A Conceptual Design for the Thirty Meter Telescope Alignment and Phasing System

Mitchell Troy[a], Gary Chanan[b], Scott Michaels[b], Randy Bartos[a], Graham Bothwell[a], Amir Give'on[a], Randy Hein[a], Max Radin[b], Jenny Roberts[a], J. Michael Rodgers[c], Lawrence M. Scherr[a], Byoung-Joon Seo[a], and David Zimmerman[b]

[a]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109
[b]Department of Physics and Astronomy, University of California Irvine, Irvine, CA 92697
[c]Optical Research Associates, Pasadena, CA 91107

ABSTRACT

The primary, secondary and tertiary mirrors of the Thirty Meter Telescope (TMT), taken together, have approximately 12,000 degrees of freedom in optical alignment. The Alignment and Phasing System (APS) will use starlight and a variety of Shack-Hartmann based measurement techniques to position the segment pistons, tips, and tilts, segment figures, secondary rigid body motion, secondary figure and the tertiary figure to correctly align the TMT. We present a conceptual design of the APS including the requirements, alignment modes, predicted performance, software architecture, and an optical design.

Keywords: Telescopes, Segmented Mirrors, Optical Alignment, Phasing

1. INTRODUCTION

The Alignment and Phasing System (APS) is a Shack-Hartmann wavefront sensor responsible for the overall pre-adaptive-optics wavefront quality of the Thirty Meter Telescope (TMT).[1] In order to produce wavefronts of acceptable quality, APS will adjust the following parameters as required: segment pistons and tip/tilts, segment surface figure (via warping harness adjustments), rigid body degrees of freedom of M2 (the secondary mirror), and surface figures of M2 and M3 (the tertiary mirror). The purpose of the APS is not to verify that individual optics, such as M2 and M3, have met their respective surface requirements, but rather to align the optics to minimize the wavefront error. The wavefront error associated with the individual optics can greatly exceed the wavefront error of the telescope as a whole.

The design of the APS is based upon that of the Phasing Camera System (PCS),[2] which fulfils a similar role for the Keck 1 telescope and later for Keck 2. In particular, PCS is responsible for aligning the Keck segments in piston, tip, and tilt; for aligning the secondary mirror in piston, tip, and tilt; and for providing segment figure measurements (for the purpose of adjusting warping harnesses). The technologies that were developed and optimized for Keck alignment and phasing are directly applicable to TMT. The segment piston, tip, and tilt alignment functions at Keck are carried out on all 36 segments in parallel and, in this respect, can be scaled up to the order-of-magnitude larger number of segments for TMT with only minor complications. The warping harness function was added to PCS only after the Preliminary Design Review and, given the constraints of the already existing design and the relatively small number of segments, a serial approach to segment figure measurement was adopted at Keck. This function will be parallelized for APS.

However, there are also some fundamental differences in the designs and philosophies of PCS and APS, driven by the much larger diameter of the TMT. For purposes of alignment, the Keck secondary and tertiary mirrors could be assumed to be perfect; in particular, there was no need to measure the figures of these latter surfaces or to disentangle the individual effects of M1 (the primary mirror), M2, and M3 from the overall wavefront. Thus on-axis measurements were sufficient and only piston, tip, and tilt of the secondary had to be monitored. (Secondary x and y decenter are nearly degenerate on axis with secondary tip/tilt.) In the case of TMT, both M2 and M3 are large enough that each will require on the order of 60 active degrees of freedom. These degrees of freedom will have to be measured, which in turn requires disentangling them from each other and from M1. This will necessitate off-axis observations. Because the footprint of M1 covers only one-quarter the area of M3, a minimum of six or seven overlapping (but sequential) measurements will be required.

2. SYSTEM OVERVIEW

APS will use starlight to measure the wavefront errors and then will determine the appropriate commands to send to align the optics. Once the optics are aligned, the various control systems will record the set points for later use. In particular, APS will align TMT by adjusting the following ∼12,000 parameters as required:

- M1 segments in piston, tip, and tilt (492 segments * 3 degrees of freedom per segment)
- M1 segment surface figure (492 segments * 21 degrees of freedom per segment)
- M2 five degrees of rigid body motion (piston, tip, tilt, and x- and y-decenter)
- M2 surface figure (∼15 degrees of freedom)
- M3 surface figure (∼15 degrees of freedom)

APS will align the telescope at various elevation angles and then from the set points for the M1, M2, and M3 control systems, lookup tables will be generated to correct for gravity-induced deformations. In a similar fashion, data will be collected at various temperatures over time, and lookup tables will be built as a function of temperature as well.

Every two to four weeks six segments will be exchanged in TMT. APS will then be used to realign these newly installed segments in piston, tip, and tilt, and to correct the segment figures. At the same time APS will adjust three of the secondary rigid body motions. The APS measurements and associated adjustments to the mirrors will take no more than 2 hours of observation time. Our experience at Keck suggests that APS should be run at least once a month even if there are no segment exchanges to ensure that the telescope remains properly aligned; such alignments will take no more than 30 minutes of observation time.

The APS is comprised of three major subsystems: the APS Optical Bench, the Component Controller (CC), and the Procedure Executive and Analysis Software (PEAS). The CC includes the computer and electronics that control the opto-mechanical devices of the APS Optical Bench, including the power supplies, the motor controllers, the shutter controllers, the Shack-Hartmann charge coupled device (CCD), the acquisition camera CCD, and the pupil image tracking CCD. The CC will conform to the TMT standard software interface definition. As a result, the APS Optical Bench can be commanded by any TMT system.

The PEAS is described in detail in Section 5. The PEAS includes all software that creates, manages, and executes alignment procedure workflows; all procedure-reporting software; and all software managing procedure configurations and procedure-data logging. The PEAS also communicates with other telescope subsystems and includes optics diagnostic software.

The layout of the APS optical bench is shown in Figure 1. The bench is split functionally into several assemblies:

- The Fore-Optics assembly
- The Acquisition Pointing and Tracking (APT) assembly
- The Collimator assembly
- The Shack-Hartmann (SH) assembly
- The Pupil and Image Tracking (PIT) assembly

Each optical assembly's requirements, functions, and design are described in more detail in Section 4. The remainder of this section provides a brief overview as to the purpose of each assembly and how it will operate in the system. Initial telescope operations require a large field-of-view (FOV) acquisition camera for pointing, acquisition, and tracking tests. The APT assembly provides a 2 arcmin-diameter FOV to acquire stars, build pointing models, and check telescope tracking.

In the fore-optics assembly, a beam splitter transmits light to the APT and reflects light into the main portion of APS, which has a nominal FOV of 25 arcseconds. Since the pupil rotates at the Nasmyth deck in an Az-El telescope, the fore-optics also include a K-mirror to derotate the pupil. The telescope light is then collimated via the collimator assembly, producing a 75-mm diameter pupil (1/400 demagnification).

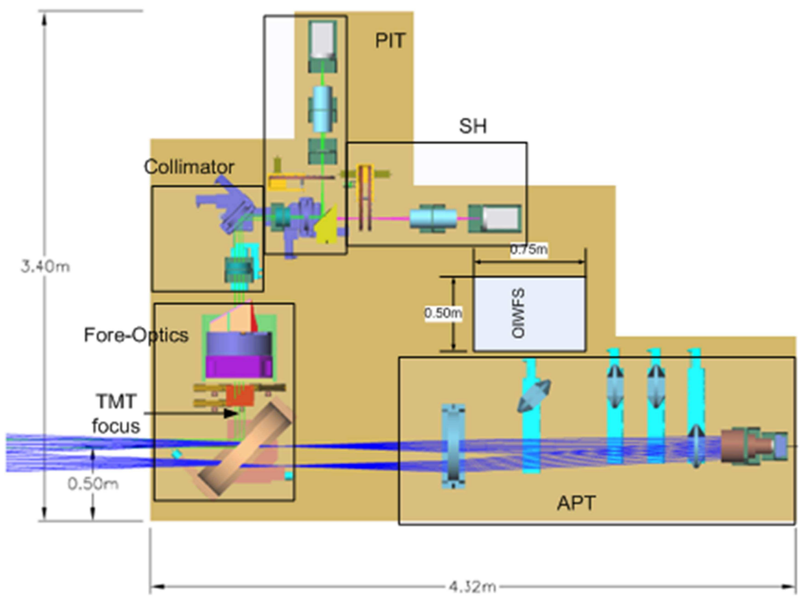


Figure 1. APS optical bench layout with assemblies labeled

The SH assembly has a filter and pupil wheel that can hold six different filters and mask/lenslet combinations respectively. The lenslet focal plane is then reimaged onto a 4k x 4k CCD. APS has a very tight tolerance on pupil position (0.03% of the diameter of the pupil); to meet this pupil position tolerance, the decision was made to add the PIT assembly to stabilize the telescope pupil over the time scales of typical APS integrations (∼60 seconds). The PIT assembly is a SH camera that will measure the pupil misregistration by balancing the intensity of SH subimages that are on the edge of the TMT primary. The PIT will then adjust the pupil position by tilting a plane-parallel plate that is in the collimated beam and by changing the angle of the K-mirror.

A typical APS procedure will occur as follows:

1. The telescope is pointed to a star.
2. The star is acquired in the APT camera and centered by repointing the telescope.
3. The star is acquired in the PIT camera and pupil and image tracking is started. This loop will run at a rate of 0.1 Hz.
   (a) Required pupil motion is sent to the K-mirror and internal APS pupil tilt mechanism.
   (b) Required image motion is sent to the telescope.
4. One or more frames of data are taken by the SH camera to make wavefront measurements. After each frame the image and pupil location are checked and, if necessary, the set points for the PIT tracking loop are adjusted.
5. Commands are sent to align the TMT optics.
6. Steps 4-5 are repeated as needed for different alignment procedures. When a different star is required this process restarts from step 1.

3. PERFORMANCE REQUIREMENTS AND PREDICTIONS

The APS has two fundamental alignment modes and two performance modes, which can be used in any combination, making a total of four operating modes. The two alignment modes are on-axis and off-axis (tomographic alignment). During on-axis alignment the following degrees of freedom are measured and adjusted: M1 segment piston, tip, tilt, M1 segment figures, M2 piston, and either M2 tip/tilt or x/y decenter. During off-axis alignment, all degrees of freedom are potentially measured and adjusted. The two performance modes are post-segment exchange and alignment maintenance. These are defined by how well aligned M1, M2, and M3 are initially, and then how long it will take APS to align them. In addition, APS will have the ability to capture and align optics that are misaligned by more than the post-segment exchange alignment tolerances, but in these cases there are no time constraints (this is an off-nominal operation). The nominal post-segment exchange capture range is ±30 microns of piston error (surface) and ±10 arcseconds of tilt in one dimension on the sky.

3.1. APS on-axis performance

The APS is required to measure the on-axis alignment such that the errors associated with these measurements are less than an 80% enclosed energy diameter (EE80) of 0.040 arcseconds. We have shown that the PCS (and thus APS) measurements are limited by atmospheric aberrations, which decrease as the square-root of time.[3] The 80% enclosed energy diameters have been calculated and are shown in Table 1 for each alignment degree of freedom for a 300 second exposure. The segment warping harness will only be used to correct 2nd and 3rd order Zernike modes. The APS measurement error over these Zernike modes is 3.4 nm RMS surface. The total M1 and M2 EE80 from measurement error is 0.043 arcseconds with a standard deviation of 0.009 arcseconds. This value is statistically the same as the requirement of 0.040 arcseconds. This error is dominated by the global segment tip/tilt measurement errors, which are set by the atmosphere.

Table 1. APS on-axis alignment errors

Aberration	RMS Surface (nm)	EE80 (mas)	
		Mean	Standard Deviation
M1 - Total	56.2	35.9	2.6
Segment Tip/Tilt	55.8	32.9	3.1
Segment Phasing	6.8	10.5	0.1
Segment Aberrations	3.4	8.0	0.0
M2 Total	49.6	23.9	7.9
Tip/Tilt	20.6	15.4	5.1
Piston	38.5	18.3	9.1
M1 and M2 Total	74.8	43.4	9.1

The APS is also required to measure the on-axis alignment such that the errors associated with these measurements are small after correction by an ideal 120 by 120 actuator deformable mirror (DM). The total allowable error from the telescope is 25 nm for this error term. We ran two adaptive optics (AO) simulations to bound the likely residual error after AO correction. In both cases we started with a 2048 by 2048 pixel phase map of the APS aberrations. In the first case we simply ran a high-pass filter over the phase map to simulate a 127 by 127 actuator DM. The resulting surface error was 5.9 nm. In the second case we ran a full-wave-optics SH simulation using ARROYO.[4] This simulation was run at a wavelength of 0.5 microns, with a 128 by 128 actuator DM and a spatially filtered SH sensor with 32 by 32 pixels per subaperture. The only input phase error was the APS measurement error; the simulation was allowed to run until the result had converged. The resulting RMS surface error is 12.4 nm.

APS is required to perform on-axis alignment in less than 30 minutes when all optics are within the alignment maintenance specifications and 120 minutes after a segment exchange. Our estimate from a bottom up analysis and comparison to current times to align Keck is that APS can perform these alignments in 30 and 104 min respectively.

3.2. APS off-axis performance

We have investigated the alignment of M1 and M2 assuming a perfect M3. In this procedure a single on-axis star is used. The simulation starts with random realizations of the mis-alignment of the M1 segments and M2. First,

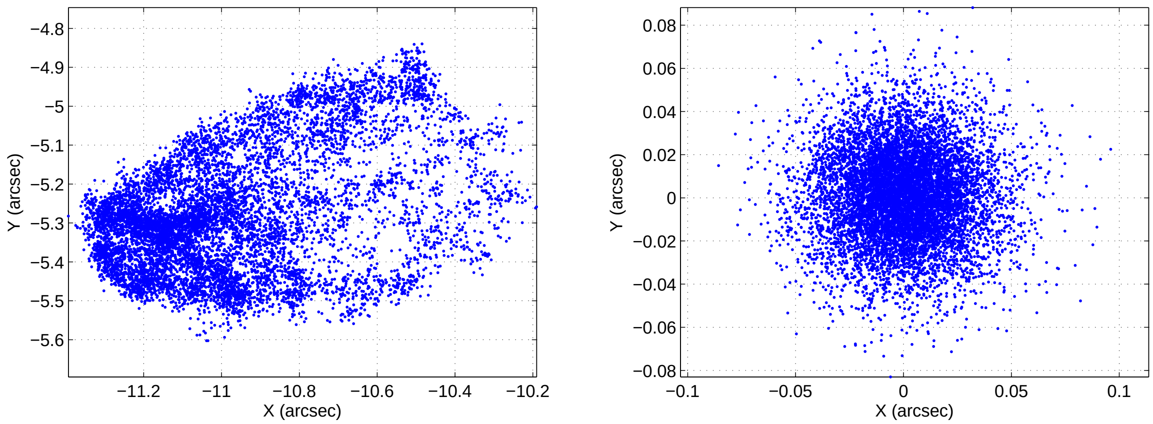


Figure 2. On-axis image before (left) and after (right) alignment of M1 and M2 in all APS controlled degrees of freedom.

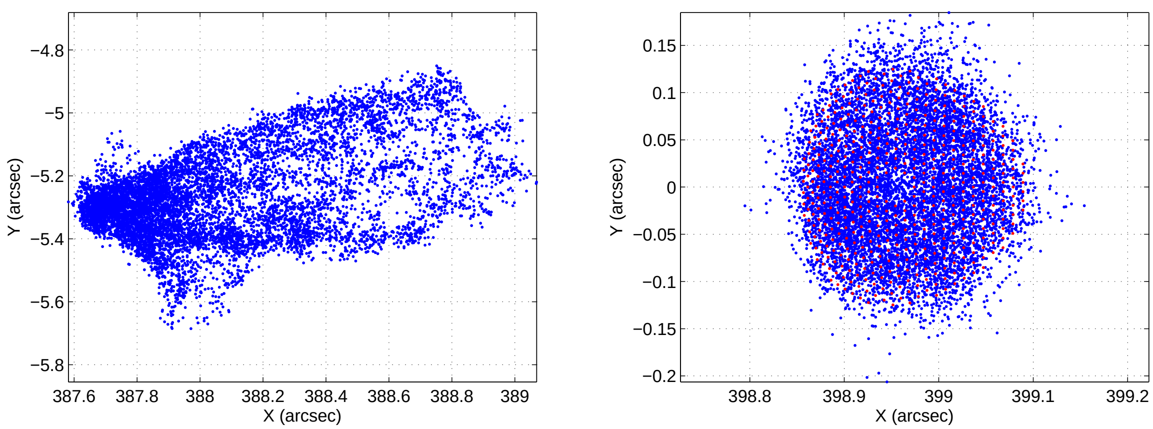
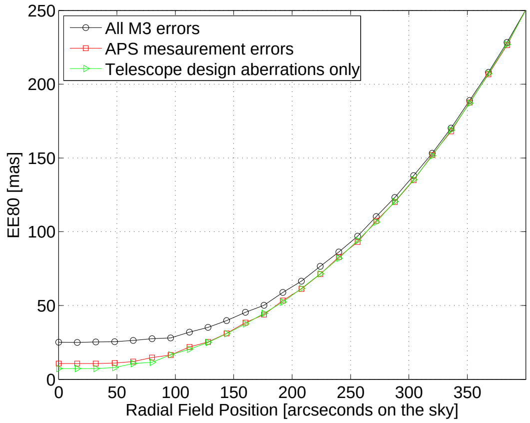


Figure 3. A 400 arcsecond off-axis image before (left) and after (right) alignment of M1 and M2 in all APS controlled degrees of freedom. The image for the perfect telescope alignment is overlaid on the off-axis image and is virtually identical.

the segments were aligned in piston/tip and tilt to minimize the edge discontinuities. Second, the alignment (shape and 5 rigid body degrees of freedom) of M2 was adjusted to produce the best possible on-axis image. Third, the 1st, 2nd and 3rd order Zernikes of the M1 segments were adjusted, again to produce the best possible on-axis image. Finally, the segments were aligned again by adjusting their pistons. Figures 2 and 3 show the before and after images for stars at 0 and 400 arcseconds off-axis. The aligned 80% enclosed energy diameters are 0.076 and 0.217 arcseconds respectively.

We have also investigated the alignment of M3 with a perfect M1 and M2. In this simulation we start with an aberrated M3 generated to look like an atmosphere with an r_0 of 4.0 m. APS then makes Shack-Hartmann measurements with 120 subapertures across the 30 meter pupil and with a measurement noise equivalent to a 300 second exposure (to minimize the residual atmospheric errors). Measurements are made at 7 field points, one on-axis and 6 off-axis points at a radius of 550 arcseconds. The global tip/tilt is subtracted from each APS measurement as pointing errors can't be distinguished from tip/tilt. Then the M3 surface is reconstructed via Zernikes. We assume APS can correct 15 Zernikes on M3, in future simulations we will use the bending modes of M3. M3 starts out with an RMS surface error of 130 nm and this is reduced to 74 nm after alignment. The RMS surface error over the first 15 Zernikes of M3 is only 44 nm afer alignment. The important metric, however,



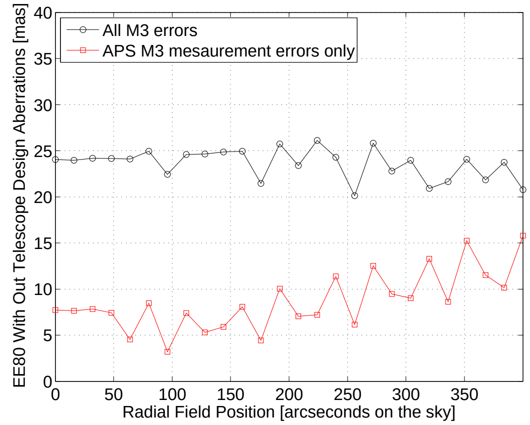


Figure 4. The left plot shows the 80% enclosed energy (EE80) from the perfect telescope, the APS measurement error in the first 15 Zernikes on M3 and all errors on M3 after alignment. The right hand plot shows the EE80 calculated by subtracting in quadrature the EE80 of just the telescope from the M3 errors. We see that on average about 25 milli-arcseconds of EE80 comes from M3, but only about 12 milli-arcseonds is from the APS error in measuring the first 15 Zernikes.

is not the RMS surface error of M3, but rather the image quality as a function of field position. The left plot in Figure 4 shows the 80% enclosed energy (EE80) from the perfect telescope, the APS measurement error in the first 15 Zernikes on M3 and all errors on M3 after alignment. At all field points the APS measurement error of the first 15 Zernikes introduces errors that are small compared to the unaberrated telescope performance. The right hand plot in Figure 4 shows the EE80 calculated by subtracting in quadrature the EE80 of just the telescope from the M3 errors. We see that on average about 25 milli-arcseconds of EE80 comes from M3, but only about 12 milli-arcseonds is from the APS error in measuring the first 15 Zernikes.

The APS is required to measure the off-axis alignment such that the errors associated with the measurements do not exceed the larger of either (1) the on-axis alignment requirement (40 milli-arcseconds) or (2) errors that increase the ideal telescope 80% enclosed energy diameter by more than 7 percent over the telescope FOV. While we have not yet demonstrated this performance the current results are promising. The current analysis indicates that we will be able to align M1 and M2 with a single on-axis star. In the future this algorithm will likley become part of the standard APS on-axis alignment procedure described in Section 3.1. Future work includes a combined simulation of alignment of M1, M2 and M3.

4. OPTO-MECHNICAL DESIGN

Figure 1 shows the optical bench layout with the various assemblies. For the design of APS, we selected a 75-mm pupil (1/400 demagnification). The requirement for good pupil image quality (Section 4.3) required a pupil larger than 50 mm. However, most lenslet manufacturers can only handle 100-mm substrates, so this placed a hard upper limit on the size of the re-imaged pupil. Cost also increases with the pupil diameter due to the required size of the optics. Once the pupil diameter was selected, the distance between the telescope focus and the collimator was set, as well as the distance between the collimator and the reimaged primary mirror. As can be seen in Figure 1, the available space between the TMT focus and collimator assembly is very crowded.

4.1. Fore-Optics Assembly

The APS acquisition fore-optics assembly has several functions:

1. Provide an artificial telescope light source with a pupil to all cameras (APT, PIT, and SH) in the APS. This calibration source will provide a common reference point for all cameras within APS. This is useful,

for example, to define what pixel locations on the APT camera correspond to a well-centered image on the SH camera. This is the only internal light source seen by the APT assembly and will be used for testing and instrument check-out. This also provides a well-defined pupil so that the functionality and performance of the K-mirror and PIT can be tested.
2. Provide a mechanism to steer the telescope pupil during observations of stars at field angles as large as 9 arcminutes.
3. Pass a 120-arcsecond field of view to the APT assembly.
4. Provide artificial telescope light sources to the PIT and SH cameras. This is used to calibrate the desired centroid positions for APS. As a result, the wavefront error in the light sources must be minimized.
5. Provide a method to de-rotate the telescope pupil as the telescope tracks stars. A stationary pupil is required by both the PIT and SH cameras.

The first optics is a large ($\sim$ 0.5 meter) beamsplitter which satisfies functions 2 and 3 above. The K-mirror provides a way to de-rotate the telescope pupil. The artificial telescope light sources associated with functions 1 and 4 above are not pictured because they have not yet been fully designed. A beamsplitter just after the telescope focus provides a way to insert calibration sources at the telescope focus (function 4) and a small mirror on a stage would be used to insert artificial telescope light before the first beamsplitter (function 1). Motion of the first beamsplitter in APS along with the ability to tip and tilt M3 and re-point the telescope allow for a way to acquire stars off-axis.

4.2. Acquisition Pointing and Tracking Assembly

The APS Acquisition Pointing and Tracking (APT) assembly has several functions. It provides the following:

1. A large ($\sim$120 arcsecond) FOV so the APS system can quickly acquire stars. The APS FOV in the Shack-Hartmann and PIT arms is only 25 arcseconds.
2. A way for the telescope to perform the necessary pointing tests to calibrate the Telescope Control System (TCS) control loops and validate that they meet the required performance.
3. A way to validate that the telescope can offset to the required accuracy.
4. A way to perform close-loop guiding and validate that the required performance is met.
5. A location to host an on-board instrument wavefront sensor (OIWFS) or similar device to validate that the telescope active-optics loops work as required.

The APT camera path transmits through the first large beamsplitter, while the SH path reflects from this beamsplitter. The beamsplitter is sized to pass the acquisition field of view (120-arcsecond FOV). TMT focus is located after the beamsplitter. The APT camera reimages the TMT focus (263-mm diameter) to a 1024 x 1024 pixel CCD for tracking and pointing control. A large-field lens is added near TMT focus so that the remaining lenses can be smaller. There is also a beam splitter that can be inserted into the beam to feed light to the OIWFS for telescope diagnostics and testing. In addition there are three neutral density filters that can be inserted in the beam.

4.3. Collimator Assembly

The APS collimator assembly is responsible for collimating the light from the telescope and forming a pupil of the appropriate size and required image quality. The reimaged pupil quality must be very high for the phasing application. In particular, a point on the primary mirror must map to the re-imaged pupil with a geometrical spot diameter of no more than 30 microns, or 10% of the diameter of the reimaged phasing subaperture. This specification holds over the full 600 nm to 900 nm phasing bandwidth. There is an additional requirement to have the ability to adjust the pupil demagnification by $\pm$1% to compensate for magnification errors from all sources, including radius errors in the telescope and temperature changes.

Optical Research Associates (ORA) first investigated a reflective design, which met the requirements (1/600 magnification) but was costly ($350k) and complicated. ORA then investigated refractive designs with reduced requirements on magnification and FOV. A refractive design was shown to meet the requirements at magnifications of 1/300 and 1/600, with the 1/600 design having only a 10% design margin. With this information, a magnification of 1/400 was selected (75-mm pupil). This magnification has sufficient margin to meet the requirements, allows enough room between the TMT focus and collimator lens to accommodate a K-mirror, and allows for reasonably sized optics.

The four-element collimator was optimized for a 1/400 magnification without a field lens. The added baseline field lens has a neutral effect at 1/400 magnification. Moving the center element of the three-element field lens from the baseline position changes the image height by 1%. The performance of the collimator was evaluated imaging over the range of field lens adjustment. Unavoidably, performance degrades as the field lens is adjusted away from the nominal setting, but the degradation is limited. Table 2 shows the worst-case 100% encircled energy diameter at best focus for five settings. Recall the required performance is 30 microns.

Table 2. Encircled energy diameters at best focus for five field-lens settings (10-arcsec FOV diameter)

-1% scale	i-0.5% scale	Nominal	+0.5% scale	+1% scale
8.0 microns	6.5 microns	5.6 microns	7.3 microns	9.6 microns

4.4. Shack-Hartmann Assembly

The SH assembly provides the majority of the measurement capability of the APS instrument. The SH assembly comprises the following elements: a pupil and filter wheel assembly, lenslet arrays, a relay lens to image subimages onto the detector, and a CCD detector.

Phasing modes measure the relative piston between two segments, so they require a subaperture that spans two segment edges. Phasing also requires that the subaperture wavefront be relatively unaffected by seeing. At Keck we have determined empirically that this is best achieved by using a 12-cm subaperture for each measurement. These modes also require excellent wavefront quality through the lenslets ($\lambda/10$). Well-sampled subimages on the CCD are also required, a minimum of 10 pixels across the subimage diameter of $2.44\lambda/d$, where d is the subaperture diameter at the primary mirror. The implied required pixel scale is 0.25 arcseconds/pixel at a wavelength of 600 nm. Each phasing mode[5,6] requires an accurately known and carefully controlled bandpass. The broadest mode uses a bandpass of 300 nm. The narrowest mode uses a bandpass of only 3 nm.

The lenslet arrays have a pitch of 446 microns and a focal length of 45 mm. The lenslet arrays will have a mask applied directly to the substrate. In the case of the phasing (edge) subapertures the mask will be 300 microns to create 12-cm subapertures at the primary mirror. The subapertures in the interior of the segments will also have masks with a diameter that has not been determined but will be no smaller than 300 microns. The larger the subapertures, the smaller the sub-images are on the CCD which reduces the risk of image crowding problems. After the lenslet array there is a relay lens with a 0.8 magnification which re-images the lenslet foci onto a 4K x 4K CCD.

The following operational modes correspond to the lenslet/masks shown in Figure 5:

A. Coarse segment tilt: This is the segment-capture mode. The most important aspect of this mode is the ability to correlate individual subimages with telescope segments. This is best achieved with one sample per segment to reduce confusion in the measurement.
B. Fine tilt and segment figure: This mode determines accurate segment tips and tilts. To achieve this, there must be multiple samples per segment. This mode must be able to capture tilts as large as 0.2 arseconds (on the sky) and have an accuracy of 0.01 arcsec of tilt (on the sky). : 37 close-packed subapertures per segment, with one edge subaperture on the outer ring of segments. This mask will be used for fine tilt and segment figure if the phasing edge subapertures create crowding problems (mask D) in the image plane.
C. Segment Phasing. This mode measures two phasing spots per edge which is a compromise between measurement error (if fewer spots are used) and problems with image crowding (if more spots per edge are used)

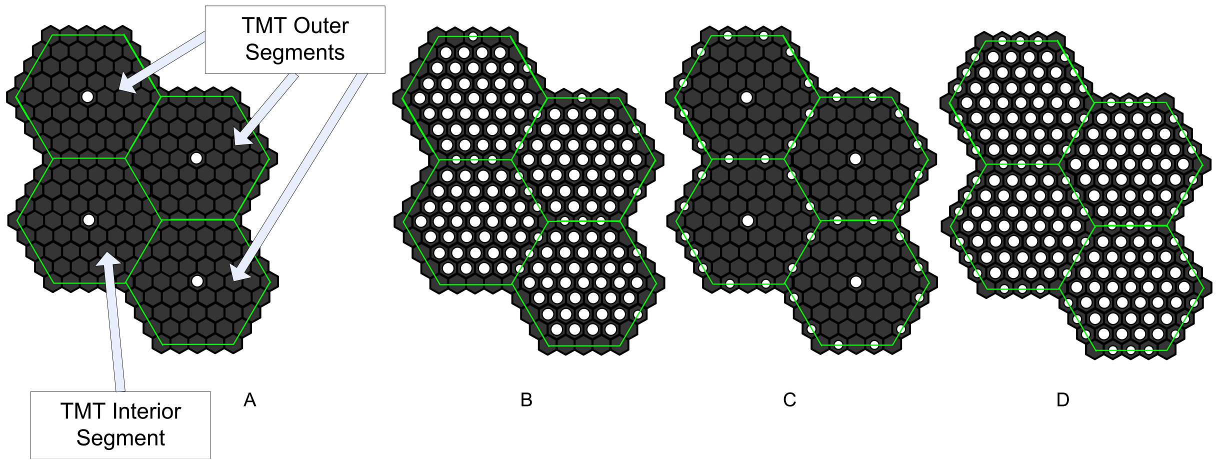


Figure 5. Detail of various mask/lenslet geometries, corresponding to four segments at or near the periphery of M1.

D. Ultimate mask: This mode has three full subapertures per intersegment edge plus a close-packed geometry internal to the segment, with 37 subapertures interior. This mask can potentially fulfill the requirements for phasing, fine tilt, and segment figure (masks B & C). However, there is a risk of image crowding which we are currently investigating.

4.5. Pupil Image and Tracking Assembly

The PIT provides for measurement and control of the pupil position, as well as a measurement of the image pointing. The APS PIT will control:

1. The telescope pupil position (x, y, and θ) within the APS at a rate of once every 10 seconds.
2. The star location (telescope pointing) within the APS at a rate of once every 10 seconds.

There is a tilt plate which enables translation of the telescope pupil. The beam splitter redirects 50% of the light to the remaining PIT optics. The PIT camera is a SH camera with a design similar to the main SH camera. There is also a filter wheel and a single mask/lenslet array subassembly. The mask/lenslet array will have one subaperture per segment edge and one subaperture at the center of each segment. The subapertures at the segment centers will give the overall image tip/tilt. The edge subapertures on the outer segments will determine the pupil registration based on balancing light intensity between the subapertures which are half-on and half-off the segments.

5. PROCEDURE EXECUTIVE AND ANALYSIS SOFTWARE

The APS Procedure Executive and Analysis Software (PEAS) provides the central interface for all alignment and phasing activities of the APS, primarily the execution of procedures and analysis computation functions that achieve the alignment and phasing of M1, M2, and M3. The PEAS interacts with the APS and with telescope software interfaces primarily M1CS, M2CS, M3CS, and TCS to analyze and correct misalignments through a set of defined procedures.

PEAS provides the software framework within which the analysis computations and alignment procedures will run. As experience at Keck has demonstrated, in addition to being used in an operational context, the PEAS system will be used for research into improving image quality.

In general, each procedure will generate commands to the APS_CC, M1CS, M2CS, M3CS, and/or TCS, then gather image data from APS detectors and mirror control system data for the purpose of image quality analysis, and finally command M1CS, M2CS, and/or M3CS to achieve better image quality.

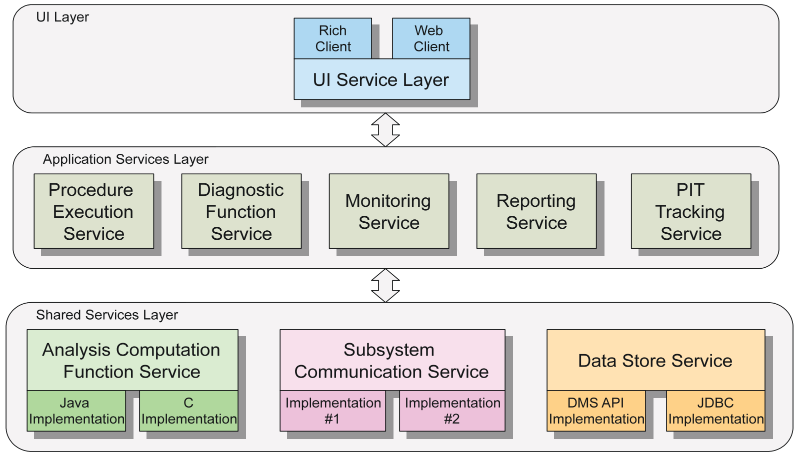


Figure 6. APS PEAS Architectural Layers

Additional functions of the PEAS are procedure result reporting, diagnostic functions, monitoring of APS subsystems, and commanding/monitoring telescope subsystems, and persisting procedure-related data

5.1. PEAS Functional Requirements

The APS is the primary system for aligning telescope optics in TMT. When unanticipated optical problems are detected, the validity of the APS results must be demonstrated. APS must self-diagnose optical problems, run ad-hoc procedures and analysis computation functions that can shed further light on unanticipated problems with the telescope, and integrate new procedures and new versions of procedures that better address problems once found.

All PEAS features will be accessible through a graphical user interface, including support for procedure configuration and execution, and analysis data visualization displays. PEAS will provide nightly summary reports and procedure detailed reports through a reporting user interface.

During execution of on-sky procedures, APS will execute a pupil and image-tracking loop that maintains correct pupil and image tracking through image analysis and commands to TCS, M3CS, and APS_CC.

PEAS will archive all data related to procedure execution to a database. This data will include all relevant procedure-configuration data, procedure image data, all relevant computed results, commands, state/health of all external interfaces and internal subsystems, and software exceptions.

Many of the functional concepts are derived from the PCS software developed for the Keck Observatory, which was also developed by the PEAS team. The functional concept retains the most successful elements from PCS, while the entire design addresses shortcomings exposed over nearly two decades of support.

5.2. PEAS architecture

PEAS will be designed using a layered architecture (see Figure 6), which will separate lower-level shared services and client user interface layer from an application services layer. Each application layer service closely mirrors features of the system, and shares services provided from the lower layer. By separating out communication and data storage services to a lower services layer, the PEAS software becomes more resilient to observatory software implementation changes in these areas.

Separating User Interface (UI) related code from application code creates a clean separation of application and user interface related concerns, and creates an Application Programming Interface (API) that will facilitate calling application services related code in the future without a user interface (automated APS functioning).

PEAS may be distributed over several physical servers because some intensive analysis computations may need to run on a higher performance server or a scalable set of servers. The distributed architecture will be facilitated

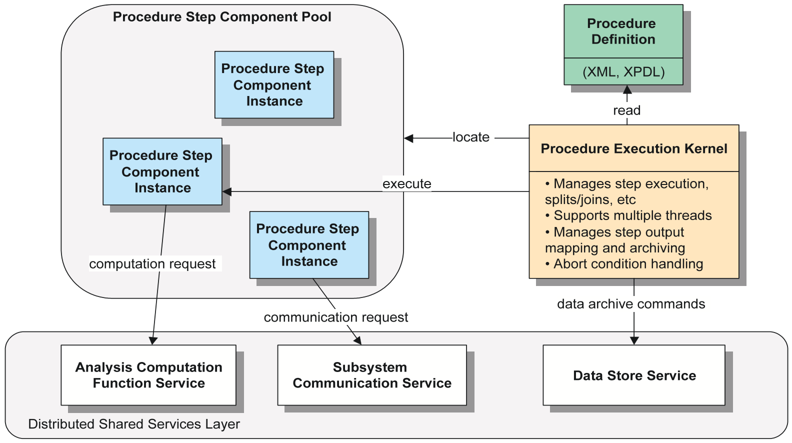


Figure 7. APS PEAS Procedure Executive framework

by a Container-Component model (CCM) and middleware. All services will be implemented as components. These components are deployed to containers running on each physical server. The CCM services make the remote distribution transparent to each component so that redistribution of components is a matter of software configuration, not rebuilding.

5.3. PEAS Procedure Executive Framework

The PEAS Procedure Executive Framework (see Figure 7) is a framework that will enable the APS scientist to create, update and maintain multiple versions of procedures and analysis computations without the need for rebuilding or revalidating the core PEAS system.

The framework consists of a Procedure Definition Document that contains the process execution instructions, the Procedure Execution Kernel which reads the definition document and executes the flow by locating and executing steps in the Procedure Step Component Pool.

The Procedure Execution Kernel is responsible for reading and executing procedures, handling thread splits and joins and step execution output data archiving. Each step component is responsible for a simple task: e.g. execution of a computation or sending a command to an interface.

This framework permits procedures to be developed separately from the rest of the system, and also supports archived procedure versions to be easily loaded to re-run previous versions. When created using a form-based design tool, procedure definitions can be self-documenting, self-validating and easy to understand by the non-programmer. The framework handles parallel processing, so the scientist-developer need only declare which steps should be processed concurrently. Data archiving of step execution outputs is automatically performed by the framework and need not be a concern for the scientist user.

6. TECHNICAL RISKS

6.1. Lenslet-Related Issues

Because of problems with lenslet image quality, PCS used an array of prisms in place of the usual lenslet array. The prisms were of extremely high optical quality and this substitution worked very well. (The focusing power normally associated with lenslets was provided by a single downstream macroscopic lens.) However, the much larger number of intersegment edges on TMT, combined with the greater pupil demagnification, makes it impractical to build prism arrays of the appropriate geometry. (The individual prisms would have to be much smaller than the 2 mm x 3 mm prisms used in PCS.) We are optimistic that lenslet manufacturing techniques have improved sufficiently in the twenty years since PCS was designed and that lenslets will now be practical for phasing, but we will verify this carefully in the laboratory. The fallback position is to use fewer lenslets per edge, make the lenslets over-sized, and stop them down with masks (applied directly to the lenslet array itself) to an appropriate size.

Finally, while the Keck segment geometry was a regular hexagonal array as seen in projection, this is not the case for TMT. Thus, the PCS lenslet pattern was also a regular hexagonal array, but the APS pattern will not be regular.

6.2. Tomographic Alignment

Limited simulations have been performed of the tomographic alignment function responsible for disentangling the M1, M2, and M3 aberrations and for determining the rotational shear that results when M3 is rotated to access different focal stations. A full-up simulation of this function must take into account the relatively small footprint of M1 on M3 (the footprint covers only about one-quarter of the overall surface of M3), which means that a total of six or seven overlapping individual measurements must be made, and these must be stitched together in order to describe the full surface of M3.

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