The design of the Pan-STARRS telescope #1

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1. Introduction

One of the main goals of the Pan-STARRS project is to collect multi-color imaging data of the entire sky visible from a single location that is limited in faintness, resolution, and photometric quality primarily by the sky conditions of a world class observing site. The goals of the project include acquiring this full sky coverage on a weekly basis in order to catalogue temporal changes in the night sky. The scientific impacts of a successful Pan-STARRS project are numerous and are discussed in other articles at this conference. It is not hyperbole to say that the Pan-STARRS project has the potential for having a significant impact on all aspects of modern day astronomical research.

The weekly coverage of approximately 31,000 square degrees of sky in 5 band-passes with a spatial resolution of ~0.6 arcseconds is a daunting challenge to the optics, the electronics, and to the software that will be used in the project. To achieve the required étendue, or throughput, the telescope must have a very wide field of view while preserving excellent image quality and the camera must have a pixel format of unprecedented size. To achieve the required efficiency of operation implied by these goals, the telescope must have the capability of rapid slews and quick settling and the camera must be capable of reading out in just a few seconds without the introduction of appreciable read noise. The telescope structure and enclosure must be designed to rapidly equilibrate so that significant time is not spent each night waiting for the optics to become useable. And the scheduling and nightly operation of the telescope must be automated to avoid inefficiencies associated with the stress and tedium of rapid and repetitive observations. All of this must, of course, be accomplished under continually changing weather conditions which makes the scheduling algorithms particularly complex and challenging.

During the development of the Pan-STARRS project it was decided that much of the technical challenge comes in the successful integration of the many required subsystems: camera, telescope, enclosure, filter mechanism, shutter, observatory scheduler, and image processing. For this reason it was concluded that producing a prototype telescope would be very beneficial for the project. The PS1 telescope is providing us the opportunity to test and debug the integration of all of these subsystems before the full telescope system is put together.

In addition to this benefit, the PS1 telescope is being assembled in order to acquire an initial view of the sky that will be used as the template with which subsequent measurements are differenced. When fully operational, the PS4 system will utilize difference images to determine what has changed in the sky between exposures. One of the main goals for the PS1 telescope is to acquire an initial astrometric and photometric survey of the sky which will be used by the PS4 array when once it is in operation.

The scientific goals, cadences, and instrument specifications are therefore slightly different from those of the full array which were discussed above. Below we will detail some of the critical design specifications for PS1 and try to point out where they differ from the PS4 specifications. In addition, there may very well be changes in the design of the full array which have been inspired by our experiences with PS1. However, that doesn't mean that PS1 is not a very powerful instrument in its own rite. For instance, some have predicted that in just the first month of operation, PS1 will discover more asteroids than have been previously discovered throughout all previous history.

2. The PS1 Optics

The layout of the PS1 optical design is given in Figure 1. The design consists of a modified Ritchey-Chrétien design with the addition of 3 refractive correctors. The primary mirror (M1) has an aperture of 1.8-m, the secondary mirror (M2) has a diameter of 0.9-m and the correctors (L1-L3) have diameters of approximately 0.6-m. The 3rd corrector (L3) forms the window of the CCD dewar and therefore must be thick enough to support the force of 1 atmosphere of pressure without deforming enough to have an impact on the image quality of the telescope.

There are three layers of filters in the PS1 design. Two filters will be held by a filter mechanism on each layer, so that the system will have a maximum capacity of 6 filters. The PS1 filters are the largest astronomical quality filters ever produced. Each filter has a clear aperture of 0.48-m. The current complement of PS1 filters includes g, r, i, z, and y band-passes.

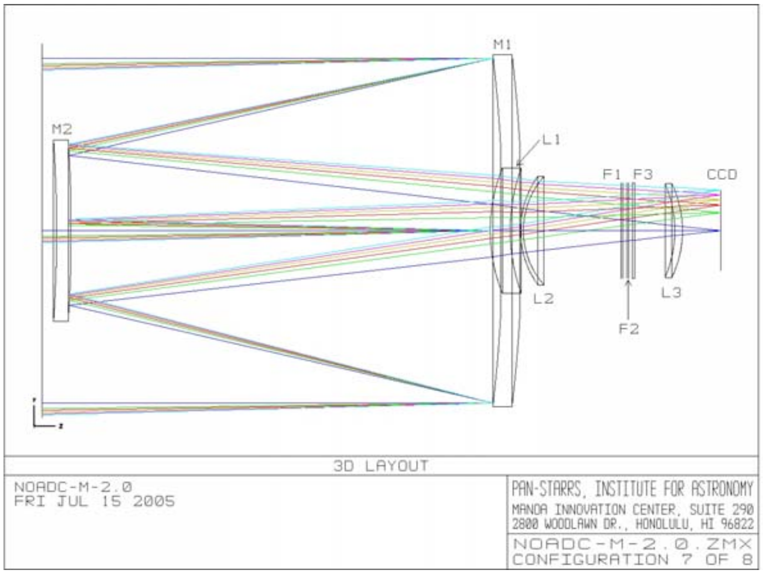


Figure 1. The PS1 Optical Layout

The PS1 optics support a very wide field of view, 3 degrees of angular diameter or 7 square degrees. The optical design utilizes aspheric surfaces on M1, M2, the lower surface of L1, and the upper surface of L3. The optics have an f/4.4 beam and a focal length of 8000 mm, which produces a plate scale of 38.8 μm/arcsecond. Even with the broadest band-pass filter which will be used for PS4 (the "w" filter has a band-pass of 400 nm), this optical design produces spot diagrams that have RMS radii ($\langle r^2 \rangle^{1/2}$) of 6.1 μm on-axis. Since $\sqrt{2}\langle r^2 \rangle^{1/2} = FWHM$, this corresponds to on-axis spots with a FWHM of 8.6 μm, or 0.22 arcseconds. This design image quality is maintained across the entire field of view. The spot radii with the w filter rise only to 7.0 μm (FWHM= 0.25 arcseconds) at field angles of 1.5 degrees.

The glass for both the primary and secondary mirrors is ULE from Corning. This low expansion glass is used to minimize the impact of thermal variations in the telescope enclosure. The corrector lenses are all made of high grade fused silica. At the size of the corrector lenses, there are very few choices of optical materials available. BK7 would have been a cheaper alternative to fused silica, but this glass has a coefficient of thermal expansion (CTE) a factor of 10 higher than fused silica, a lower thermal conductivity, and impurity levels that are sometimes high enough to admit significant radioactive components into the glass. Radioactive impurities in the glass needed to be avoided especially for L3 owing to its proximity to the CCD camera which is sensitive to radioactive emissions.

The design of the L1 corrector lens is not an optimum solution for the PS1 optics. The optical performance of the telescope could be improved by decreasing the thickness of L1. However, the L1 design has been chosen because it allows the direct substitution of a unique 3-element Atmospheric Dispersion Corrector (ADC) in its place. One of the main scientific goals of both the PS1 telescope and the PS4 system is the detection of asteroids in our solar system. Surveys for asteroids benefit significantly by spending a large amount of time looking near the asteroid "sweet spots", which are regions of the sky at dawn or dusk near 70 degrees zenith angles where the orbits of main belt asteroids are concentrated. At these large zenith angles, the addition of an ADC will improve the telescope Point Spread Function (PSF) and decrease the detection limit. It is hoped that the project will be able to eventually find the funds necessary for the ADC optics so that the design of the ADC can be tested on PS1.

3. The Telescope Structure

The PS1 telescope has been designed and fabricated by EOS Technologies. Although the PS1 primary mirror is only 1.8-m in diameter, the telescope has both a very large secondary and a very heavy Cassegrain instrument package. That and the desire to utilize pneumatic supports for the primary mirror drove us to use a telescope fork that was originally designed for a 2.4-m mirror. Figure 2 shows a rendering of the PS1 base, fork, primary mirror cell, gimbal, truss, and the instrumentation package.

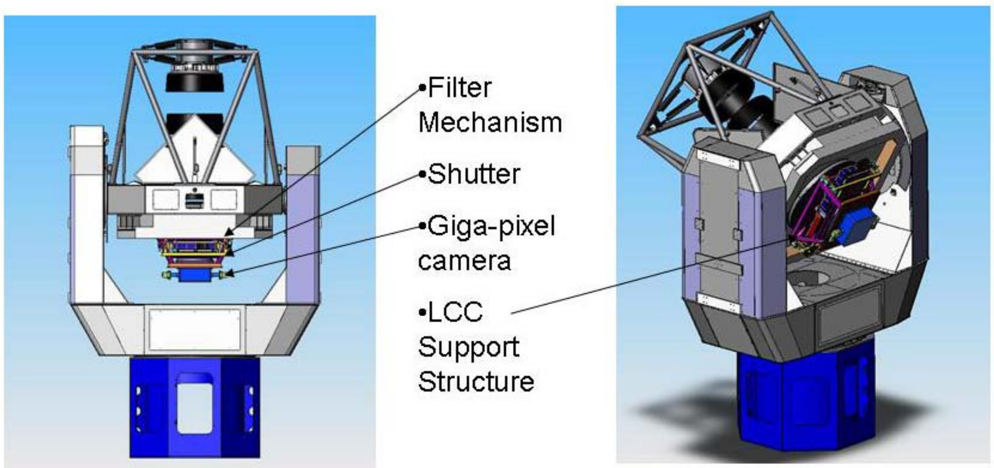


Figure 2. The PS1 Telescope

One of the most important telescope structure specifications for the success of the PS1 surveys is that the telescope be capable of slewing a distance of 3 degrees and settling to within and RMS tracking error of 0.1 arcseconds within 5 seconds. Ideally, the telescope would be able to do this over the entire range of operational altitudes. While it currently appears that the telescope will be so capable, the enclosure will limit the time of the telescope step and settle at altitudes above about 60 degrees. Tests of the step and settle time of the telescope will begin in about two weeks from the time of this conference. Pointing and tracking tests of the telescope are currently underway. We will discuss some of the results of those tests later in this paper.

4. Collimation Requirements

The wide field of view of the PS1 telescope comes at the obvious expense of the addition of the three refractive corrector optics. This is not a trivial matter. The aggregate cost of the corrector lenses rivals the cost of the primary mirror. But, there are additional costs to the wide field associated with the need to maintain very tight specifications on the collimation of the optics.

Table 1 shows the estimated collimation requirements for each of the telescope optics based on an image budget for the telescope that requires that the image PSF is dominated by the site seeing of approximately 0.8 arcseconds. To do this, the design optics need to deliver spot sizes that are approximately 0.4 arcseconds FWHM near zenith and spot sizes that are approximately 0.5 arcseconds FWHM at zenith angles near 70 degrees. The decenter and despace requirements on all the optics save the filters are tight. These are specifications that include all sources of error from the stack-up of all the structural elements that hold these elements in place.

Table 1. PS1 Collimation Requirements

Optic	Decenter (μm)	Tip & Tilt (arcseconds)	Despace (mm)
M1 and M2	150	10	0.5
L1 and L2	150	60	0.25
L3	150	215	0.30
Filters	5000	3000	10

To accomplish and hold the collimation of the telescope the mirror support design incorporates 4-axis control of the primary mirror and 5-axis control of the secondary mirror. The primary mirror is supported axially by 36 pneumatic "Bellofram" actuators. Figure 3 shows the layout of the M1 actuators in the primary mirror cell. In addition to the 36 axial actuators, there are 16 transverse Airpel actuators in a "push-pull" configuration that support the mirror when the telescope points towards the horizon. The Airpel cylinders are made by Airpot Corporation and provide very low stiction support of the mirror. The low stiction allows precise and repeatable control of the lateral actuator forces. The Bellofram actuators were modeled after the design of the APO 3.5-m and the Sloan 2.5-m actuators.

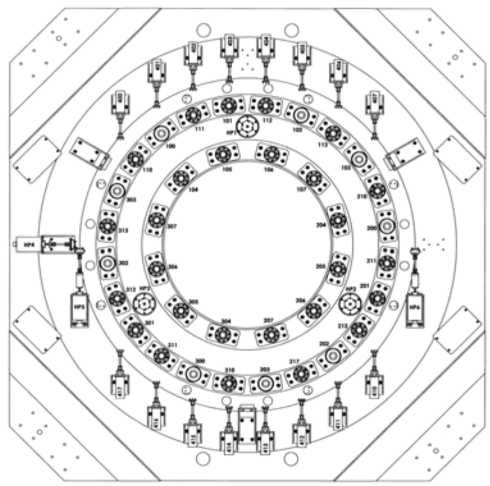


Figure 3. Primary Mirror Cell Actuator Layout (with permission from EOS Technologies)

The primary mirror actuators allow computer control of tilt, tip, piston, and translation of the mirror in the direction of gravity when the telescope is pointed toward the horizon. This direction is designated as the "y" direction for the telescope and is the vertical direction in Figure 3. The primary mirror is only manually adjustable in the "x" direction (the horizontal direction in Figure 3).

The automated y control of the primary mirror was included in the telescope design in order to compensate for flexures in the camera supports. Owing to their size, the camera, the filter mechanism, and the shutter on this telescope weigh about 1430 lbs (650 kg). To maintain excellent focus over the entire field of view, the tilt of the camera focal plane must be maintained perpendicular to the optical axis to within about 10 arcseconds. Despite a stiff design, the mirror cell itself is predicted to flex by approximately 8 arcseconds as the telescope points toward the horizon. The instrument support structure will add to these flexures. It is therefore necessary to compensate for these tilts as the telescope moves in altitude. To make the proper compensations both the primary and secondary must be adjustable in tilt, tip, and y motions as a function of altitude.

The use of pneumatic actuators in the primary mirror cell was chosen because they can be configured to work in unison using a minimal number of control circuits. And, they produce very little heat even when in full support of the mirror. For the tilt, tip, and piston motions only three control loops are required. A forth control loop is required for the lateral supports. The only heat that is dissipated in the mirror cell is from the operation of the high speed control valves that regulate the pressure to the actuators. Most of the heat for the mirror control is generated and spent three floors below the telescope where the air compressor for the system is located. The use of pneumatic actuators is also relatively safe for the glass. The geometry of the actuators themselves limits the amount of force that can be placed on the mirror.

The downside of this type of mirror support system is that it is very sensitive to any contamination in the air lines. In order to maximize the high frequency response of the system, the air lines must be kept small and the runs for the lines need to be kept as short as possible and nearly equal in length between actuators. The small size of the lines (1/16") makes them susceptible to clogging by contaminants in the lines. The primary source of contamination is from water vapor in the air itself. It is therefore necessary to include a regenerative drying system with the air compressor.

In a Cassegrain telescope spherical and coma aberrations can be largely controlled by piston, tilt, tip, and decenters of the primary and secondary mirrors. Astigmatism is harder to control by these methods largely because these degrees of freedom are already being used to correct for the other aberrations. In a telescope with a conventional field of view this is often acceptable because astigmatism grows with field angle. On-axis it is often small enough to ignore. But with the PS1 telescope's wide field of view, even small astigmatic errors in the wavefront will have a serious effect on the outer portions of the telescope's field of view. It was therefore assumed in the specifications of the telescope that an independent way of correcting for astigmatism in the telescope wavefront was required.

Twelve of the 36 axial supports in the outer ring of actuators were configured to act as an astigmatism correction system. These actuators have 12 independent control loops that can apply up to about 14.5 lbs (65 N) of differential force to the perimeter of the mirror. This is calculated to be sufficient to induce or correct for approximately 2 waves of astigmatism in the wavefront. Load cells on each of these 12 actuators measure a differential force between them and the average force being placed on the mirror by the rest of the support actuators. Tests of this astigmatism correction system are currently being done.

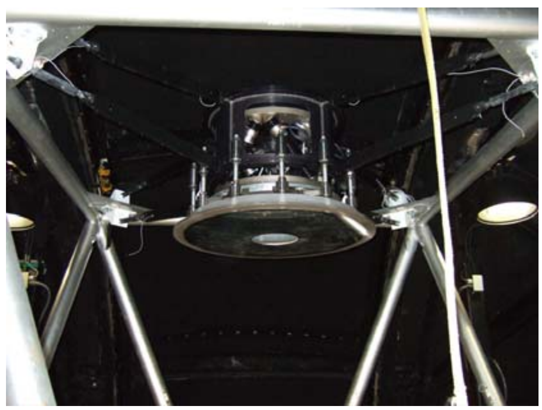


Figure 4. M2x on the PS1 Truss

Figure 4 shows the PS1 secondary mirror on the telescope. The secondary is actuated in 6 axes by an off the shelf hexapod which is made by Physik Instrumente (PI). Five of these degrees of freedom will be commonly used to keep the telescope in collimation and focus during observations. The 6th degree of freedom, rotation of the secondary mirror, is only of marginal use, but comes as a natural result of the hexapod. The hexapod provides approximately 5 mm of piston while maintaining the ability to tilt and tip the mirror by about a degree. The hexapod motion is rapid and precise. It is able to move the mirror through the full range of piston in less than a minute and can position the mirror to an accuracy of about 2 μm.

The axial support of the secondary mirror has been accomplished by the use of a conventional "whiffle tree" structure. Six whiffle trees provide an 18 point support system for the secondary. This large number of support points is required owing to the large size of the secondary mirror and to its light weighting. These whiffle trees are attached to the mirror by use of flexures that provide several degrees of motion in two dimensions (tilt and tip). The lateral support of the secondary mirror is accomplished by a counterweight system behind each of the whiffle tree support points. Six of these counterweights can be seen in Figure 4. They are the "bars" that appear vertically behind the mirror perimeter in this figure. In early tests of the telescope pointing and tracking it was discovered that a dampening system is required on these counterweights. During slews these counterweights can become excited, causing unwanted vibration of the secondary which can persist for several minutes. Early attempts at applying simple foam dampening system seem to be effective at solving this problem.

One significant drawback of the use of the hexapod for the secondary mirror actuation was the limitation that this mechanism put on the weight of the secondary mirror. In order to fit both the secondary mirror and the secondary mirror counterweight system onto the hexapod, it was necessary to lightweight the secondary mirror itself. 42% of the mirror weight had to be removed. This was accomplished by cutting out two rings of material into the back of the mirror and the center hole. Compared to many light-weighting efforts, this is a modest reduction in weight. But it was mandatory for the use of the PI hexapod. The light-weighted secondary mirror weighs 129.9 lbs. The entire structure supported by the hexapod including counterweights, flexures, and whiffles trees weighs 266.8 lbs.

5. The Upper Cassegrain Core

As shown in Figure 1, there are three corrector lenses in the PS1 optical layout. The third corrector lens (L3) forms the window to the CCD dewar and is therefore more properly discussed in the context of the PS1 camera. The point that we must make about L3 is that it has been calculated that when the camera cooling is on, the upper surface of L3 will drop below freezing. This requires the instrument package to provide a dry air environment to this lens surface to prevent frost from forming on this optic and has a large impact on the design of the instrument package that fits above the camera.

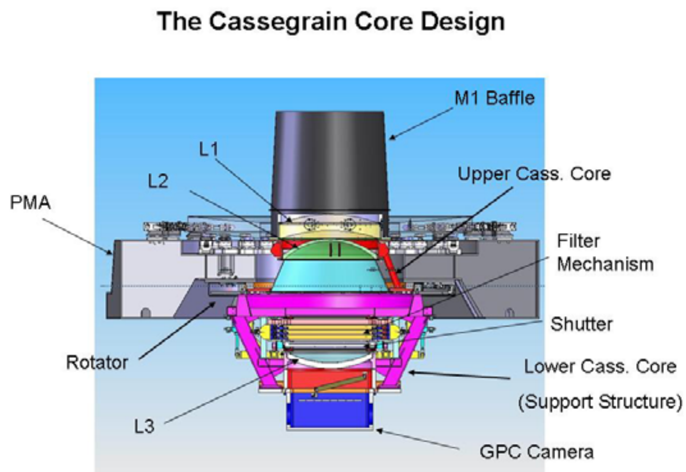


Figure 5. The PS1 Cassegrain Core

The first and second corrector lenses (L1 and L2) are supported in a structure that fits above the instrument rotator that is known as the Upper Cassegrain Core (UCC). Figure 5 shows a cut-away of the PS1 Cassegrain Core. The Primary Mirror Assembly (PMA) is the structure that holds the primary mirror, the primary mirror actuators and the instrument rotator. The red part in this figure is the Upper Cassegrain Core Support Structure. It supports two cylindrical lens cells for L1 (in yellow) and L2 (in green) that bolt on above and below it. The UCC Support Structure holds the L1 and L2 lens cells in place with 4 legs that have been designed to flex in a way that partially compensates for flexures in the PMA as a function of altitude. The turquoise section seen just below L2 is a neoprene membrane that helps to form the dry air chamber that extends from the lower surface of L2 to the upper surface of L3 (in white). The UCC Support Structure is attached to the fixed section of the instrument rotator. It therefore does not rotate as the instrument rotator moves.

The L1 and L2 lens cells are cylindrical steel structures that surround and support the corrector lenses though the use of a continuous ring of Corning 3112 RTV. The RTV rings are approximately 3 mm thick in the axial direction and about 50 mm thick parallel to the optical axis. They are designed to support the lenses without inducing any significant thermal stresses into the glasses. FEA calculations show that the design limits the stresses in the glass to about 50 psi over a temperature range of 40 C.

6. The PS1 Instrumentation

As a specialized survey telescope, the PS1 will have a fixed instrument package. This package consists of the camera, a filter mechanism, and a shutter. This entire instrument package is referred to as the Lower Cassegrain Core (LCC).

In Figure 5 the LCC Support Structure is shown in pink. This section is attached to the moving part of the instrument rotator. The pink structure holds the filter mechanism, the shutter, and the Giga-Pixel Camera (GPC). The LCC Support has been designed to allow the removal and servicing of the filter mechanism without detaching the camera from the telescope. The shutter is attached directly to the filter mechanism. They are removed from the telescope as a single unit and then disassemble. Inflatable seals are utilized to fill up the gaps needed for the installation and removal of the filter mechanism. The details of the design and installation of the filter mechanism are covered in another paper at this conference.

The shutter for the GPC was built at the University of Bonn and has a clear aperture of 480 mm square. It utilizes a dual blade design that is stepper motor driven. It is capable of providing accurate and uniform exposures over the entire GPC focal plane for exposures as short as 0.1 seconds. The accuracy and uniformity of exposure duration was specified to be better than 0.5% over the entire focal plane and for the full range of shutter exposures. This is the largest astronomical quality shutter that has been built to date. Full testing of this shutter will not begin until the GPC camera has been installed on the telescope. However, the shutter and the filter mechanism should be installed in the telescope in about 6 weeks.

7. The Telescope Baffles

Figure 6 shows the PS1 baffles. These baffles have not yet been installed on the telescope, but should be within the next month. The PS1 baffle system is a three baffle system that was modeled after the Sloan 2.5-m baffle system. The use of the three baffle system as opposed to a two baffle solution allows greater system throughput at the expense of a very slight increase in the diffraction profile of the telescope point spread function. This three baffle design causes only 37.8% obscuration compared to the 46.7% that an equivalent 2-baffle design would have caused. The middle baffle in this design is supported by thin "piano wire" that runs from the middle of the truss to a strengthening ring in the middle of the central baffle. These wires are aligned with the secondary vanes, so on-axis they do not contribute to diffraction in the telescope. But, an increase in the off-axis diffraction is unavoidable with this design. Keeping the size of the support wires small keeps this increase to a very acceptable minimum. There is very little (11%) variation in the obscuration as a function of field angle with this baffle design. On-axis the obscuration is only 33.7% while the 2-baffle on-axis obscuration is 42.3%.

The PS1 Baffles

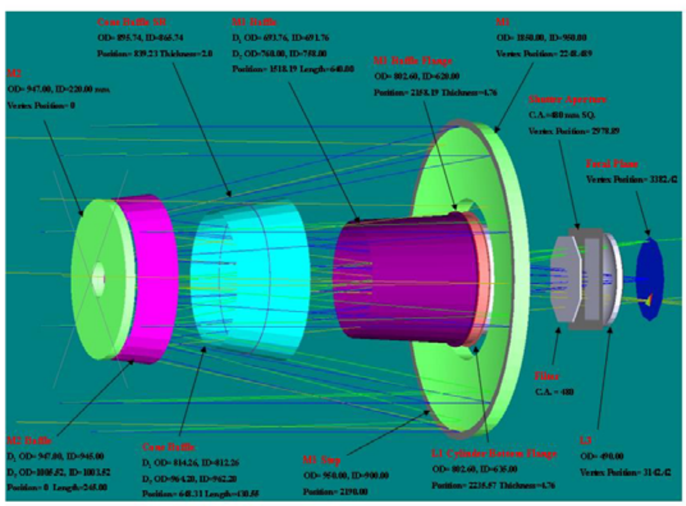


Figure 6. The PS1 Baffles.

8. The Current State of the Telescope Optics

Most of the telescope optics have yet to be installed. The primary mirror is the only optic that is completely finished and in place. The polishing for this optic was done by Rayleigh Optical Corp. in Maryland (ROC). The polishing specification for both the primary and secondary mirrors was given in terms of a structure function which allows errors in the optical figure to rise with the large scale limitations that the atmosphere places on the optics. Figure 7 shows the specified surface errors (dashed blue line) along with the final polish errors on the mirror (red line) and the surface errors present in the polishing run just prior to mirror completion. The project is very satisfied with the fabrication of this mirror. ROC successfully met all of our specifications which were considered to be tight. The primary mirror was given a protected aluminum coating by the EMF Corporation in Newark.

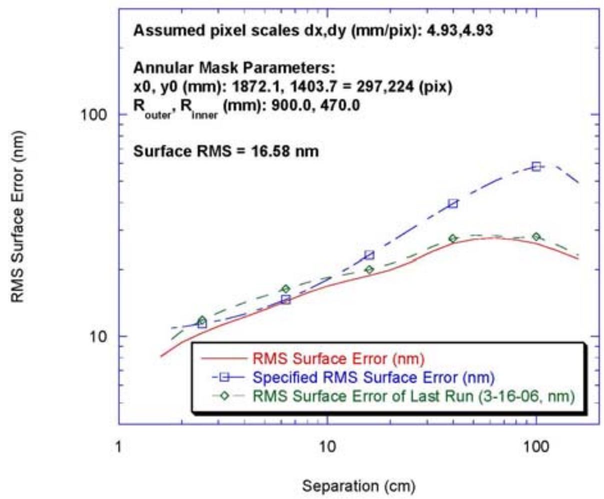


Figure 7. The Primary Mirror Polish

Despite appearances, the fabrication of the secondary mirror is not yet complete. An accident occurred during the fabrication of the secondary mirror which has delayed its final installation into the telescope. While drilling one of the holes in the back of the secondary which are used to hold the secondary support flexures, a piece of the secondary mirror's front face broke off and was pushed out. The polisher immediately purchased a new blank at their own expense as a replacement for the broken secondary. Facing this delay, the project decided to utilize the broken secondary, which we have labeled M2x by having the broken plug cemented back into its hole and by having the secondary refigured so that it could be used for on-axis imaging without the presence of the corrector optics.

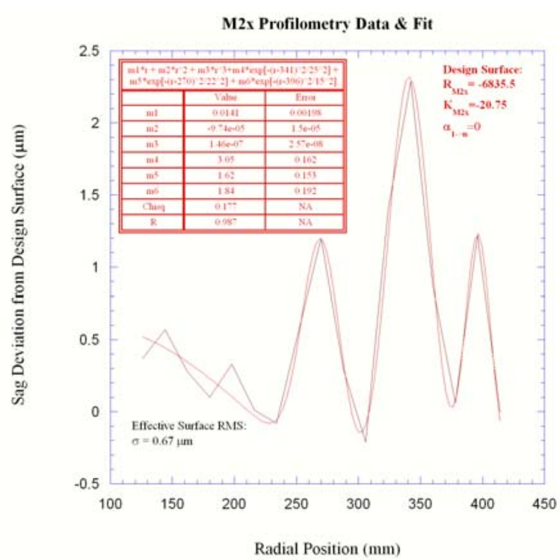


Figure 8. M2x Profilometry

Since the need for M2x was immediate and temporary, we chose not to have a full polish put on the glass, but instead to stop the process at the point were profilometry measurements could no longer be used reliably to measure figure error.   Figure 8 shows the current figure errors on M2x as measured by profilometry. As shown in the figure, these figure errors were fit by a model. This model was then applied in ray tracing calculations in order to estimate their effects on the telescope PSF in the absence of other errors in the telescope. Figure 9 shows a comparison of the measured and expected telescope PSFs based on the M2x profilometry shown in Figure 8. The actual telescope image of a star is shown on the left and the ray tracing calculations are shown on the right. The agreement is excellent.

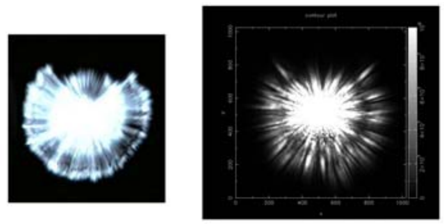


Image from telescope (note partial obscuration)

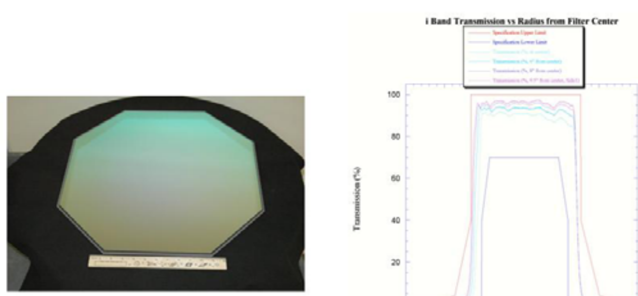
Kaiser PSF model based on ROC profilometry

Figure 9. A Comparison of Measured and Theoretical PSFs

The current telescope PSF has a core width of about 3-4 arcseconds, but the wings of the distribution are approximately 60 arcsecond in width. This is sufficient to allow us to do tracking, pointing, and step and settle tests of the telescope while we wait for the delivery of the final telescope secondary and the corrector optics. The secondary is currently expected to be delivered near the end of this year.

The delivery of the corrector optics and their support cells are consistent with the telescope having a full compliment of optics by the end of this year. All three of the corrector optics have been finished by the polishers and are now at coating facilities. We expect to have all three optics in hand to start their installation into the lens cells by the end of October. The lens cells themselves should be done by the end of September.

The filter complement for the PS1 telescope is slightly different than that chosen for the full PS4 array. In particular, the PS1 does not yet plan on utilizing a w filter, although this may happen in the future. All but one of the PS1 filters have already been delivered. Figure 10 shows a photograph of the PS1 i band filter along with measurements of its transmission as a function of radius on the filter. The solid red and blue lines in the transmission plot show the filter specification limits. Similar measurements are available for all of the delivered filters (g, i, r, and z) along with measurements of the filter transmission as a function of azimuth. These filters are scheduled to be potted into their frames in about 6 weeks.



PS1 i Band Filter

PS1 i Band Transmission

Figure 10. The PS1 i Band Filter

9.   Pointing Test Measurements

Some of the first measurements that have been done on the telescope are pointing tests. For these tests a pointing model of the telescope is first produced using a series of “model stars” which are scattered uniformly across the sky. Then, using this model, the telescope is commanded to point to a number of "test stars" which are previously unmeasured stars. The differences between where the telescope pointed using the model and the actual test star positions are measured.   During the development of the pointing model both pre-fit and post-fit measurements of the star positions are measured and an RMS post-fit residual is given which is a measure of how well the pointing model describes the data on which the model was made. If the model stars are truly representative of all stars in the sky, then the post-fit residual is also an indication of how well the telescope should point to a random star in the sky. The measurement of the test stars is a test of that assumption.

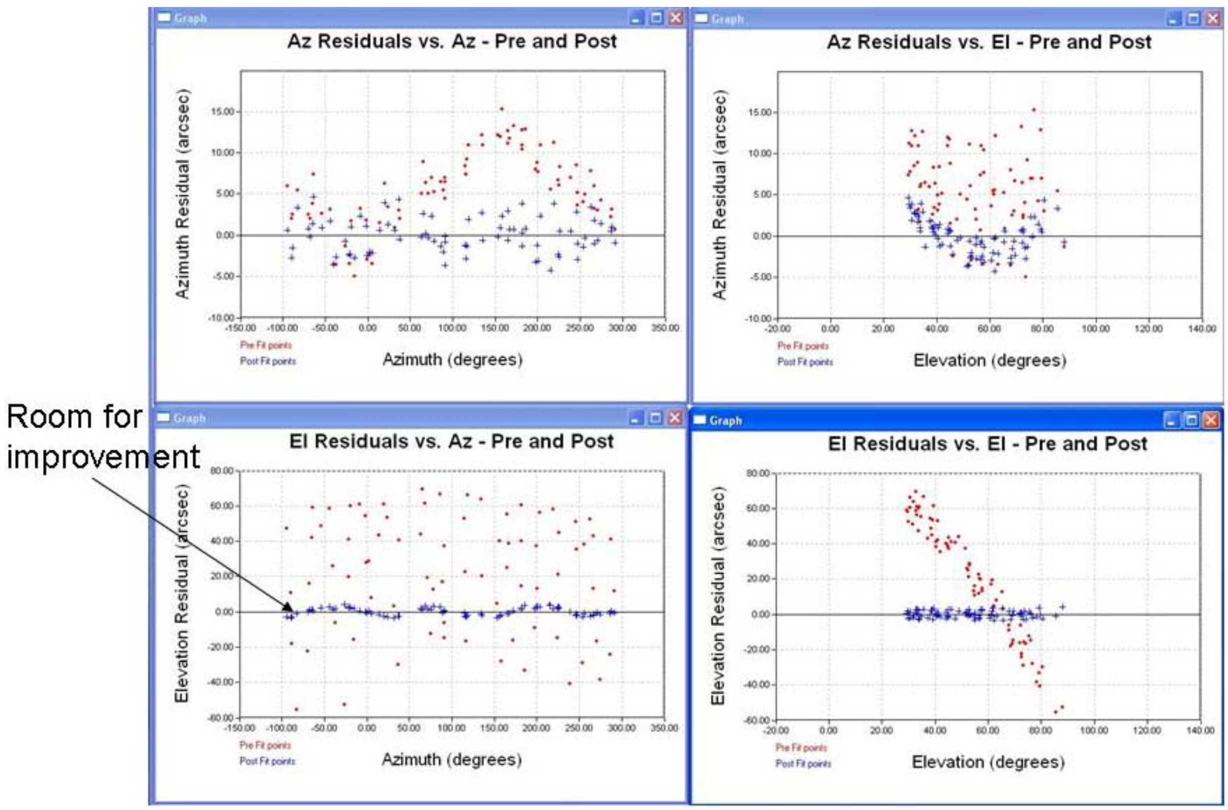


Figure 11. PS1 Pointing Model Residuals

Figure 11 shows the pre- and post-fit residuals of a 160 star mount model that was taken on 30 August 2006. The model fit included 11 terms. The post-fit residuals show an RMS scatter of only 2.47 arcseconds. After this model was applied, the pointing residuals to 70 test stars were measured. The scatter in the test star positions was found to have an RMS value of 2.64 arcseconds, which we consider to be in excellent agreement with the post-fit prediction. It is therefore clear that the model is an accurate description of the telescope pointing. The graphs in Figure 11 indicate that the post-fit residuals are fairly random with the exception of the Elevation Residual vs. Azimuth graph (lower left in the figure). In this case, it is clear that the model would benefit by the addition of an elevation term that varies as sin(3*Az). This term will be added in the future, but the pointing of the telescope is already far in excess of what we require that this improvement is not a high priority.

10. Acknowledgements

The Pan-STARRS project gratefully acknowledges the truly significant and outstanding contributions that many at EOS Technologies, Inc. have had in the development of this instrumentation. In particular, we would like to thank Kevin Harris, Kerry Gonzales, Chris Lambert, Aaron Evers, and Britt Kayner. Without your help and dedication we would be lost!