shall be contained in air tight, temperature controlled enclosures.

The exceptions to this requirement are the drive motors themselves. The allowable heat from sources inside the telescope that are not in controlled environments shall be less than 50 Watts. The allowable uncontrolled heat from sources nearby the telescope shall be less than 200 Watts. The primary intent of this specification is to limit heat sources near the optical path of the telescope. This is especially important for electronics inside and on the outside of the primary mirror assembly. The secondary intent is to limit heating in the dome which could have an impact on dome seeing.

4.2.16 The altitude and azimuth axes of the PS4 telescope shall have maximum velocities ≥ 1.0°/second and ≥ 2.0°/sec, respectively.

The impacts of this requirement are discussed in section 7.3 of the Notes section below.

4.2.17 The PS4 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. The telescope move will begin while the telescope is tracking at a sidereal rate. The open loop tracking errors are specified in paragraph 4.5.4.4. 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.

4.2.18 For intermediate step angles (from 0.002 to 0.01 degrees) the PS4 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 4.5.4.4. 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.

4.2.19 For small step angles (from 0.00003 to 0.002 degrees) the PS4 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 4.5.4.4. 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.

4.2.20 The telescope mirror cell design shall be compatible with the PS4 primary mirror blank.

The physical dimensions of the M1 mirror blank are described in PSTD-020-001. This drawing is reproduced below in Figure 6. The weight of the M1 mirror blank is approximately 1100 lbs (500kg). 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. The PS2 and PS4 primary mirrors are identical with the PS1 primary mirror.

4.2.21 The M1 Support shall be compatible with the location of the primary mirror support pads given in PSTD-020-001.

The M1 Support is defined in Figure 1 as the mechanical interface between the primary mirror and the telescope primary mirror cell. Figure 6 is a reproduction of PSTD-020-001, sheet 1. This figure shows the physical dimensions of the PS4 (and PS1) primary mirror blanks. Figure 7 is sheet 2 of this same drawing set. This figure shows the location of the axial support pads used during the polishing of the PS4 primary mirrors. The axial pads are invar blocks machined to fit the meniscus shape of the mirror backside and glued to it with Hysol, a high strength epoxy. The lower sides of these Invar blocks are smooth cylindrical surfaces at two different levels, corresponding to the inner and outer ring of support pads. Figure 8 (sheet 3) shows the locations of the lateral support pads. These are also Invar cylinders epoxied to the mirror at the given locations. Note that in Figure 8 the axial pads have been omitted for clarity. The figure shows the mirror in the same views as in Figure 7.

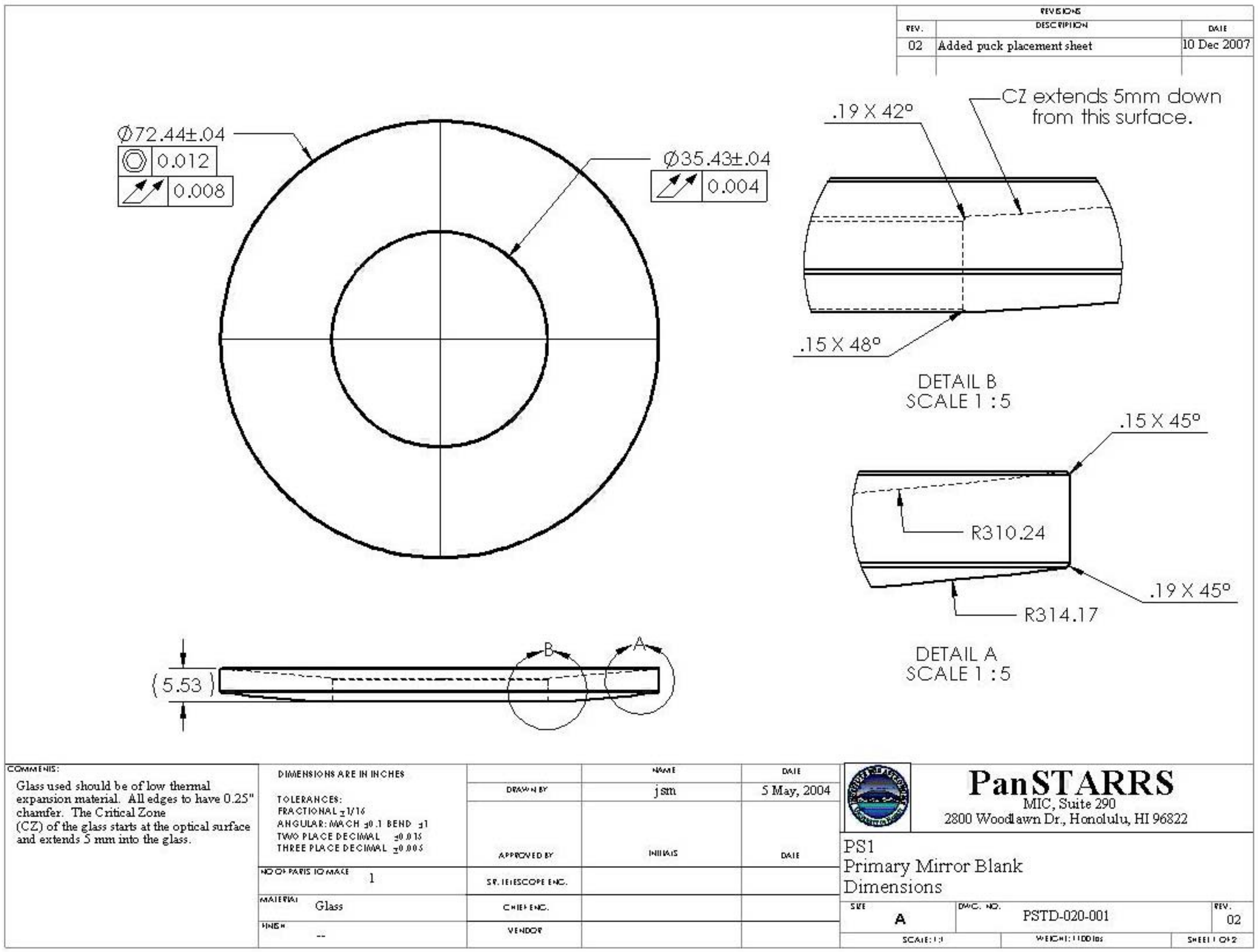


Figure 6. The mechanical layout of the primary mirror (PSTD-020-001 sheet 1).

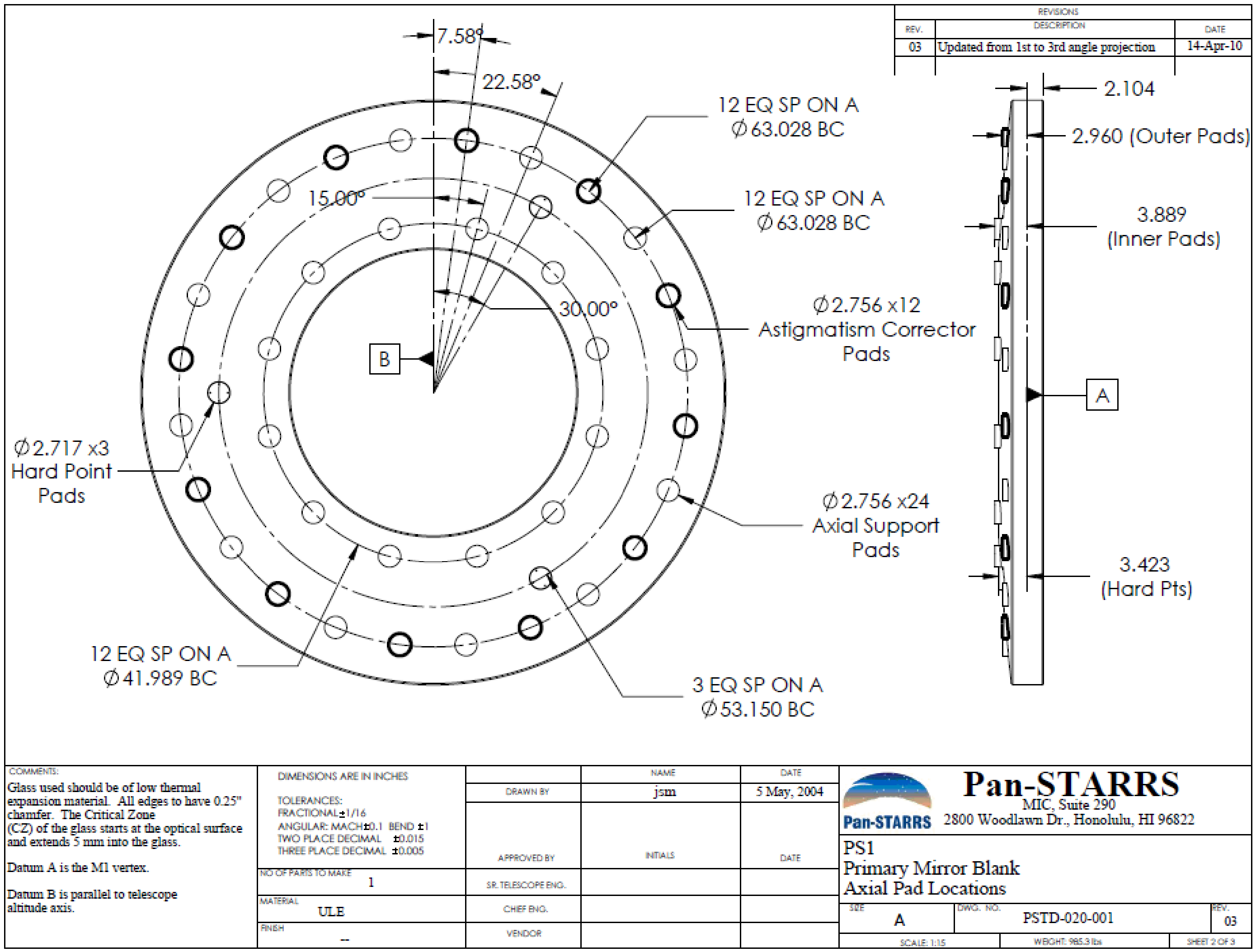


Figure 7. The M1 support pad locations (PSTD-020-001 sheet 2).

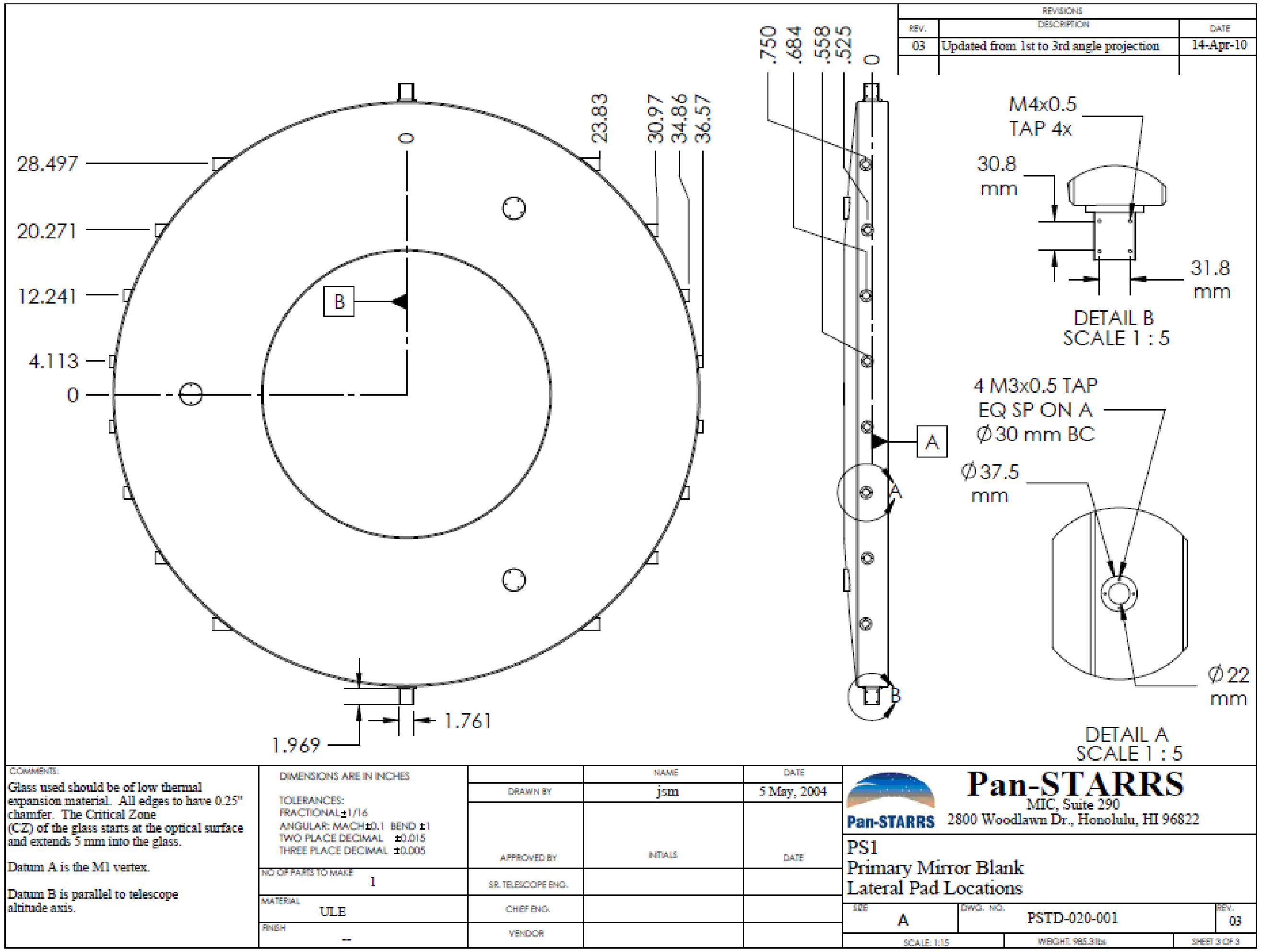


Figure 8. The location of the M1 lateral supports (PSTD-020-001, sheet 3).

4.2.22 The telescope secondary support structure shall be compatible with the PS4 secondary mirror blank.

The physical dimensions of the M2 mirror blank are described in PSTD-020-003. This drawing is reproduced below in Figure 9. The weight of the M2 mirror blank is approximately 126 lbs (57kg). 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. The PS2 and PS4 secondary mirrors are identical with the PS1 secondary mirror.

4.2.23 The telescope fork assembly shall allow a minimum clearance of 21” (550mm) between the bottom of the instrument package and the top of the fork when the telescope is at zenith.

The bottom of the Giga-Pixel Camera (GPC) forms the bottom of the instrument package. This specification allows sufficient room for the installation of the GPC with a wheeled cart while the telescope is pointed toward zenith. Note that this specification will be met by designing to the instrument package envelopes that will be supplied by the Project. See the Project technical representative for drawings and SolidWorks part and assemblies of the instrument package envelopes.

4.2.24 The telescope fork assembly shall provide a swing clearance ≥ 6” (150mm) with a solid fork bottom.

This refers to the minimum clearance between the bottom of the instrument package and the fork at all altitude angles. It is anticipated that this specification will automatically be met if specification 4.2.23 is satisfied. The fork structure may have a hole in it if the vendor sees fit, but if such a hole exists the vendor should provide a cover for this whole that is capable of fitting flush with the rest of the fork base. This cover must be capable of supporting the weight of the camera assembly and its cart.

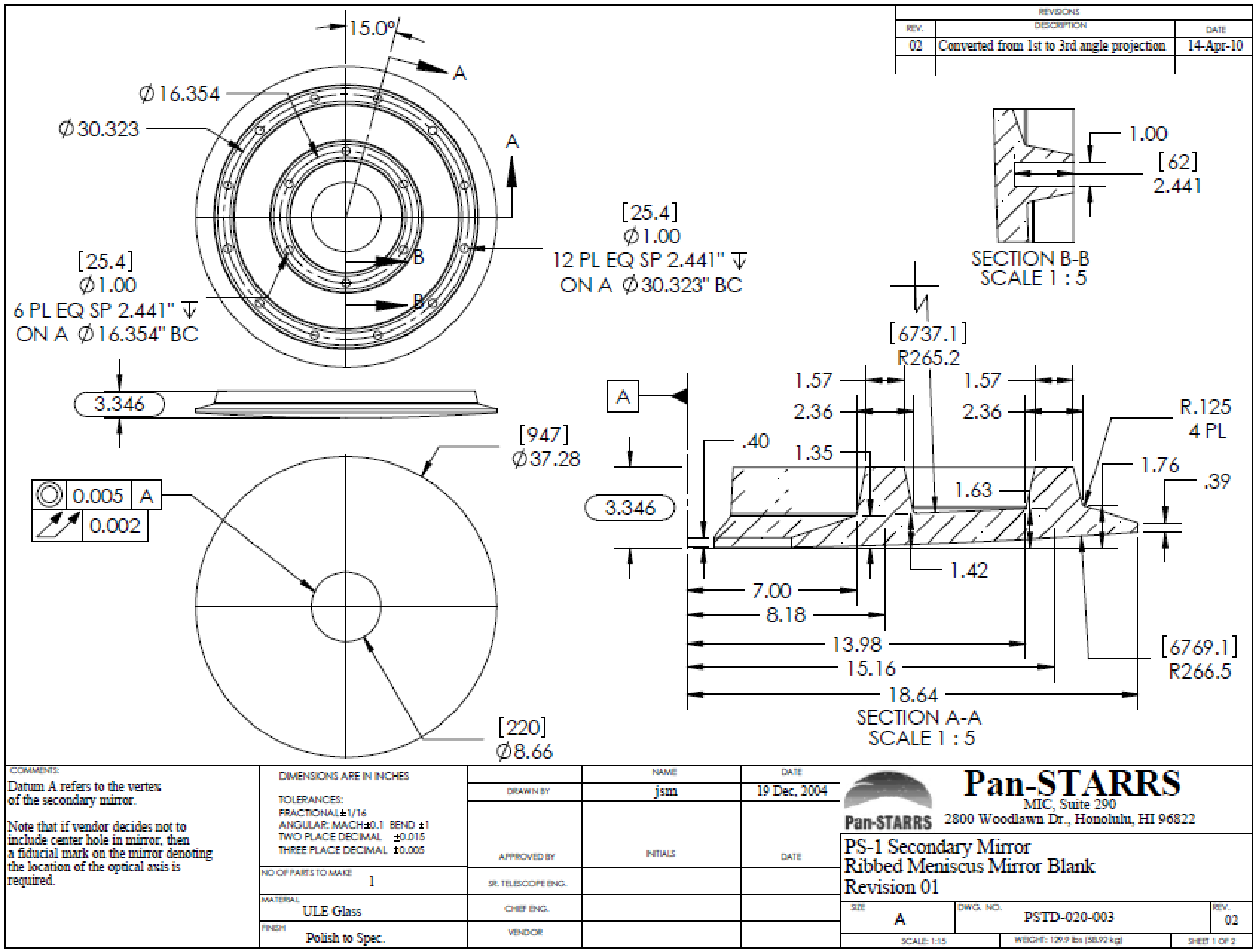


Figure 9. The PS1 Secondary Mirror Blank Dimensions

4.2.25 The telescope structure and mirror supports shall maintain the registration of the secondary mirror to the values in Table 4 without adjustment of its actuators

This specification is based on the range of motion specified for the M2 actuators. This motion will be characterized by the mount model and alignment will be maintained over the operational altitude range. Any non-repeatable motion of M2 contributes directly to the telescope pointing requirements in paragraphs 4.5.4.1 and 4.5.4.2.

Table 4. Mirror Registration Stability

Relative Displacements (10° to 70° zenith angle)		Maximum Flexure Motion
M2 to PMA	Focus	2000 μm
	Decenter	1000 μm
	Tilt	100 arcsec

4.2.26 The secondary spider supports shall be insulated or made of low CTE material.

Temperature changes in the spider vane supports can cause significant and rapid changes in the telescope focus and pointing. If the vanes are to be made from steel or aluminum, insulation of the vanes should be sufficient to provide time constants of ≥ 30 minutes for changes in the vane metal or simulations must be made to show that the vane material has sufficient thermal inertia to achieve such a time constant. If a low CTE material such as carbon fiber is used for the secondary support vanes, then no insulation is required.

4.3 Required States and Modes

The SCD calls out several operational states for the telescope/enclosure subsystem. 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. The telescope states are controlled via the Project-supplied software with the exception of telescope interlock system. The operational states for the PS4 telescope are as follows:

4.3.1 Observing Mode

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 Project-supplied software that they are operational. User intervention via the Project-supplied software 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.

4.3.2 Calibrating State

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 Project-supplied software and by user intervention via the Project-supplied software.

4.3.3 Hibernating State

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

4.3.4 Protected State

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 Project-supplied software.

4.3.5 Servicing Mode

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 Project-supplied software.

4.3.6 Off State

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 Project-supplied software or long-term failure of power to the site.

4.3.7 Failure State

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 Project-supplied software. It can only be exited through user intervention.

4.4 Software Requirements

This section describes requirements on the vendor-supplied telescope software (SW).

4.4.1 The Vendor shall supply low level telescope software that will interface to the Project-supplied SW.

4.4.2 The Vendor shall provide a SW interface allowing control of the telescope subsystems with minimum latencies by the Project-supplied SW.

This interface shall include access to the servo controllers, the secondary mirror controller, the primary mirror controller, the temperature monitors and the primary mirror cover controller.

4.4.3 The Vendor-supplied interface(s) should provide the capability for the Project to add a minimum of eight (8) new data sources

The update rates for new data sources are expected to be between 0.1-10 Hz. Details to be determined after contract award. It is expected that these data sources would most likely be extra temperature sensors.

4.4.4 The Vendor shall provide interface control descriptions (ICDs) between Vendor-supplied and Project-supplied SW.

4.4.5 The Vendor-supplied SW shall provide the capability to control velocity, acceleration, and position of all telescope axes for celestial tracking.

The Vendor-supplied SW should have the capability to provide all celestial tracking.

4.4.6 The Vendor-supplied SW shall provide the capability for Project-supplied SW to control velocity, acceleration, and position of all telescope axes in real time.

4.4.7 The Vendor-supplied SW shall provide the capability for Project-supplied SW to read and control all control loop parameters and diagnostics.

This requirement is directed primarily towards providing access to PID loop control parameters to the servo motors.

4.4.8 Vendor-supplied SW shall use velocity commanded control with position feedback as opposed to position/time command control.

Velocity commanded control is common among the telescope community and has several advantages. With position/time mode there is an inherent latency between the time an offset is sent and the time it appears in the position/time track that the low level software is following.

4.4.9 The Vendor-supplied SW shall include any software needed for PID tuning of each servo axis.

4.4.10 The Vendor-supplied SW shall include software that is required to move each axis under computer control.

4.4.11 The Vendor-supplied SW shall include the capability to monitor all of the raw encoder counts, motor currents, and pressure and temperature sensor data.

The following minimum data rates shall be accommodated:

Table 5. Minimum Telemetry Data Rates

Telemetry Source	Minimum Data Rate (Hz)
Motor Currents	100
Encoder Position	10
Pressure Sensors	1
Temperature Sensors	0.1

4.4.12 The Vendor-supplied interface(s) shall support Linux-based Project-supplied SW.

4.5 System Capability Requirements

4.5.1 Image Quality

The requirements presented in this section are vendor specific specifications that contribute either directly or indirectly to the image quality. A detailed discussion of the PS4 image quality error budget can be found in PSDC-300-027.

The Project's telescope image budget summary is given in the notes section of this document (Section 7), including a description of how to interpret and translate the PSF related values given in the requirements below. This information is also available in PSDC-300-027.

4.5.1.1 The support of the primary mirror shall contribute ≤ 0.025 µm RMS surface errors to the primary surface near zenith and ≤ 0.060 µm RMS surface errors at a zenith angle of 70°.

This requirement is from the RSS combination of the primary mirror actuator, axial, and lateral support errors given in PSDC-300-027. These RMS surface error values correspond to spot radius errors of ≤ 1.12 µm RMS near zenith and ≤ 2.36 µm RMS at 70° zenith angle.

The translation between these two values comes from ray trace tolerances assuming variations in coma, astigmatism, trefoil, and quatrefoil.

4.5.1.2 The support of the secondary mirror shall contribute ≤ 0.050 µm RMS surface errors to the secondary surface near zenith and ≤ 0.070 µm RMS surface errors at a zenith angle of 70°.

This requirement is from the RSS combination of the secondary mirror actuator, axial, lateral support errors given in PSDC-300-027. These RMS surface error values correspond to spot radius errors of ≤ 1.31 µm RMS near zenith and ≤ 1.70 µm RMS at 70^{o} zenith angle. The translation between these two values comes from ray trace tolerances assuming variations in coma, astigmatism, trefoil, and quatrefoil.

4.5.1.3 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.

4.5.2 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.

4.5.2.1 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 Project-supplied software to keep the telescope in focus and in collimation at all times.

4.5.2.2 The secondary mirror 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”.

4.5.2.3 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.

4.5.2.4 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.

4.5.2.5 The y-translation of the primary mirror shall be automatically adjustable.

This axis shall be controlled by the Project-supplied software software via an interface with the TCS, as shown in Figure 1. The y-axis is perpendicular to both the altitude and optical axes of the telescope.

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

It is assumed here that these actuators shall be placed somewhere near the perimeter of the primary mirror. This precision and range therefore respectively correspond to an angular precision of 2.2 arcseconds and an angular range of 560 arcseconds.

4.5.2.7 The primary mirror x- and y-translation shall have a precision ≤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.

4.5.2.8 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.

4.5.2.9 The telescope primary mirror cell shall have a fiducial surface whose axial distance from the M2 actuator mounting surface is known to within ±150 µm.

This axial separation may be calibrated on-site or at the factory. But the Project will wish to review the process whereby this separation is measured if the vendor chooses to do this at the factory.

4.5.2.10 It is recommended that the telescope shall utilize a pneumatic support system for the primary mirror.

This is not a strict requirement. This type of a support system is preferred owing to its simplicity, low cost, proven functionality, and the potential lack of heat sources under the mirror. However, other types of systems will be considered for the design of these telescopes.

4.5.2.11 The air pressure and humidity 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 Project-supplied software. 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.

4.5.2.12 The primary mirror support shall incorporate a 12 point astigmatism correction system that attaches to the primary mirror.

4.5.2.13 The astigmatism correction system shall be controllable by the Project-supplied software software.

4.5.2.14 The astigmatism correction system shall be capable of correcting for a range of 2.0 waves of either astigmatism or trefoil errors in the telescope wave front to a precision of 0.05 waves.

4.5.2.15 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 0.5 waves without corrections from this system in order to allow the astigmatism correction system the capability of removing residual astigmatism in the optics.

4.5.2.16 The telescope telemetry of the primary and secondary mirror's position shall be independent of the mirror actuators.

The mirror actuators may use these same sensors to close their control loops, but the mirror position relative to the PMA reported by the telescope must be independent of assumptions about the actuator mechanics. This includes assumptions about gear ratios and motor positions.

4.5.2.17 The resolution of the primary mirror position measurement shall be ≤2 μm in translation and ≤0.5" in tip/tilt relative to the PMA

4.5.2.18 The resolution of the secondary mirror position measurement shall be ≤2 μm in translation and ≤1.0" in tip/tilt relative to the M2 mounting interface

4.5.3 Telescope Throughput

Section 0 details how we are defining the telescope throughput; this section defines vendor specific requirements with respect to 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. That is why issues such as servicing schedules are contained in this section.

Some issues relating to fundamental aspects of the telescope geometry are given in this section. Some issues, that might correctly be considered fundamental throughput issues, are not. Consistency in this regard is difficult owing to the broad reach of this topic. For example, the top level specification 4.2.3 states that the telescope aperture shall be 1.8m. This is effectively a telescope throughput specification. Another example is the 3^o step and settle specification for the telescope given in specification 4.2.17. This specification directly affects the efficiency at which the survey can be done. But other step and settle specifications deal more with guiding and tracking than they do efficiency so it was decided to leave them all in one place.

4.5.3.1 The obscuration from telescope secondary vanes and cone baffle supports shall be ≤1% at the edge of the telescope's field of view.

This requirement relates to the value of $\omega(\theta)$, which is defined in section 0. It specifically refers to the contribution of $\omega(\theta)$ that comes from the obscuration from the secondary vane and cone baffle supports. The current baffle design has $\omega(\theta_{max}) = 35.5\%$ where $\theta_{max}=1.65^o$. This requirement forces $\omega(\theta_{max}) < 36.5\%$.

4.5.3.2 The telescope drives, motors, amplifiers, encoders, bearings, compressors, actuators, and mirror supports shall have a cumulative MTBF of ≥ 450 hrs.

This requirement is justified in section 0 below. Note that this MTBF refers to the total telescope mount sub-system. Any individual telescope component must have a much greater MTBF to meet this cumulative specification. This MTBF refers to hours of operation, not calendar days.

4.5.3.3 Repair of a telescope failure between the service intervals given below in Table 6 shall not require more than 8 hours, assuming adequate spare parts are stocked at the observatory.

Table 6. Telescope Service Schedule

Service Interval	Service Tasks
1 week	Cleaning of primary mirror Water purging of air compressor holding tank
1 month	Re-collimation of telescope optics Pointing model recalibration
6 months	Lubrication of telescope bearings Cleaning of L1 corrector lens
Yearly	Replacement of air compressor belts Cleaning of air venting passage ways

Service Interval	Service Tasks
	Replacement of air compressor dehumidifying filters Purging and cleaning of M1 support pneumatic lines Flushing of glycol cooling lines Cleaning of encoder tapes Cleaning of secondary mirror Reattachment of mirror temperature sensors
5 Years	Replacement of M1 positioning servo motors Replacement of telescope limit switches Replacement of M1 support actuators Replacement of telescope signal conditioners Replacement of pneumatic tubing and pneumatic connection hardware Replacement of servo motor encoders Replacement of air compressor motor Replacement of UPS batteries
10 Years	Replacement of main telescope axes motors (altitude, azimuth, and instrument rotator servo motors) Replacement of servo controllers Replacement of major cable harnesses or cable wrap energy chains Replacement of TCC Re-leveling of telescope azimuth bearing

4.5.4 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 Project-supplied software 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 4.2.17 through 4.2.19 and the settling time required by the telescope structure and the mirror mounts will define these quantities.

4.5.4.1 The telescope pointing accuracy shall be ≤5 arcseconds 2-D RMS

This is an operational efficiency requirement which directly affects the system value of the parameter t_{closed} discuss in section 0. Note that this specification must also include contributions from the instrument rotator. For this reason, this specification will be verified NOT from the location of the GPC1 camera bore sight, but from a distance of 1.5^o from the camera bore sight.

4.5.4.2 The telescope pointing precision shall be ≤2 arcsec 2-D RMS over a week's time.

4.5.4.3 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 4.2.17.

4.5.4.4 Open-loop tracking error shall be ≤ 110 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 minimal impact on the telescope PSF. 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 0.078″ RMS, then the tracking errors increase the atmospheric motions by less than an 10%. To convert this to a 2-D number we multiply by $\sqrt{2}$.

This is the combination of the rotator, altitude and azimuth servo following errors combined with the appropriately scaled motions of M1 and M2. The motions of the mirrors will be measured as a combination of their required encoding for low frequency with accelerometers supplied by the Project for high frequency. The rotator following error motions are assumed here to apply to an outer radius of 220 mm on the focal plane. These motions are also assumed to apply to tracking near zenith. As detailed in PSDC-300-027 it is expected that tracking will improve at lower altitudes.

4.5.4.5 The wind-induced tracking error shall be ≤ 130 mas 2-D RMS near the operational zenith limit and shall be ≤ 230 mas at a zenith angle of 70°.

This tracking error is the RSS combination of the rotator, altitude and azimuth servo following errors combined with the appropriately scaled motions of M1 and M2 on their supports in the specified maximum operational wind conditions of 10 m/s.

4.5.4.6 The telescope shall be able to track between zenith angles of 10 and 70 degrees for periods up to 5 minutes without interruption.

This flows down directly from SCD requirement 5.2.11. This requirement influences requirements on the rotator limits (4.5.4.9) because of the upper limit on the zenith angles that the telescope is required to track to.

4.5.4.7 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. Note that the mechanical limits of the altitude axis must also be compatible with the pinning requirements given in 4.8.2.

4.5.4.8 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.

4.5.4.9 The instrument rotator operational limits shall be ≥ ± 96 degrees.

It is not planned to operate the instrument rotator beyond these limits, but limit switch actuation means the rotator will need to move slightly more than this operational limit. The intent of this restriction is to minimize the requirements for the cable wrap on the instrument rotator. These limits include a margin to allow tracking for approximately 5 minutes at a maximum rotator speed of 75 arcsec/sec once the rotator is initially positioned to ±90°. This speed corresponds to the maximum rotator speeds encountered near the zenith keyhole at 80° altitude.

4.5.4.10 The instrument rotator slew speed shall be ≥ 2.3°/sec.

Travel time from one end of the rotator limit to the other should be ≤ 84 seconds.

4.5.4.11 The instrument rotator shall support an out-of-balance torque load up to 50 ft-lbs (68 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 and by the camera shutter. These torques are not constant and cannot be passively counter-balanced because they change with the camera status. The filters weigh 15 lbs. The filter frames weigh 5 lbs. They move a total of 1.6 ft when placed in and out of the beam. The camera shutter blades weigh 1 lb and move about the same distance. The total active torque is therefore at least 34 ft-lbs. A safety factor of 1.5 gives a required torque of 50 ft-lbs. Counter-balance weights will be used to take care of static torque loads.

The application of this load should be considered for the tracking requirement in paragraph 4.5.4.4.

4.5.4.12 The instrument rotator shall support a load of 1660 lbs (753 kg) with a center of mass 17” (0.432 m) from its mounting face (datum A on the ICD).

This is the estimated weight and center of mass for the Lower Cassegrain Core instrument package. Motions resulting from this load are contributions to the focal plane stability requirements of paragraphs 4.7.3.1 and 4.7.3.2.

4.5.4.13 The telescope mirror cell shall support a load of 606 lbs (275 kg) with a center of mass 10.7” (271 mm) from the UCC mounting face (datum A on the ICD).

This is the estimated weight and center of mass for the Upper Cassegrain Core instrument package with the M1 baffle.

4.5.4.14 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 by the TCS to the bandwidth of the axis servo systems. The bandwidth of the axis servo systems is in large part determined by specification 4.2.19.

4.6 The Telescope Temperature Monitors

The telescope temperatures are used to correct for thermal distortions of the telescope structure. The outputs of these sensors are processed through the telescope mount model to generate the corrections in the M1 and M2 positions.

4.6.1 All mirror and truss temperature sensors shall have a temperature accuracy of <0.3°C, resolution <0.02° C over a range of -10° C to +25° C.

It is acceptable for the vendor to require on-site calibration of these sensors to achieve the accuracy requirement, but a plan for access to all of the sensors and a calibration procedure would then be required for the on-site work. If the vendor chooses to do factory calibration of these sensors, then calibration data for each sensor shall be required. Some sensors, like those below the primary might be best done at the factory. Note that if RTDs are used for these sensors, the accuracy specification here requires at least Class A devices. 1/3 DIN devices or 1/10 DIN devices would be preferred. Class B devices are ruled out by this specification. Three or four wire connections to these sensors would be strongly preferred.

4.6.2 The primary mirror shall have a total of 8 sensors measuring radial temperature differences on the back side of the glass every 90° around its circumference.

It is intended that on four radii on the back of the primary mirror that there will be two sensors. One sensor will be placed near the perimeter of the primary mirror and the other will be placed near the primary mirror’s Cassegrain hole.

4.6.3 The secondary mirror shall have a total of 4 sensors measuring temperatures on the back of the glass every 90° around its circumference.

4.6.4 The secondary support cage shall have 2 sensors measuring the temperature of the support cage.

One of these sensors is to be placed as close as practical to the primary mirror and the second sensor is to be place as far as practical from the primary mirror.

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

If the spider supports are to be insulated as discussed in 4.2.26, then these sensors must measure the metal temperature below the insulation.

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

4.6.7 The temperature of each leg of the LCC shall be monitored.

This implies a total of 4 sensors for the LCC measurements.

4.7 System interface requirements.

Almost all of the external interfaces for the telescope are control interfaces with the observatory control software, Project-supplied software. In particular, the software interface between the Project-supplied software and the TCS is the most prominent external interface. 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. Almost all of the internal interfaces are mechanical interfaces. This division is the direct result of defining Project-supplied software as its own subsystem and the TCS as vendor supplied software.

4.7.1 Interface identification and diagrams.

Figure 1 in section 3.1 shows the telescope control interfaces as red lines. The arrows on these lines show the flow of control signals. In the same manner, Figure 10 shows the enclosure control interfaces. Once again, the control lines with open arrows are defined elsewhere. Table 7 is a summary of the control interfaces shown in both Figure 1 and Figure 10. Table 8 is a summary of the mechanical interfaces.

The only mechanical interface shown in Figure 1 that is not a telescope subsystem interface is the mechanical interface to the camera. This is shown in Figure 1 by the blue line marked “CAMERA MI”. This interface is not a concern to the vendor. The filter mechanism mechanical interface to the LCC (FILTER MECH MI), the shutter mechanical interface to the filter mechanism (SHUTTER MI), the L1 Cell mechanical interface to the LCC (L1 MI), and the L2 Cell mechanical interface to the LCC (L2 MI) are not the vendor’s responsibility even though these are telescope subsystem interfaces. The project is responsible for these mechanical interfaces.

Table 7. The Telescope and Enclosure Control Interfaces

Interface	Data/Commands		Data Flow
	Source	Destination	
Telescope Interfaces			
TCS	Project-supplied software	TCS	Bi-directional
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	Project-supplied software	Filter Mechanism	Bi-directional
CAM SHUTTER	Project-supplied software	Camera Shutter	Bi-directional
TEL TEMPS	Tel. Temp. Sensors	TCS	Uni-directional
TEL ENV	Tel. Env. Sensors	Project-supplied software	Bi-directional

Table 8. 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
B4 MI	Baffle 4	Truss
B3 MI	Baffle 3	M2 Mirror Cell
B2 MI	Baffle 2	Truss
B1 MI	Baffle 1	Upper Cassegrain Core
B0 MI	M1 OD Mask	M1 Mirror Cell
UCC MI	Upper Cassegrain Core	M1 Mirror Cell
L1 MI	L1 Corrector Lens	Upper Cassegrain Core

	Mating Parts	
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

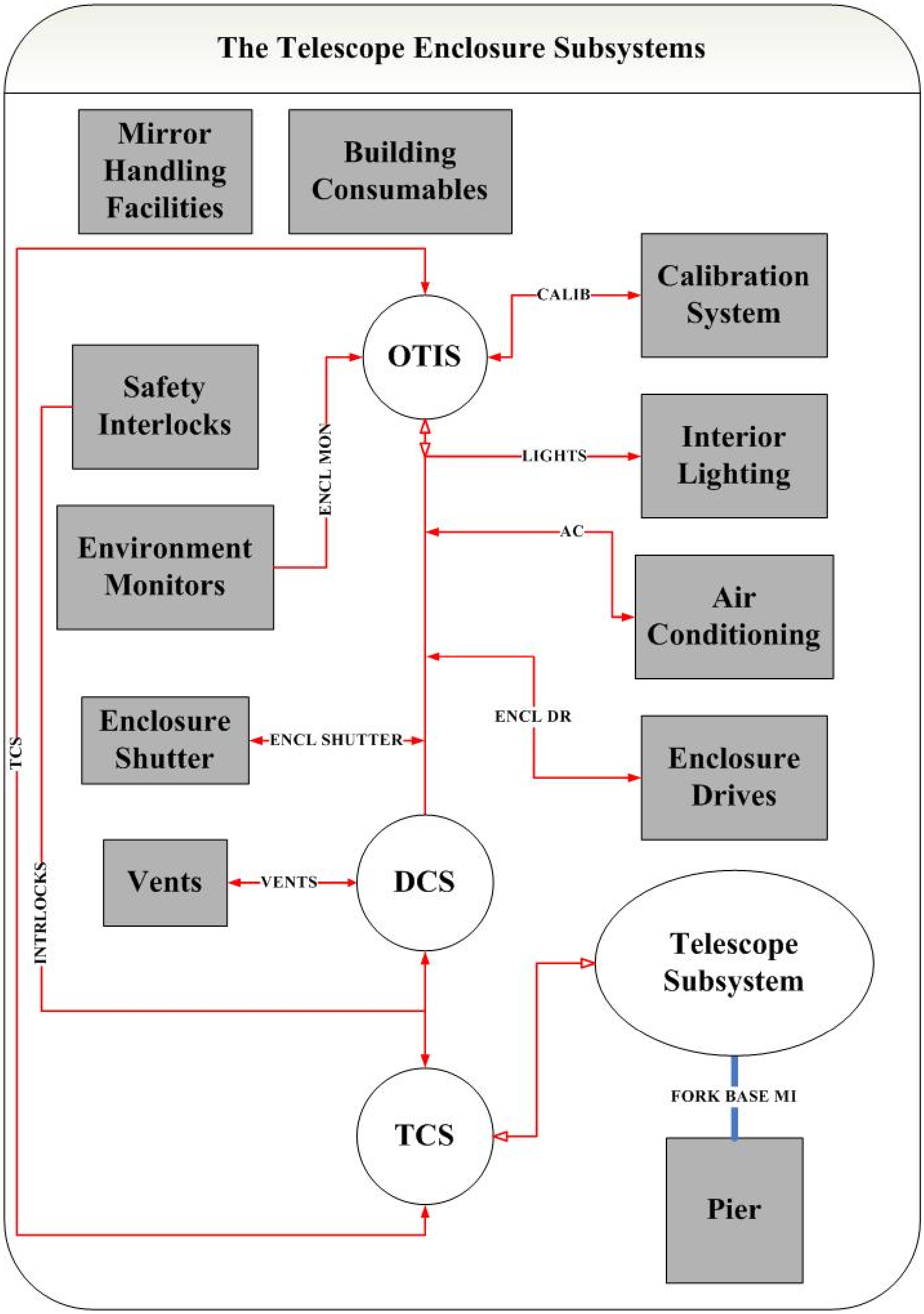


Figure 10. The Enclosure Control Interfaces

4.7.2 External interface requirements

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

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

4.7.2.3 The instrument rotator shall be remotely controllable with position and limit switch, and motor current feedback.

4.7.3 System internal interface requirements

Figure 1 in section 3.1 and Figure 10 in section 4.7.1 show internal (mechanical) interfaces as blue lines. Table 8 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.

4.7.3.1 The instrument rotator shall maintain the position of the camera focal plane to ≤40µm over its full range of motion and altitude operational range of motion.

This defines the radial runout of the instrument rotator and flexure of its mounting interface over the full range of motion of the telescope. This value represents the pointing uncertainty of 1" given the plate scale of the camera.

4.7.3.2 The instrument rotator shall maintain the parallelism of the LCC mounting surface to the telescope X-Y Plane to ≤6 µm over its full range of motion and altitude operational range of motion.

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 $\lambda = 0.5\,\mu\text{m}$ and $F = 4.44$ we have $\Delta z \leq \pm 19.7$ µm. But this error is shared with the camera optics. This specification represents the instrument rotator's allocation to the error budget.

4.7.3.3 The Lower Cassegrain Core

Figure 1 illustrated that the Filter Mechanism (FM) is one of three subsystems that make up the Lower Cassegrain Core (LCC). The other LCC subsystems are the shutter and the camera. Figure 11 illustrates the layout of subsystems in the LCC. This figure shows the current design 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 dimensions in this drawing serve to illustrate the location of these subsystems with respect to the optical elements in the current telescope design. Refer to PSTD-620-030, PSTD-730-000 and

PSTD-700-001 for the interface details and 3-dimensional volumes required for the GPC, LCC and FM. Figure 12 shows the LCC ICD

Note that any deviation from the following requirements needs to be immediately transmitted to the Pan-STARRS project office, in order to perform the necessary modifications on the LCC Support.

4.7.3.3.1 The bottom of PMA shall be less than 6.4” (163 mm) below the LCC mounting surface

During installation and removal operations, the FM needs to slide under the PMA, hence the need for a sufficient margin.

4.7.3.3.2 The LCC mounting surface is located 17.746” [450.76 mm] below the M1 vertex

4.7.3.3.3 The inner diameter of the rotating part of the Instrument Rotator shall be larger than 42.322” [1075 mm]

.

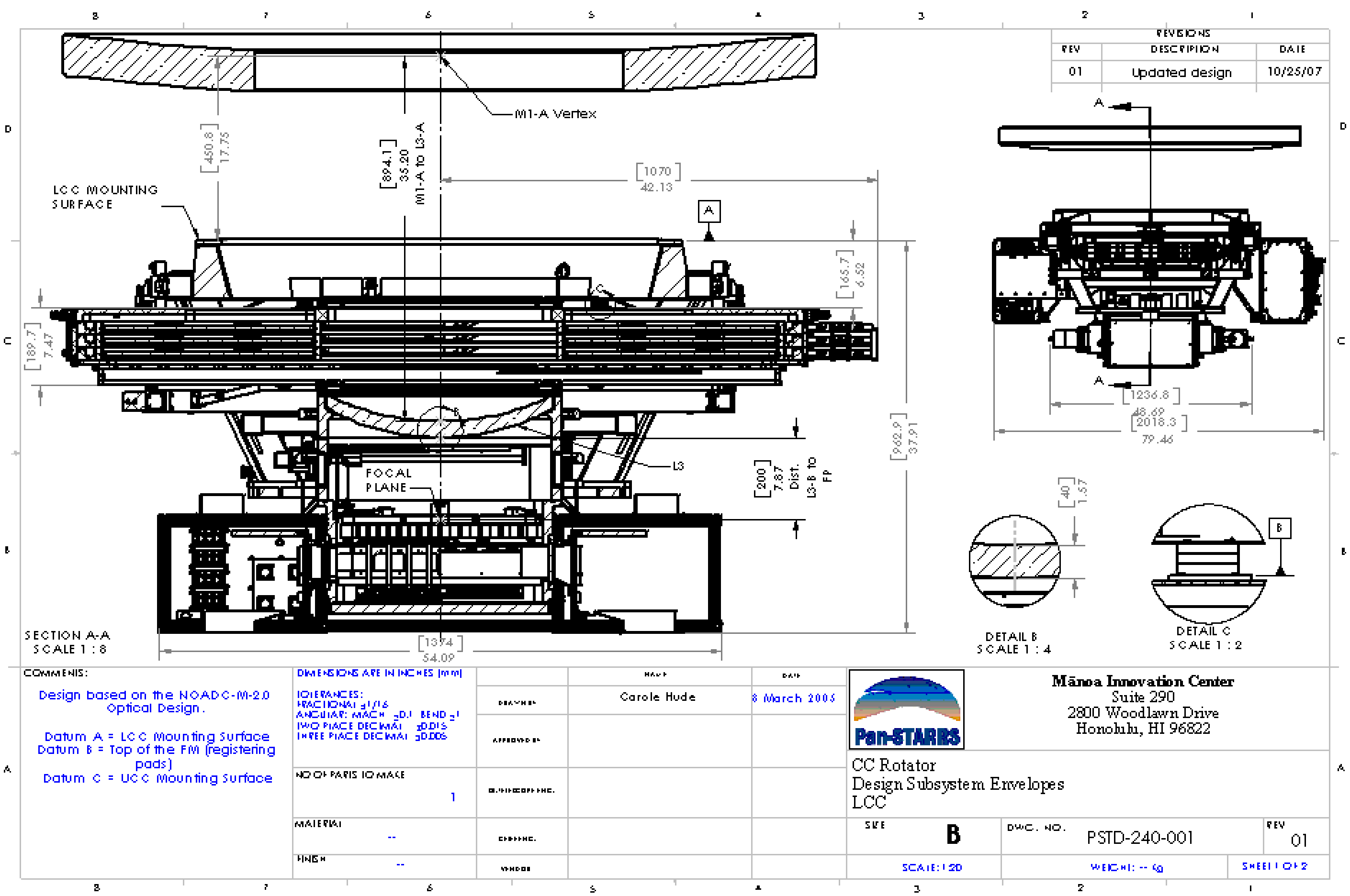


Figure 11. Physical layout of the Lower Cassegrain Core Subsystems (PSTD-240-001)

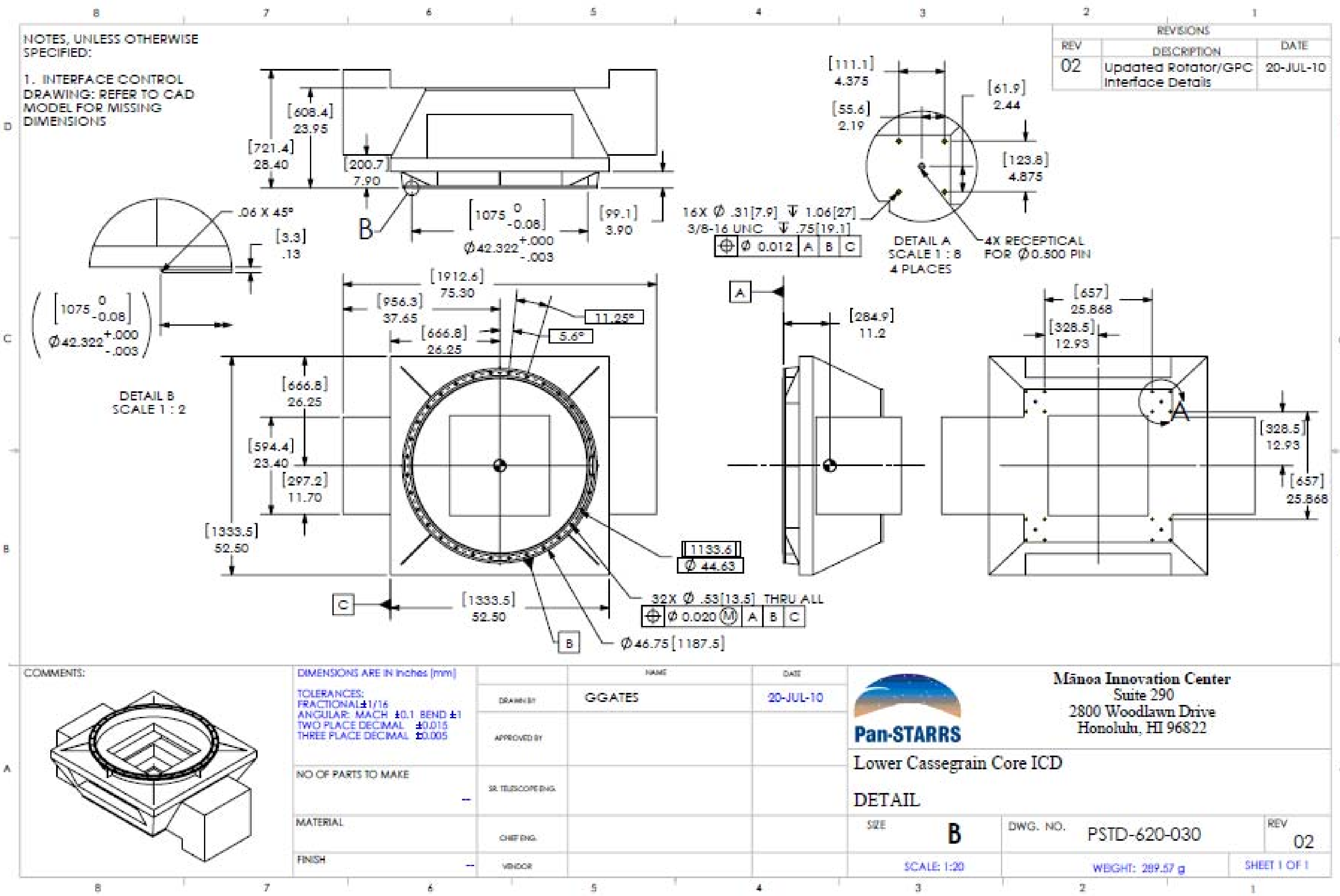


Figure 12 LCC Interface Control Document

4.7.3.4 The Upper Cassegrain Core

Note that any change in the following requirements needs to be immediately transmitted to the Pan-STARRS project office, in order to perform the necessary modifications on the UCC mounting plate. Refer to PSTD-600-002 , shown in

Figure 13, for the interface details and 3-dimensional volume required for the UCC.

4.7.3.4.1 The UCC mounting surface is located 1.182” [30 mm] above the LCC mounting plane.

4.7.3.4.2 The inner diameter of the fixed race of the Instrument Rotator shall be larger than 38.750” [984 mm].

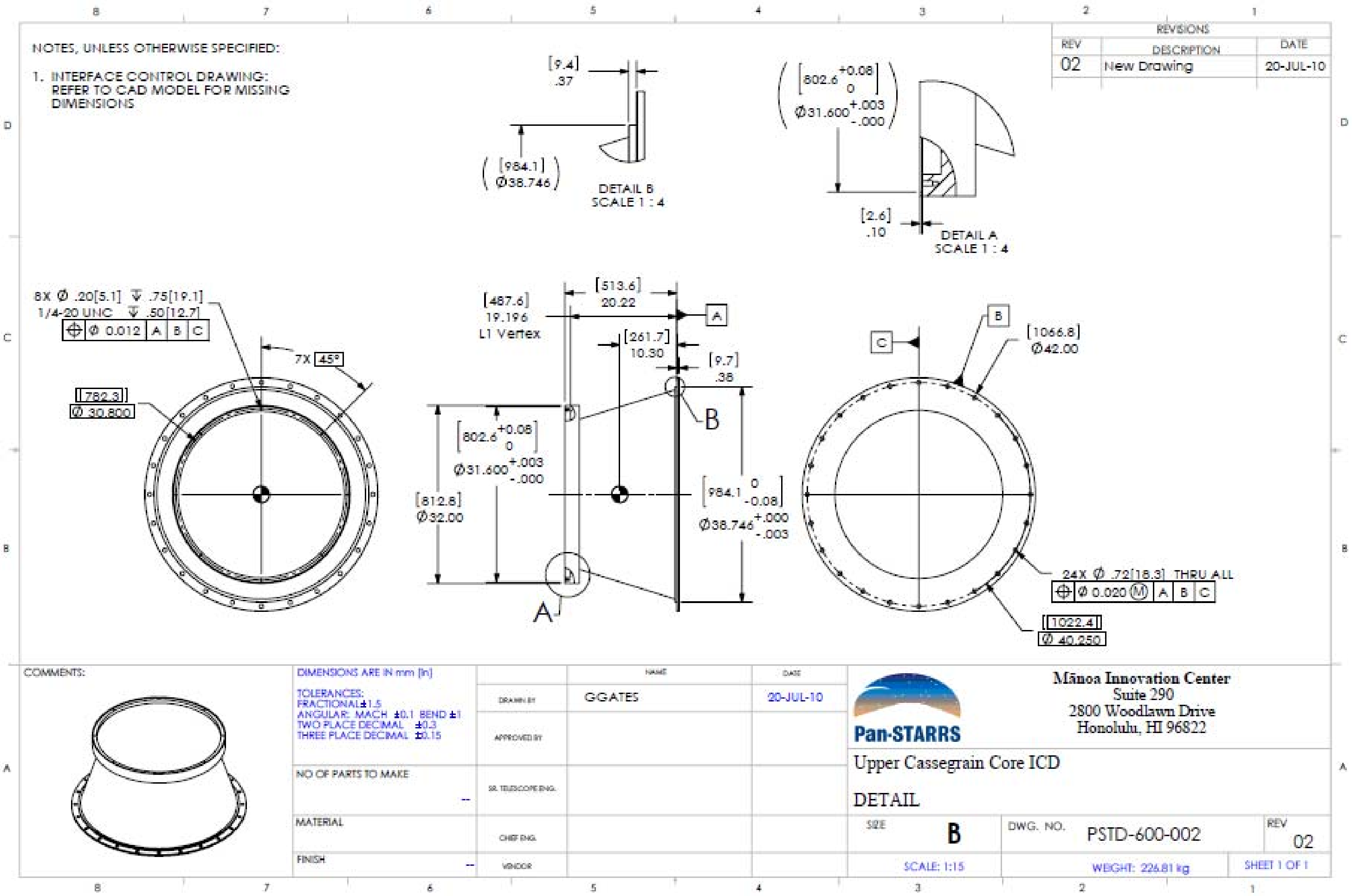


Figure 13. Upper Cassegrain Core ICD

4.7.3.5 Baffles and Stray Light Mitigation

Figure 14 shows a schematic of the PS4 baffle design. Considerable work was done on PS1 to minimize elevated backgrounds and image glints caused by moon light. This design reflects the product of that effort. Materials chosen for coating the baffles must withstand handling and be durable enough to survive the life of the mission without recoating.

The vendor is responsible for the design of the baffles to this schematic. The M1 Baffle is the only mechanical interface to Program provided hardware. It must conform to the interface specification given below.

4.7.3.5.1 Baffle Tolerances

The tolerances for the mounted baffles are given in Table 9. The radial position tolerances per ANSI Y14.5M – 1994 are given relative to the Z-axis. The diameter tolerances apply to the installed condition. The position tolerance along the z-axis is ±10 mm for the edges described in Figure 14.

Table 9. Baffle Tolerances

Feature	Radial Position tol. (mm)	Diameter tol. (±, mm)
Truss Baffle ID	1.5	1
M2 Baffle Tip	1.5	1
Cone Baffle IDs	2.5	2
M1 Baffle IDs (including internal baffle rings)	1.5	1
M1 Stop OD	1.5	1
M1 Stop ID	1.5	1

4.7.3.5.2 The area of the PMA around M1 must be coated with a finish that has reflectivity <2% from 400nm to 1100nm

Pin-hole images from PS1 showed sources of stray light from the PMA that were mitigated by a low reflectivity cover. Ideally this would be a cover over this area to act as a radiant shield to minimize cooling the PMA by exposure to the sky. The vendor should note that normal black and flat black paints have fairly high reflectivity (~20%) between 800 and 1100 nm.

4.7.3.5.3 Baffle finishes shall have reflectivity <2% from 400nm to 1100nm

All surfaces of the baffles except for mounting surfaces shall be coated with a material that has a reflectivity less than the specification to prevent increased background levels and glinting in the GPC images.

4.7.3.5.4 The Truss Mask shall be adjustable radially by 1.0cm

The assembled mask shall have the provision of fine adjustment while mounted to top of the truss to minimize vignetting the telescope field of view.

4.7.3.5.5 A tool shall be provided to register the Cone Baffle to the telescope

While working on PS1, we found it very useful to have a tool to align the cone baffle to the telescope after its removal. Removal of the cone baffle facilitated other work on the telescope and was done often enough to warrant a specialized tool. If the cone baffle is not self-registering, a registration tool will be required.

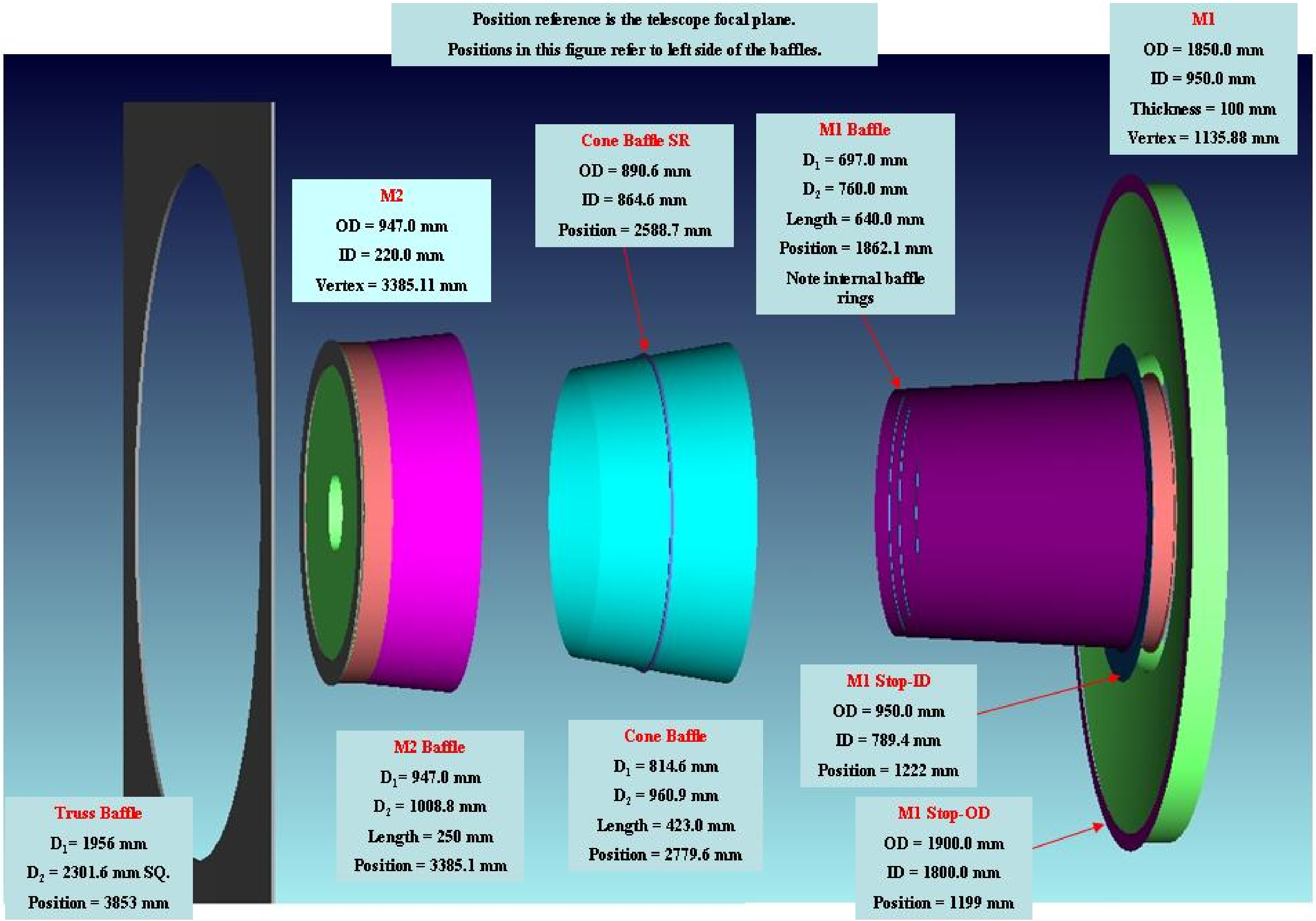


Figure 14 PS4 Baffle Design

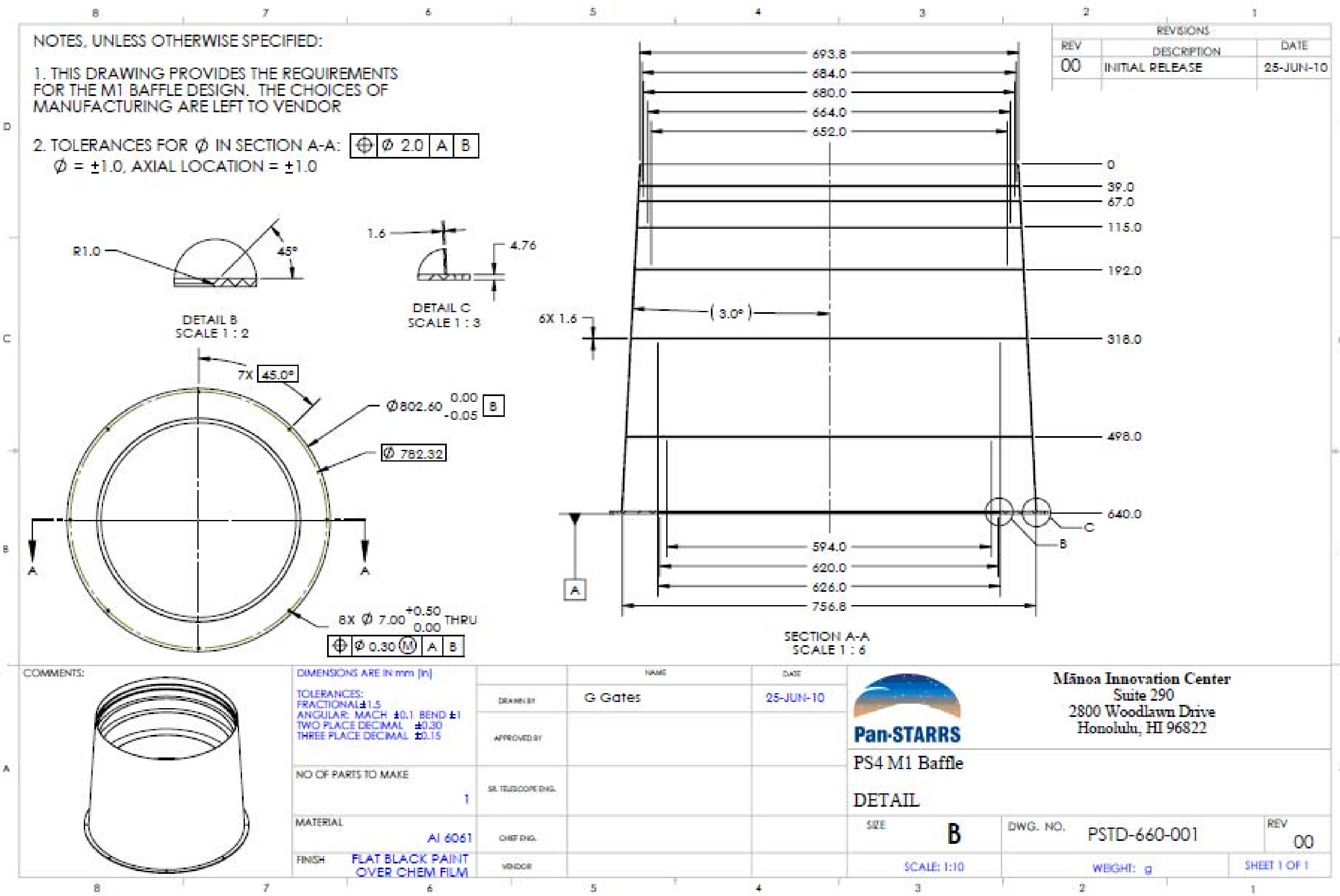


Figure 15 Physical Layout of the M1 Baffle

4.7.3.5.6 M1 baffle shall conform to PSTD-660-001.

The ICD of the M1 Baffle is shown in Figure 15. Note that this drawing shows the location of 6 internal rings that are required for stray light mitigation inside this baffle. The details of the ring attachments to the external surface of the baffle are left to the vendor.

4.7.3.6 Mirror Covers

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

4.7.3.6.2 The telescope mirror covers shall be remotely operable and capable of closing from a completely open position within 30 seconds.

4.7.3.6.3 The mirror covers shall be remotely operable by the Project-supplied software software.

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

4.7.3.6.5 The telescope mirror covers shall have a fail-safe mechanism to protect against power failures.

The telescope software must have a way of sensing power failures and the telescope hardware must have sufficient UPS power to close the telescope mirror covers in this situation.

4.7.3.7 The minimum bend radius for cable and service management system shall not be less than 170mm (6.69”).

The cable and service management system consists of the Instrument Cable Wrap, Telescope Cable Drape and the Telescope Cable Wrap. It is important for vendors to note that one critical design requirement of the cable and service management system is that it must accommodate the minimum bend radius of the Helium gas lines that are used to cool the camera focal plane. The Helium lines have a minimum bend radius of 170mm (6.69”). Violating this minimum bend radius by even 10mm (3/8”) will result in a much shorter expected lifetime for the Helium gas lines.

4.7.3.8 Instrument Cable Wrap

The Instrument Cable Wrap will handle all of the cables and utilities for the hardware mounted to the LCC. Table 10 lists the Project provided cables that will be managed by the Instrument Cable Wrap.

PS1 highlighted the challenges of an unbalanced Instrument Cable Wrap design. The Project encourages the vendor to avoid an unbalanced design for PS4.

Table 10. Instrument Cable Wrap Project Provided Cables

Item	Cable Description	Cable Diameter (in)	Quantity
1	He Compressor Hose	0.75	4
2	Filter Mechanism Control Cable	0.546	3
3	Compressed Air Line	0.561	1
4	Shutter Control Cable	0.519	1
5	GPC Communications Fiber Bundle	0.450	2
6	AC Power Cable	0.433	2
7	Glycol Cooling Line	0.625	2
8	CTI Cooling Head Power Cable	0.277	2
9	Filter Mechanism Sensor Cable	0.286	1
10	LAN Communications Cable	0.217	2
11	LCC Leg Temperature Cables	0.09	4
12	Auxilliary Camera Controller Cables	0.25	3

4.7.3.8.1 The Cable Wrap shall permit the Instrument Rotator to move relative to the PMA over its full range of motion.

This specification includes compatibility with the tracking requirements listed in specification 4.5.4.4, the pointing requirements listed in specification 4.5.4.1, and the large angle step and settle requirement listed in specification 4.2.17.

4.7.3.8.2 The Cable Wrap shall not obstruct the installation and removal of the Camera, LCC, UCC, or Filter Mechanism

These items are to be installed by means of carts which roll onto the telescope fork. They are subsequently lifted in place by means of jacks and then bolted onto the telescope. Clearance for the installation of these units must be maintained between the telescope fork and the bottom of the telescope rotator mounting surfaces. The filter mechanism, in particular is difficult because it must be inserted between the telescope and the installed camera. Specification 4.7.3.3.1 gives a maximum distance between the bottom of the PMA and the bottom of the LCC mounting surface. This distance is set by the clearance needed by the filter mechanism to be installed into the LCC. The cable wrap may not obstruct this pathway either.

4.7.3.8.3 The Cable Wrap shall contain and guide all cables and utilities required for the Filter Mechanism, Camera Shutter, LCC and GPC.

4.7.3.8.4 The Cable Wrap shall be compatible with the instrument rotator torque capacity.

Note that the torque capacity listed in specification 4.5.4.11 is required to deal with the active torques placed on the instrument rotator from the shutter and filter mechanisms. If the instrument rotator is to be used for actuation of the cable wrap, then it must maintain additional overhead torque to simultaneously fulfill specification 4.5.4.11.

4.7.3.9 Telescope Cable Drape

The cable drape will handle all of the cables and utilities for the hardware mounted to the Instrument Rotator, Center Section and Truss. In addition to the Project provided cables for the Instrument Cable Wrap, Table 11 lists the additional Project provided cables that will be managed by the Cable Drape.

Table 11. Telescope Cable Drape Project Provided Cables

Item	Cable Description	Cable Diameter (in)	Quantity
1	Accelerometer Coaxial Cable	0.07	6
2	Auxilliary Telescope Instrumentation (ISP) 110 V Power	0.25	1
3	Auxilliary Telescope Instrumentation Ethernet	0.20	1

4.7.3.9.1 The Cable Drape shall permit free motion of the altitude axis between 80° and -5° from zenith.

4.7.3.9.2 The Cable Drape shall permit the PS4 yoke to move relative to the dome in azimuth.

4.7.3.9.3 The Cable Drape shall contain and guide all cables and utilities required for the PMA, M2, Center Section, Truss, Spider Vanes, Filter Mechanism, Camera Shutter, LCC and GPC.

4.7.3.10 The Telescope Cable Wrap shall contain and guide all cables and utilities required for the Altitude Axis, PMA, M2, Center Section, Truss, Spider Vanes, Filter Mechanism, Camera Shutter, LCC and GPC

4.8 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.

4.8.1 Response to an open Interlock shall result in controlled stop of all telescope axes and application of all axis-brakes

Emergency stop (E-stop) switches will be located throughout the dome as a manual safety intervention. The E-stop opens the interlock circuit.

4.8.2 The telescope altitude axis shall have pinned locations at 0° and 75° zenith angle for service.

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.

4.8.3 The state of locking pins shall be remotely sensed to prevent the enabling of their respective axes when the pin is engaged.

4.8.4 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 manual over-rides for each axis.

4.8.5 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 or during service. The telescope interlock needs to protect against unintended use of these manual over-rides.

4.9 Packaging requirements

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

5 Telescope Coordinates

Figure 4 shows the coordinates for the PS4 telescope. The X-axis is coincident with the altitude axis and is positive to telescope-left. The Y-axis is perpendicular to the X-axis and is positive toward the back of the telescope. The Z axis is coincident with the theoretical optical axis and is positive toward M2.

6 Compliance Matrix

The compliance matrix for the specifications given in the preceding section is given here as Table 12. The entries in the third column of this table are defined as follows:

A = Verification by analysis

I = Verification by inspection

T = Verification by testing

The forth column in this table gives clarifications on the testing method.

Table 12. Telescope System Compliance Matrix

Paragraph Number	Requirement	Method	Clarifications
4.1.1	The telescope shall operate at 4267 meters (14000ft) elevation.	A	
4.1.2	PS4 will observe in winds averaging 10m/s (22 mph) or less with gusts not to exceed 15m/s (34 mph)	T	
4.1.3	The environmental temperatures will be between 5° and -10°C during observations	T	
4.1.4	All mirror components shall be operable after the application of seismic forces with accelerations < 0.3g.	A	
4.1.5	Observations will be performed in relative humidity of 80% or less	T	
4.2.1	The telescope volume shall be contained within the dimensions given in PSTD-780-001	I	
4.2.2	The PMA volume shall be contained within the dimensions given in PSTD-540-001	I	
4.2.3	The telescope aperture shall be 1.8 m in diameter	I	
4.2.4	The telescope operational altitude range shall be 10° to 70° zenith angle.	T	
4.2.5	The half-angle of the telescope field of view shall be 1.5°	I	

Paragraph Number	Requirement	Method	Clarifications
4.2.6	The telescope focal length shall be 8.0m	I	
4.2.7	The PS4 telescope shall utilize an altitude-over-azimuth mount.	I	
4.2.8	The PS4 stray light management shall include a fully baffled focal plane, contamination control and other measures to mitigate the impact of stray light.	I	
4.2.9	The PS4 state and errors shall be reported and logged.	T	
4.2.10	The telescope shall be remotely operable.	T	
4.2.11	The Telescope Control Computer (TCC) shall be remotely bootable from an “off”, “protected” or “hibernating” state (see paragraph 4.2.25).	T	
4.2.12	The telescope and TCC shall recover from a power outage without personnel on-site.	T	
4.2.13	PS4 telescope shall support maintenance and service.	I	
4.2.14	All lubricants used within the telescope shall be low temperature compatible and the lubricants within purchased components shall be replaced with low temperature compatible lubricants during construction.	I	
4.2.15	All heat sources on, in or near the telescope shall be contained in air tight, temperature controlled enclosures.	I	
4.2.16	The altitude and azimuth axes of the PS4 telescope shall have maximum velocities ≥ 1.0°/second and ≥ 2.0°/sec, respectively.	T	
4.2.17	The PS4 telescope axes shall be capable of slewing 3.0° and settling to the nominal open loop tracking errors in a 5 second time interval.	T	

Paragraph Number	Requirement	Method	Clarifications
4.2.18	For intermediate step angles (from 0.002 to 0.01 degrees) the PS4 telescope shall be capable of slewing and settling to the nominal open loop tracking errors in a 2 second time interval.	T	
4.2.19	For small step angles (from 0.00003 to 0.002 degrees) the PS4 telescope shall be capable of slewing and settling to the nominal open loop tracking errors in a 1 second time interval.	T	
4.2.20	The telescope mirror cell design shall be compatible with the PS4 primary mirror blank.	I	
4.2.21	The M1 Support shall be compatible with the location of the primary mirror support pads given in PSTD-020-001.	I	
4.2.22	The telescope secondary support structure shall be compatible with the PS4 secondary mirror blank.	I	
4.2.23	The telescope fork assembly shall allow a minimum clearance of 21" (550mm) between the bottom of the instrument package and the top of the fork when the telescope is at zenith.	I	
4.2.24	The telescope fork assembly shall provide a swing clearance ≥ 6" (150mm) with a solid fork bottom.	I	
4.2.25	The telescope structure and mirror supports shall maintain the registration of the secondary mirror to the values in Table 4 without adjustment of its actuators	T	
4.2.26	The secondary spider supports shall be insulated or made of low CTE material.	I	
4.3.1	Observing Mode	T	
4.3.2	Calibrating State	T	
4.3.3	Hibernating State	T	
4.3.4	Protected State	T	

Paragraph Number	Requirement	Method	Clarifications
4.3.5	Servicing Mode	T	
4.3.6	Off State	T	
4.3.7	Failure State	T	
4.4.1	The Vendor shall supply low level telescope software that will interface to the Project-supplied SW.	T	
4.4.2	The Vendor shall provide a SW interface allowing control of the telescope subsystems with minimum latencies by the Project-supplied SW.	T	
4.4.3	The Vendor-supplied interface(s) should provide the capability for the Project to add a minimum of eight (8) new data sources	I	
4.4.4	The Vendor shall provide interface control descriptions (ICDs) between Vendor-supplied and Project-supplied SW.	I	
4.4.5	The Vendor-supplied SW shall provide the capability to control velocity, acceleration, and position of all telescope axes for celestial tracking.	T	
4.4.6	The Vendor-supplied SW shall provide the capability for Project-supplied SW to control velocity, acceleration, and position of all telescope axes in real time.	T	
4.4.7	The Vendor-supplied SW shall provide the capability for Project-supplied SW to read and control all control loop parameters and diagnostics.	T	
4.4.8	Vendor-supplied SW shall use velocity commanded control with position feedback as opposed to position/time command control.	I	
4.4.9	The Vendor-supplied SW shall include any software needed for PID tuning of each servo axis.	I	

Paragraph Number	Requirement	Method	Clarifications
4.4.10	The Vendor-supplied SW shall include software that is required to move each axis under computer control.	T	
4.4.11	The Vendor-supplied SW shall include the capability to monitor all of the raw encoder counts, motor currents, and pressure and temperature sensor data.	T	
4.4.12	The Vendor-supplied interface(s) shall support Linux-based Project-supplied SW.	T	
4.5.1.1	The support of the primary mirror shall contribute ≤ 0.025 µm RMS surface errors to the primary surface near zenith and ≤ 0.060 µm RMS surface errors at a zenith angle of 70°.	A	
4.5.1.2	The support of the secondary mirror shall contribute ≤ 0.050 µm RMS surface errors to the secondary surface near zenith and ≤ 0.070 µm RMS surface errors at a zenith angle of 70°.	A	
4.5.1.3	The entrance pupil of the telescope shall be defined by the outside diameter of the primary mirror and the tip of the secondary baffle.	I	
4.5.2.1	The secondary shall be actuated in 5 axes: x-tilt, y-tilt, piston, x-translation, and y-translation.	T	
4.5.2.2	The secondary mirror actuators shall have a resolution ≤2 µm and a range of motion ≥5 mm.	T	
4.5.2.3	The primary mirror shall be adjustable in 4 axes: x-tilt, y-tilt, x-translation, and y-translation.	T	
4.5.2.4	The tilt and x-translation of the primary mirror shall be either manual or automated.	I	
4.5.2.5	The y-translation of the primary mirror shall be automatically adjustable.	T	

Paragraph Number	Requirement	Method	Clarifications
4.5.2.6	The primary mirror tilt actuators shall have a precision ≤10 µm and allow a range of piston motion ≥ 5 mm.	T	
4.5.2.7	The primary mirror x- and y-translation shall have a precision ≤25 µm and allow a range of motion ≥1 mm.	T	
4.5.2.8	The primary mirror shall reposition to within 100 µm after having been removed and replaced in the telescope.	I	
4.5.2.9	The telescope primary mirror cell shall have a fiducial surface whose axial distance from the M2 actuator mounting surface is known to within ±150 µm.	I	
4.5.2.10	It is recommended that the telescope shall utilize a pneumatic support system for the primary mirror.	I	
4.5.2.11	The air pressure and humidity for the primary mirror pneumatic support system shall be monitored.	I	
4.5.2.12	The primary mirror support shall incorporate a 12 point astigmatism correction system that attaches to the primary mirror.	I	
4.5.2.13	The astigmatism correction system shall be controllable by the Project-supplied software software.	T	
4.5.2.14	The astigmatism correction system shall be capable of correcting for a range of 2.0 waves of either astigmatism or trefoil errors in the telescope wave front to a precision of 0.05 waves.	A	
4.5.2.15	The primary and secondary support systems shall have support errors that are compatible with the astigmatism correction system.	A	

Paragraph Number	Requirement	Method	Clarifications
4.5.2.16	The telescope telemetry of the primary and secondary mirror's position shall be independent of the mirror actuators.	I	
4.5.2.17	The resolution of the primary mirror position measurement shall be ≤2 μm in translation and ≤0.5" in tip/tilt relative to the PMA	I	
4.5.2.18	The resolution of the secondary mirror position measurement shall be ≤2 μm in translation and ≤1.0" in tip/tilt relative to the M2 mounting interface	I	
4.5.3.1	The obscuration from telescope secondary vanes and cone baffle supports shall be ≤1% at the edge of the telescope's field of view.	A	
4.5.3.2	The telescope drives, motors, amplifiers, encoders, bearings, compressors, actuators, and mirror supports shall have a cumulative MTBF of ≥ 450 hrs.	A	
4.5.3.3	Repair of a telescope failure between the service intervals given below in Table 6 shall not require more than 8 hours, assuming adequate spare parts are stocked at the observatory.	A	
4.5.4.1	The telescope pointing accuracy shall be ≤5 arcseconds 2-D RMS	T	
4.5.4.2	The telescope pointing precision shall be ≤2 arcsec 2-D RMS over a week's time.	T	
4.5.4.3	The telescope altitude and azimuth encoders shall have 0.01″ resolution or better.	I	
4.5.4.4	Open-loop tracking error shall be ≤ 110 mas 2-D RMS for 1 minute of time.	T	
4.5.4.5	The wind-induced tracking error shall be ≤ 130 mas 2-D RMS	T	

Paragraph Number	Requirement	Method	Clarifications
4.5.4.6	The telescope shall be able to track between zenith angles of 10 and 70 degrees for periods up to 5 minutes without interruption.	T	
4.5.4.7	The mechanical limits on the altitude axis shall be beyond a zenith distance of 75 degrees.	I	
4.5.4.8	The azimuth tracking limits shall be ± 220 degrees with an azimuth cable wrap null point at 100 degrees measured from north toward east.	I	
4.5.4.9	The instrument rotator operational limits shall be ≥ ± 96 degrees.	T	
4.5.4.10	The instrument rotator slew speed shall be ≥ 2.3°/sec.	T	
4.5.4.11	The instrument rotator shall support an out-of-balance torque load up to 50 ft-lbs (68 N-m).	A	
4.5.4.12	The instrument rotator shall support a load of 1660 lbs (753 kg) with a center of mass 17" (0.432 m) from its mounting face (datum A on the ICD).	A	
4.5.4.13	The telescope mirror cell shall support a load of 606 lbs (275 kg) with a center of mass 10.7" (271 mm) from the UCC mounting face (datum A on the ICD).	A	
4.5.4.14	The telescope guiding bandwidth shall be ≥1 Hz.	T	
4.6.1	All mirror and truss temperature sensors shall have a temperature accuracy of <0.3°C, resolution <0.02° C over a range of -10° C to +25° C.	I	
4.6.2	The primary mirror shall have a total of 8 sensors measuring radial temperature differences on the back side of the glass every 90° around its circumference.	I	

Paragraph Number	Requirement	Method	Clarifications
4.6.3	The secondary mirror shall have a total of 4 sensors measuring temperatures on the back of the glass every 90° around its circumference.	I	
4.6.4	The secondary support cage shall have 2 sensors measuring the temperature of the support cage.	I	
4.6.5	The temperature of each of the secondary spider supports shall be monitored.	I	
4.6.6	The temperature of each of the main truss supports shall be monitored.	I	
4.6.7	The temperature of each leg of the LCC shall be monitored.	I	
4.7.2.1	The altitude and azimuth axes shall be remotely controllable with position, limit switch, and motor current feedback.	T	
4.7.2.2	All actuators in the primary and secondary mirror cells shall be remotely controllable with position and limit switch feedback.	T	
4.7.2.3	The instrument rotator shall be remotely controllable with position and limit switch, and motor current feedback.	T	
4.7.3.1	The instrument rotator shall maintain the position of the camera focal plane to ≤40µm over its full range of motion and altitude operational range of motion	A	
4.7.3.2	The instrument rotator shall maintain the parallelism of the LCC mounting surface to the telescope X-Y Plane to ≤6 µm over its full range of motion and altitude operational range of motion	A	
4.7.3.3.1	The bottom of PMA shall be less than 6.4” (163 mm) below the LCC mounting surface	I	
4.7.3.3.2	The LCC mounting surface is located 17.746” [450.76 mm] below the M1 vertex	I	

Paragraph Number	Requirement	Method	Clarifications
4.7.3.3.3	The inner diameter of the rotating part of the Instrument Rotator shall be larger than 42.322" [1075 mm]	I	
4.7.3.4.1	The UCC mounting surface is located 1.182" [30 mm] above the LCC mounting plane.	I	
4.7.3.4.2	The inner diameter of the fixed race of the Instrument Rotator shall be larger than 38.750" [984 mm].	I	
4.7.3.5.1	Baffle Tolerances	I	
4.7.3.5.2	The area of the PMA around M1 must be coated with a finish that has reflectivity <2% from 400nm to 1100nm	A	
4.7.3.5.3	Baffle finishes shall have reflectivity <2% from 400nm to 1100nm	I	
4.7.3.5.4	The Truss Mask shall be adjustable radially by 1.0cm	I	
4.7.3.5.5	A tool shall be provided to register the Cone Baffle to the telescope	I	
4.7.3.5.6	M1 baffle shall conform to PSTD-660-001.	I	
4.7.3.6.1	The telescope shall have mirror covers that shield both the primary mirror and the Cassegrain corrector optics from dust and minor precipitation.	I	
4.7.3.6.2	The telescope mirror covers shall be remotely operable and capable of closing from a completely open position within 30 seconds.	T	
4.7.3.6.3	The mirror covers shall be remotely operable by the Project-supplied software software.	T	
4.7.3.6.4	The telescope mirror covers shall have both fully closed and fully open limit switch feedback.	T	
4.7.3.6.5	The telescope mirror covers shall have a fail-safe mechanism to protect against power failures.	T	

Paragraph Number	Requirement	Method	Clarifications
4.7.3.7	The minimum bend radius for cable and service management system shall not be less than 170mm (6.69”).	I	
4.7.3.8.1	The Cable Wrap shall permit the Instrument Rotator to move relative to the PMA over its full range of motion.	T	
4.7.3.8.2	The Cable Wrap shall not obstruct the installation and removal of the Camera, LCC, UCC, or Filter Mechanism	I	
4.7.3.8.3	The Cable Wrap shall contain and guide all cables and utilities required for the Filter Mechanism, Camera Shutter, LCC and GPC.	I	
4.7.3.8.4	The Cable Wrap shall be compatible with the instrument rotator torque capacity.	I	
4.7.3.9.1	The Cable Drape shall permit free motion of the altitude axis between 80° and -5° from zenith.	T	
4.7.3.9.2	The Cable Drape shall permit the PS4 yoke to move relative to the dome in azimuth.	T	
4.7.3.9.3	The Cable Drape shall contain and guide all cables and utilities required for the PMA, M2, Center Section, Truss, Spider Vanes, Filter Mechanism, Camera Shutter, LCC and GPC.	I	
4.7.3.10	The Telescope Cable Wrap shall contain and guide all cables and utilities required for the Altitude Axis, PMA, M2, Center Section, Truss, Spider Vanes, Filter Mechanism, Camera Shutter, LCC and GPC	I	
4.8.1	Response to an open Interlock shall result in controlled stop of all telescope axes and application of all axis-brakes	T	

Paragraph Number	Requirement	Method	Clarifications
4.8.2	The telescope altitude axis shall have pinned locations at 0° and 75° zenith angle for service.	I	
4.8.3	The state of locking pins shall be remotely sensed to prevent the enabling of their respective axes when the pin is engaged.	T	
4.8.4	The telescope axes shall have brakes to prevent unwanted motions of the telescope and enclosure.	I	
4.8.5	Manual over-rides of telescope axes brakes shall be monitored by a safety interlock system.	T	
4.9.1	Parts for the telescope must be compatible in envelope and weight with shipment over U.S. roads.	I	

7 Notes

7.1 Telescope Image Budget Summary

Table 13 shows our breakdown of the PS2/PS4 image budget. The 6 columns in the table show the image budget allocations in terms of spot size (RMS Radius, in μm), the Fried Parameter (R_0, cm), and Full Width at Half Maximum image blur size (FWHM, arcsec). Translations between these parameters may be found in PSDC-300-027. Some of these allocations vary with zenith angle and so the allocations are given at zenith and at a zenith angle of 70°. The last row in this table shows the full telescope image budget allocation specified by the higher level full system allocations. Other system level allocations include contributions from the camera system and the enclosure. There are lower level allocations that break down the contributions of most of the elements shown in Table 13. These details are available in PSDC-300-027. For the purposes of this document it has been necessary to use ray trace calculations to translate between the spot size allocations shown in this table and physical tolerances like surface figure errors, element despacing, and element tilts and tips.

Table 13. Telescope Image Budget

2-Aug-10	PS4 Telescope Image Budget					
	RMS Radius (μm)		R0 (cm)		FWHM (arcsec)	
	z=0	z=70	z=0	z=70	z=0	z=70
Optical Design	6.7	6.7	41.35	41.35	0.24	0.24
M1	2.5	4.8	110.82	58.22	0.09	0.17
M2	2.2	3.2	125.94	86.15	0.08	0.12
L1	2.5	3.7	110.82	75.81	0.09	0.13
L2	2.4	3.5	115.44	78.97	0.09	0.13
L3	2.4	2.4	115.44	115.44	0.09	0.09
Filters	2.2	3.2	125.94	86.15	0.08	0.12
Collimation	2	2.9	138.53	94.76	0.07	0.11
Focus	1.5	2.1	184.71	133.88	0.05	0.08
Despace						
M1-M2	0.2	0.2	1385.30	1385.30	0.01	0.01
M2-UCC	0.6	0.6	461.77	461.77	0.02	0.02
UCC-LCC	0.6	0.6	461.77	461.77	0.02	0.02
Subtotal	0.9	0.9	317.81	317.81	0.03	0.03
Tilt						
UCC	0.6	1.2	461.77	225.62	0.02	0.04
LCC	1.1	2.3	251.87	123.07	0.04	0.08
Subtotal	1.3	2.6	221.12	108.04	0.05	0.09

Tracking	3.1	1.6	89.37	174.21	0.11	0.06
Wind						
Truss & Drives	3.0	5.3	92.35	52.65	0.11	0.19
M1 Support	0.6	1.1	461.77	263.23	0.02	0.04
M2 Support	2.0	3.5	138.53	78.97	0.07	0.13
Subtotal	3.7	6.4	75.80	43.21	0.13	0.23
Focal plane flatness	1.5	2.2	184.71	126.35	0.05	0.08
Subtotal (without tracking & wind)	**9.46**	**12.03**	29.30	23.04	0.34	0.44
Total	**10.60**	**13.72**	**26.13**	**20.19**	**0.39**	**0.50**
(System Tel. Budget)	10.70	14.55	25.89	19.04	0.39	0.53

7.2 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.

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 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 $\boldsymbol{\frac{t_{open}}{t_{open}+t_{closed}}}$ 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 PS4.

7.3 Motor drive acceleration and maximum velocities

The basic requirements on the telescope drives come from the maximum velocity specifications given in paragraph 4.2.14 and from the step and settle specifications given in paragraphs 4.2.17 through 4.2.19. But it is useful to consider what approximate accelerations are implied by these specifications.

Paragraph 4.2.17 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 $\boldsymbol{D}$, the distance moved by the telescope, is related to $\boldsymbol{a}$, the telescope acceleration, and $\boldsymbol{v_m}$, the maximum telescope velocity, by the equation

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

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

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

And the total step and settle time will be $\boldsymbol{T = T_m + T_s}$ where $\boldsymbol{T_s}$ 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 14 shows the minimum drive accelerations and the maximum velocities required to attain these minimum accelerations when different settle times are assumed.

Table 14. 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 $\boldsymbol{t_2 = 0}$ can be dropped. Under these circumstances we have

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

If we assume that $\boldsymbol{v_m} = 1^\circ / \mathbf{sec}$, $\boldsymbol{D = 3}^\circ$, and $\boldsymbol{T_m} = 4 \sec$, then $\boldsymbol{t_2} = 2 \sec$ and $\boldsymbol{a} = 1^\circ / \mathbf{sec^2}$. This move profile has a settle time and total move time identical to the second row in Table 14. 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 14, $\boldsymbol{v_m} = 2^\circ / \mathbf{sec}$, $\boldsymbol{D = 3}^\circ$, and $\boldsymbol{T_m} = 2.5 \sec$, then $\boldsymbol{t_2} = 0.5 \sec$ and $\boldsymbol{a} = 2^\circ / \mathbf{sec^2}$. In this case $\boldsymbol{T_s} = 2.5 \sec$ 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.

8 Acronyms

Table 15. Pan-STARRS Acronym List

Acronym	Description
B0-4	Baffles
DCS	Dome Control System
DHC	Detector Hardware Controller
GPC	Giga-Pixel Camera
IfA	Institute for Astronomy
IPP	Image Processing Pipeline
ISP	Integrated Sky Probe
L1-3	Corrector Lenses
LCC	Lower Cassegrain Core
M1-2	Mirror Designations
MI	Mechanical Interface
MTBF	Mean Time Before Failure
OBS	Observing Sequencer
OCS	Observatory Control System
OTA	Orthogonal Transfer Array
Pan-STARRS	Panoramic Survey Telescope and Rapid Response System
PMA	Primary Mirror Assembly
PS1-4	Pan-STARRS Telescope Identifiers
PSF	Point Spread Function
RMS	Root Mean Squared
SCD	System Concept Definition
SGS	System Goals Statement
SSS	System/Subsystem Specification
SW	Software
TBD	To Be Determined
TCC	Telescope Control Computer
TCS	Telescope Control System
UBC	Uniform Building Code
UCC	Upper Cassegrain Core
ULE	Ultra-Low Expansion Fused Silica