The Alignment and Phasing System for the Thirty Meter Telescope: Risk Mitigation and Status Update

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ABSTRACT

Alignment and Phasing System (APS) is responsible for the optical alignment via starlight of the approximately 12,000 degrees of freedom of the primary, secondary and tertiary mirrors of Thirty Meter Telescope (TMT). APS is based on the successful Phasing Camera System (PCS) used to align the Keck Telescopes. Since the successful APS conceptual design in 2007, work has concentrated on risk mitigation, use case generation, and alignment algorithm development and improvement. Much of the risk mitigation effort has centered around development and testing of prototype APS software which will replace the current PCS software used at Keck. We present an updated APS design, example use cases and discuss, in detail, the risk mitigation efforts.

Keywords: Telescopes, Segmented Mirrors, Optical Alignment, Phasing

1. INTRODUCTION

APS is a Shack-Hartmann (SH) 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), secondary mirror (M2) piston and tip/tilt (or X/Y decenters), and tilt and rotation of the tertiary mirror (M3).

In December of 2007, APS passed a Conceptual Design Review (CoDR).[2] Since that time there have been several significant changes in the design of TMT as well as progress and risk mitigation efforts related to APS. The changes to TMT that impact APS include the decision to build passive (not active) M2 and M3 mirrors. In addition, analysis has shown that the TMT Global Metrology System (GMS) can position the M2 rigid body degrees of freedom to sufficient accuracy that APS is no longer required to make off-axis measurements to align M2 in all 5 degrees of freedom.

In Sec. 2 we give an overview of APS followed by a description of the baseline use cases for APS in Sec. 3. We then (Sec. 4) discuss the changes made to the optical-mechanical design as well as summarize risk mitigation efforts that occurred related to lenslet arrays for phasing. In Sec. 5 we present APS software and algorithm development and risk mitigation efforts which have already resulted in development of software that is used to run the Keck PCS.

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 in three degrees of rigid body motion (piston, and either tip/tilt, or x-/y-decenter)
- M3 in two degrees of rigid body motion (tilt and rotation)

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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.

The design of APS is based upon that of the Phasing Camera System (PCS),[3] which fulfills a similar role for the Keck 1 and 2 telescopes. 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, Charge Coupled Device (CCD) and the relatively small number of segments, a serial approach to segment figure measurement was adopted at Keck. APS will measure all segment figures simultaneously as well as calculate and send the needed commands to adjust the segment figures via the warping harnesses.

However, there are also some fundamental differences in the designs and philosophies of PCS and APS, driven by both the much larger diameter of the TMT and experience at Keck. They are:

- APS is ∼4 times larger in length and width than PCS
- APS needs to handle ∼30,000 subimages vs. ∼500 for PCS which results in the need for a very high level of automation in the software as well as the need for a large CCD.
- Unlike at Keck, the segment warping harness algorithms will be directly incorporated into APS and using automated motors APS will correct the segment figure errors in real-time. This also enables the ability to iterate the control for potentially better performance.
- APS will have the ability to perform pupil and image tracking at a ∼0.1 Hz rate, as well as guiding at 10 Hz.
- APS phasing masks will use Fresnel propagation, not micro-prisms (see Sec. 4 for more details).
- APS will have the ability to make off-axis wavefront measurements.
- APS will have the ability to image the telescope pupil.

Since the APS CoDR in 2007 both the M2 and M3 mirror designs have changed from active shape control to passive optics with only rigid body control.[4,5] In the case of M2, the primary mirror with its approximately 12,000 degrees of freedom can effectively correct any static errors on M2. In the case of M3, M1 can only correct for the on-axis errors and even then effectively only for the APS instrument location. That is, when M3 rotates to a different instrument, the M1 pupil rotates on M3. As a result, the correction of M3 errors by M1 will be incorrect and in general increase the wavefront error by $\sqrt{2}$. However, it has been shown[4] that a passive M3 will still meet the TMT performance requirements. Related to both of these changes is that it has been shown that off-axis measurements cannot effectively disentangle the M2 or M3 errors. APS requirements have changed accordingly. The new APS requirement is to have the ability to measure the wavefront at any field of view, but not to determine which optics are causing any observed errors.

APS is comprised of three major subsystems: the APS Optical Bench, the Instrument Control System (ICS) and the Procedure Executive and Analysis Software (PEAS). The ICS 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 SH CCD, the acquisition camera CCD, and the pupil image tracking CCD. The ICS will conform to the TMT standard software interface definition. As a result, the APS Optical Bench can be commanded by any TMT system. This is critical as APS is also the first light Nasmyth platform TMT instrument and will be used for early commissioning and the related pointing and guiding tests.

The PEAS is described in detail in Sec. 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.

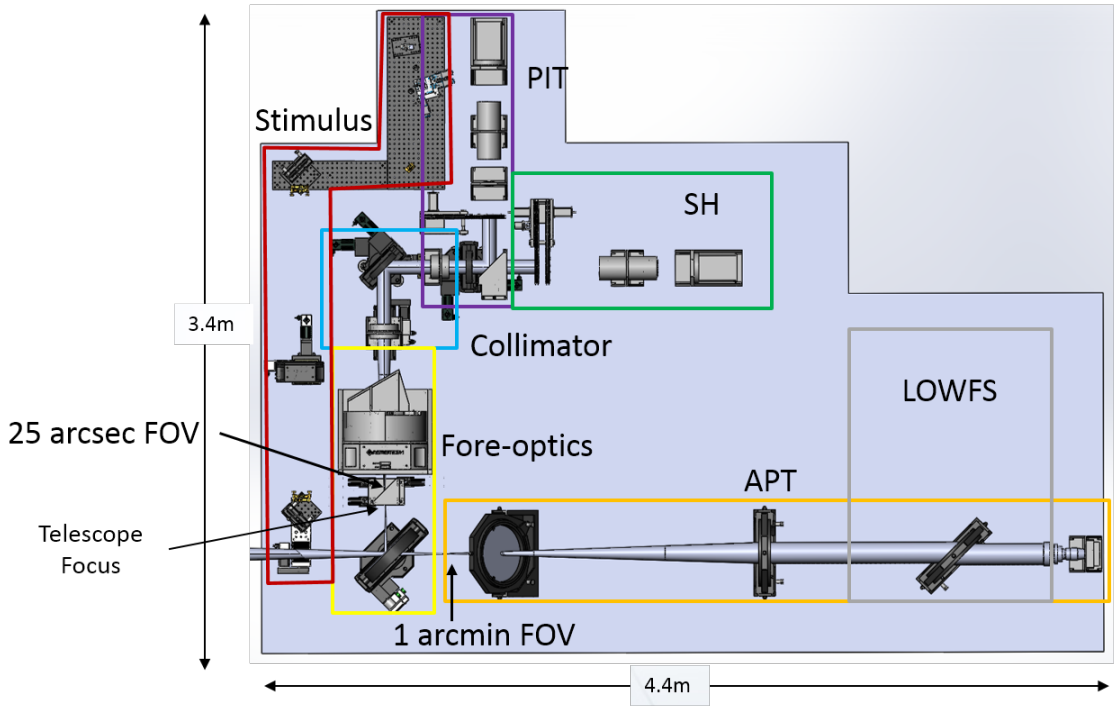

Figure 1. APS optical bench layout with assemblies labeled

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

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

Sec. 4 provides an update on the design and risk mitigation efforts related to the optical bench. The remainder of this section provides a brief overview of 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 1 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).

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 9k x 9k 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 ($\sim$60 seconds). The PIT assembly is a SH camera that will measure the pupil misregistration by balancing the intensity of SH subimages from subapertures 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.

Sec. 3 describes the APS use cases in detail. 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, centered and guiding is started.
3. The PIT loop is started and will run at a rate of 0.1Hz.
   (a) Required pupil motion is sent to the K-mirror and internal APS pupil tilt mechanism.
   (b) Required image motion if any is adjusted by changing the guiding set point sent to the telescope.
4. One or more frames of data are taken by the SH camera to make wavefront measurements.
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. USE CASES

As part of the APS preliminary design we are developing use cases in Systems Modeling Language (SysML) as described elsewhere.[6] These use case are being used to help develop, derive and verify interfaces to external sub-systems, help perform early verification of APS timing requirements, and specify APS software needs and specifications. By developing APS use cases, we will be able to better communicate with other TMT sub-systems, and TMT as a whole, how we plan to operate APS in order to align and phase the telescope.

As we develop each of these activities, the APS team holds regular meetings with the TMT systems engineering team and other sub-systems to ensure everyone understands how the telescope will be aligned, and what is needed from each of the sub-systems. For brevity, we only highlight some of these use cases and activity diagram here; however, we are also developing a much more detailed document to be delivered to TMT that contains the full list of use cases with their entrance criteria and requirements, and all of the lower level activities. This provides a very clear understanding of how TMT will be aligned to everyone involved.

In this Section we begin by describing the main use cases that we are developing and their status. We then show the details of the post segment-exchange alignment, which is one of the more demanding use cases.

3.1 List of Use Cases

The following list provides a brief overview of APS use cases and the status of their development. Many of the use cases also have requirements on how quickly they need to be executed; we present both the requirement and our Current Best Estimate (CBE) for the execution time. One of the benefits of using SysML is that its constructs and diagrams carry meaning that can be interpreted by a computer. Therefore, specifying the behavior and timing of atomic actions performed by components of the system enables one to derive characteristics such as the total time taken for a use case to execute.[6]

Post segment-exchange alignment (Done) This use case re-aligns the telescope after new segments have been installed or exchanged. The current TMT baseline is that during normal operations ∼8 segments will be exchanged in a single day every two weeks; this use case will then be run to re-align the telescope. Our current estimate is this procedure could be started 20 minutes (To Be Resolved (TBR)) after sunset. The requirement is that APS execute this use case in less than 2 hours and our CBE is 1 hour and 20 minutes.

Maintenance alignment (Done) This use case is used to re-align the telescope in between segment exchanges, as a type of tune-up alignment. The end result is the same as the Post segment-exchange alignment use case; however, this use case has a smaller capture range for segment piston, tip and tilt errors. The current TMT baseline calls for the telescope to be aligned by APS at least monthly. So, if there are no segments exchanged in a given month then this use case would be executed. In addition this use case can be used to check/adjust the alignment just before specific observations that are very sensitive to wavefront errors. The requirement is that APS execute this use case in less than 30 minutes and our CBE is 25 minutes.

Rigid body M3 alignment (Done) APS has a requirement to align M3 in rigid body motion. The main impact of M3 motion is pupil motion, which APS can measure. This use case will align M3 at a single elevation angle. There is currently no requirement on the time to execute this use case, but our CBE is

less than 2 minutes. This use case will likely be incorporated into both the maintenance alignment and post segment exchange use cases.

Off-axis wavefront measurements (Done) This use case is used to make off-axis wavefront measurements at any point in the telescope field of view. It will be used to diagnose telescope problems as well as confirm the telescope performance off-axis. There is currently no requirement on the time to execute this use case; the CBE is 45 minutes.

APS pre-observing internal calibrations (Next to develop) There are several internal APS calibrations that need to be performed either before or during observing. The majority if not all of these can be executed using internal light sources during the day in an automated fashion. This use case is designed to execute these calibrations in order to minimize APS on-sky time.

Post segment-exchange M1 Control System (M1CS) sensor calibration (Planned) After segments are exchanged it will be necessary to perform some type of calibration of the M1CS sensors. The details of this are being worked out by the M1CS (and APS) teams. The most likely scenario will involve executing the phasing activities at multiple elevation angles. APS will collect the required data, but M1CS will analyze the data and update the sensor calibrations.

Collection of M2 and M3 gravity calibration data (Planned) This use case will align M2 and M3 at multiple elevation angles in order to provide the data needed for generation of calibration of M2 and M3 motion with telescope elevation angle. APS is responsible for collecting this data, but the other sub-systems are responsible for using this data to generate the needed calibrations.

Measurement of segment warping harness influence functions (Planned) This use case will be used to make on-sky measurements of the segment warping harness influence functions. These measurements, potentially combined with the analytical influence functions, will be used to generate the control matrix for the warping harness used in the rigid body and segment figure activity. This use case will likely only need to be executed during Assembly, Integration and Verification (AIV), trouble shooting and/or periodically (yearly) to confirm that the warping harness influence function are not changing with time.

APS pre-segment exchange checkout (Planned) This use case will execute a series of APS tests using internal light sources to confirm that it is functioning correctly. This standard procedure will be to execute this use case the day before a segment exchange starts in order to minimize telescope down time due to any APS problems.

3.2 Sample Use Case: Post Segment-Exchange Alignment

After segments are exchanged in the telescope, typically for re-coating, APS will be used that night to execute this use case to re-align the telescope. Assuming the entrance requirements are met (all segments are within tip/tilt and piston capture range, etc.) then the time to run this test is independent of the number of new segments installed (nominally 8 segments per night will be exchanged).

Fig. 2 shows the post-segment exchange alignment use case, represented as a state machine.[7] For each of the use cases, APS starts in the standby mode. Once the user initiates the start of the use case, a star will be acquired within the coarse tilt alignment activity. This activity, which is described in Sec. 3.2.1, will capture and align the segments in tip/tilt. Once this has completed the broadband phasing 30 micron activity will be executed (see Sec. 3.2.2). As part of this activity, the telescope will be requested to start guiding, as we now have a single star image on the APT camera, and APS will close the PIT loop using the same star used in the coarse tilt activity. This activity will reduce the initial segment piston errors to $\sim$1 micron. At this point the M1CS will be commanded to minimize sensor readings to insure the M1CS sensors are in their most linear range. The next activity (rigid body and segment figure) aligns M1 segments in tip/tilt, M2 in piston and either tip/tilt or x/y translation as well as measuring the segment figures and correcting them via warping harnesses. Nominally this activity is repeated twice to allow for iteration of the segment figure adjustments. After this, the segments are aligned to 30 nm RMS surface piston error using first the broadband phasing 3 micron and followed by the 1 micron activities. Each of these will require acquisition of new stars of the appropriate magnitude. The final

M1 segment piston alignment is executed using the narrowband phasing activity which includes measurements with 2 different wavelength filters.

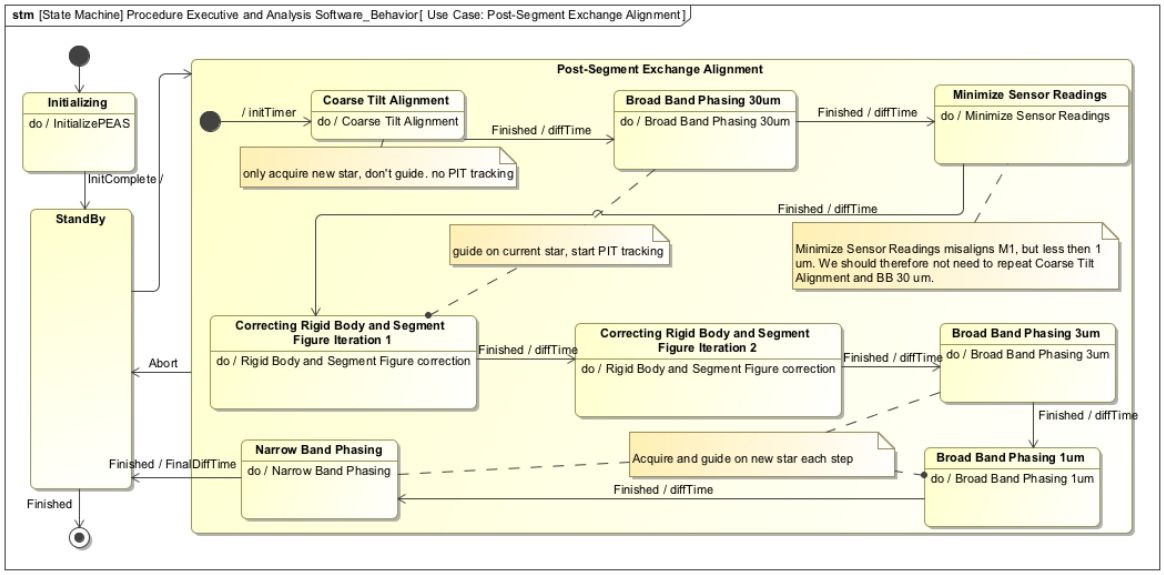

Figure 2. State machine diagram of the Post Segment-Exchange Alignment use case

3.2.1 Coarse Tilt Alignment

The purpose of the coarse tilt alignment procedure is to capture segments in tip/tilt after their initial installation or after a segment exchange. The tip/tilt capture range of ± 12 arcseconds is such that we can image and identify one spot per segment. A field stop insures that there is no confusion about which spot belongs to which segment. The procedure will correct the segment image tip/tilts to within 0.3 arcseconds (one dimension, RMS), which is then within the capture range of the rigid body and segment figure alignment activity (not documented here for brevity).

As can be seen in Fig. 3, we begin most of these activities with configuring the bench, acquiring a star, and possibly starting to guide (a True/False flag seen on the "doGuide" input parameter). Note that each of the actions with an upside-down fork-like symbol are further detailed in another activity diagram. At the lowest level of refinement, only atomic actions remain. It is only for these atomic actions that we specify time estimates. The setup activity is followed by taking an exposure with the main SH camera. The resulting image is analyzed and various autonomous actions take place, such as centering the image on the SH camera by sending the guide loop offset commands. In addition, the operator is asked if the commands should be sent to the primary mirror (M1CS), and if so, a new configuration is saved.

3.2.2 Broadband Phasing

The Broadband Phasing activity is the heart of the Keck phasing method.[8] For TMT, this will be the method used to capture segments with large piston errors, up to 30 μm and with 3 iterations with different filters, bringing it down to 30 nm RMS surface. In the case of TMT, the requirement for phasing is 6.8 nm RMS surface which will be achieved using the Narrowband phasing method.[9] Note that the latter is not needed for Keck; however, we are currently developing and testing the method using the Keck telescopes as part of the PEAS PCS (PEAS-PCS) project. The status of this method is documented elsewhere in these proceedings.[10]

Fig. 4 illustrates how we begin by configuring the APS bench and acquiring a new star. After this, a look-up table is used to step the primary mirror segments through nominally 11 different piston configurations and the first configuration is sent to M1CS. Next a SH image is taken and the pupil registration and pointing error are

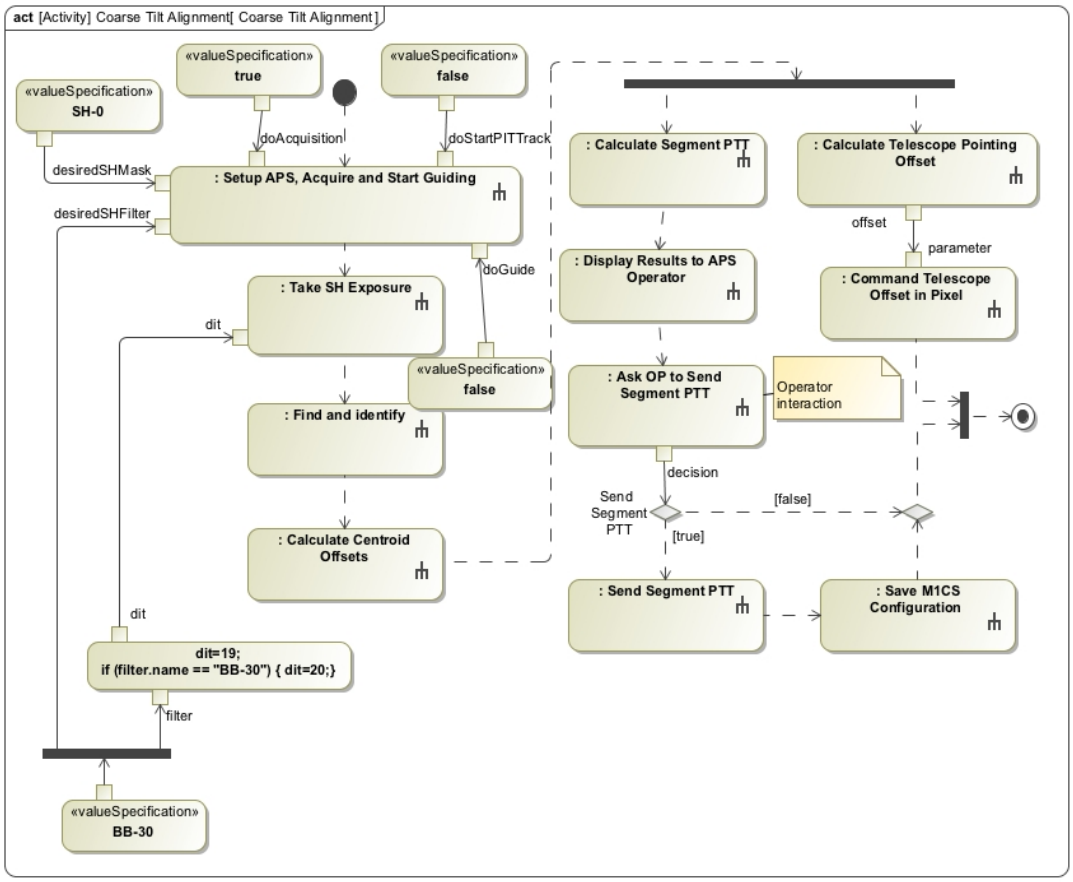

Figure 3. Activity diagram of the Coarse Tilt Alignment procedure

calculated and sent to the appropriate sub-systems. Finally, the coherence parameters for each subimage are calculated (as these are needed in a later step). In parallel to this the commands are sent to M1CS for the next mirror configuration. This process is repeated for all piston configurations. After the last configuration, the edge steps for each phasing subimage are calculated and the segment piston errors calculated. As with Coarse Alignment, the results are displayed and the operator is asked if the commands should be send to the primary mirror and a new snapshot of the configuration is saved.

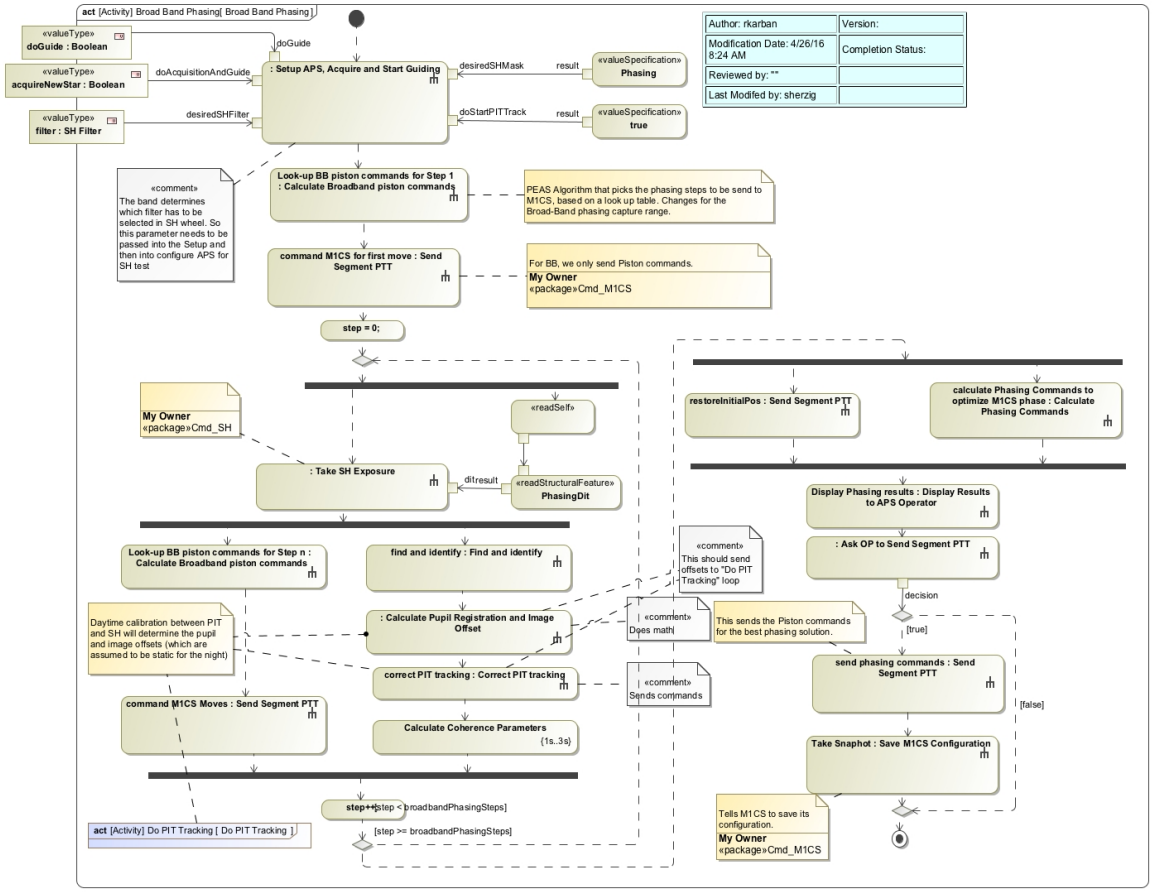

Figure 4. Activity diagram of the Broadband Phasing procedure

4. OPTO-MECHNICAL DESIGN AND RISK MITIGATION

The primary function of the opto-mechanical design is to reimage the telescope pupil to the measurement plane in APS (to lenslets or masks) and then image the resulting spots to the detector. The APT system is used to acquire a source, the fore-optics and collimator provide the reimaged telescope pupil in the correct orientation, the PIT provides feedback to the K-mirror and tilt plate to maintain the pupil position for the SH, and the SH camera takes the images for APS measurements.

Most of the elements of the APS system have been described previously.[2] A few changes have been made due to modified requirements and to mitigate risks. A telescope stimulus has been designed to use for testing of hardware and software both before APS is built and throughout the life of the instrument. The APT has been redesigned for a smaller field of view (60 rather than 120 arcseconds) and to better accommodate a Low Order Wavefront Sensor (LOWFS). The SH camera designs have been adjusted to use Fresnel diffraction rather than lenslets for phasing data.[11]

4.1 Telescope Stimulus Design

A test light source common to all the sensors in the system was envisioned in the conceptual design but at that time, the use case and associated requirements had not been developed. To test the most critical elements in the system, the stimulus must be capable of providing light for testing the measurements of APS SH and PIT cameras as well as testing the ability to use those measurements to control the K-mirror, pupil tilt plate and to align segments. It must also be capable of providing light to test the imaging of the acquisition camera, on-axis, as well as a LOWFS to be located along the acquisition path. By including the stimulus as a an addition to the

APS system, these tests can be performed at any time during the life of the instrument. With the addition of an external phasing camera assembly (using a less expensive detector than the final SH camera), the stimulus can also be used during APS development to test algorithms and software before the final APS system is built.

The stimulus as shown in Fig. 5 includes: a broadband (600-950nm), fiber-fed light source with 3-axis motion control to introduce tip/tilt and focus, a pupil stop with motorized X-Y and rotation adjustments to accommodate masks that simulate the telescope pupil, a segmented Deformable Mirror (DM) to simulate the motion of the telescope segments and a motorized stage to insert or remove the stimulus light from the optical path. The DM is a unique element in the stimulus system. It is an IRIS AO PTT489 with 163 segments, each with independent tip/tilt and piston adjustability and 5 μm of overall stroke per segment. Each hexagonal segment is 700 μm across the corners, for a full diameter of 7.7 mm. This provides enough segments to simulate the inner 7 rings of the TMT primary mirror, just over half the diameter. Since the TMT segments do not map to regular hexagons in a flat plane, it would be difficult to match a DM to the outer segments without significant cost, even if a DM were available with more segments. The available segment tilt on the DM maps to 0.79 arcseconds on-sky, which is sufficient for testing fine segment tip/tilt, but not the full range of coarse capture. The 5 μm of segment stroke will enable testing and verification of Narrowband Phasing and at least one of the Broadband Phasing modes. The DM will not be used for testing segment warping harness control. Overall the IRIS mirror is an excellent compromise between capability and a readily available device. The stimulus also has the ability to manually insert a flat mirror in place of the DM, enabling testing and calibration of the system using the full TMT pupil.

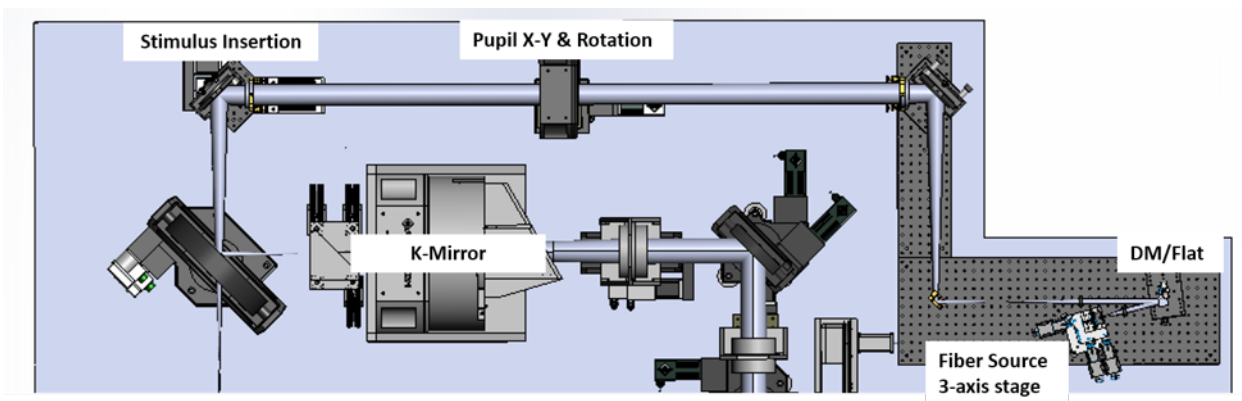

Figure 5. The stimulus provides an f/15 beam to simulate the beam coming from the telescope. It can be accommodated within the existing APS bench footprint.

4.2 Acquisition Pointing and Tracking Assembly Design

The APS APT assembly has several functions. It provides the following:

1. A large (60 arcsecond) FOV so APS can quickly acquire stars. The APS FOV in the SH and PIT arms is only 25 arcseconds.
2. A CCD to enable the Telescope Control System (TCS) to perform pointing and tracking tests and calibration as well as to validate that they meet the required performance.
3. The needed hardware to perform close-loop guiding and validate that the required performance is met.
4. A fast-framing mode (100Hz) to capture possible vibrations.
5. A location to host a LOWFS for commissioning the telescope and active optics system.

The APT camera is shown in Fig. 6. Light from the telescope (or stimulus) transmits through the first large beamsplitter, while the SH path reflects from this beamsplitter. The beamsplitter is sized to pass the 60-arcsecond acquisition FOV. In the current design 5% of the light is transmitted through the beamsplitter. The TMT focus is located after the beamsplitter. There is a corrector optic immediately after the beamsplitter to remove aberrations induced by going through the beamsplitter. The beam is then collimated before being imaged onto the detector. The collimated space allows for a beamsplitter (for the LOWFS) and filters to be

inserted with minimal induced aberrations. The APT camera reimages the TMT focus to a 1024 x 1024 pixel CCD with a plate scale of 0.05 arcseconds/pixel.

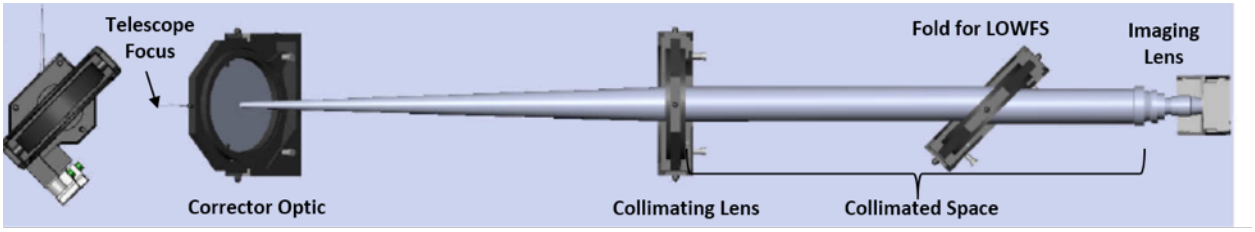

Figure 6. The APT has a 60-acrsecond FOV and feeds both a LOWFS and forms an image on a CCD for acquisition, guiding, and other needed telescope tests.

4.3 Risk Mitigation of Pupil Sampling for Phasing

APS, like PCS, will perform segment phasing using a SH wavefront sensor with subapertures that span adjacent segments. However, one potential limitation to the absolute accuracy of this technique is that it relies on a lenslet array (or a single lens plus a prism array) to form the subimages. These optics have the potential to introduce wavefront errors and stray reflections at the subaperture level that will bias the phasing measurements. To better quantify this risk several representative lenslet arrays were purchased and tested.[12] The RMS systematic error measured for lenslet arrays produced using photolithography was 0.70 nm RMS (consistent with the measurement noise of the experiment) while epoxy replicated lenslet arrays had an error of 4.5 nm RMS. The prims used in PCS for phasing have an RMS error of 1.9 nm. These results demonstrated that lenslet arrays produced using photolithography have acceptable measurement biases, comparable to the prisms used in PCS.

As part of these experiments it was realized that the Fresnel numbers of the lenslet arrays for APS are such that a lenslet-free approach using Fresnel diffraction to form the subimages at the CCD might work. Several masks were obtained and tested using the European Southern Observatory (ESO) Alignment and Phasing Experiment (APE)[13] in both closed and open loop operation. The measurement repeatability was 3 nm RMS and the absolute accuracy was better then 6 nm and 10 nm without and with artificial atmospheric turbulence.[11] We expect APS results to be even better as neither the Fresnel number or pixel sampling was optimal in the experiments. As a result of these experiments the baseline design for APS is now to use Fresnel phasing. The design of the SH camera was modified to include a stage, which will allow dynamic adjustment of the propagation distance (and thus the Fresnel number) as well as the capability to re-image the telescope pupil onto the CCD.

5. PROCEDURE EXECUTION AND ANALYSIS SOFTWARE

APS PEAS (APS-PEAS) provides the central graphical interface for all alignment and phasing activities of APS, primarily the execution of procedures and analysis computation functions that achieve the alignment and phasing of M1, M2, and M3. APS-PEAS interacts with the APS ICS in addition to the M1CS, TCS and Executive Software (ESW) to analyze and correct misalignments through a set of defined procedures. In the current TMT software architecture, the M2 Control System (M2CS) and M3 Control System (M3CS) are commanded via TCS. APS-PEAS provides the software framework within which the analysis computations and alignment procedures will run. The design and development of the analysis computations and alignment procedures are not part of APS-PEAS, however the implementation of these, once developed, occurs in APS-PEAS. APS-PEAS also provides all needed data visualization displays. A database is used for storage and retrieval of all collected and analyzed data as well as all configuration information.

5.1 PEAS-PCS Introduction

As part of a risk reduction effort, in February, 2014 we started a collaboration with Keck on a project called PEAS-PCS. This is a joint TMT and Keck effort which started out as an effort to prototype the TMT APS-PEAS and alignment algorithms and use them operationally at Keck for PCS.

The PCS software at Keck started development in ∼1989 (27 years ago), the software has been upgraded many times, but never re-written from scratch. As a result the current version of PCS, called PCS Ported (PCSP) has become so brittle that it has been frozen and effectively no code changes can be made. PEAS-PCS has now replaced PCSP and is used during routine alignment operations at Keck.

PEAS-PCS mitigates risks for both APS and TMT in the following areas:

- Testing the design of decomposing the system when the computations are workflow activities.
- Investigating the use of a web based User Interface (UI), specifically in the areas of asynchronous popups and visualization displays.
- Developing verification and documentation of the needed APS algorithms, including on-sky testing.
- Testing and understanding how best to implement and modify the TMT defined software development process.
- Providing TMT with experience with real segmented telescopes and the associated problems.
- Testing of additional TMT algorithms and procedures such as segment warping.

All of the above will help to reduce the needed amount of time to perform integration and test activities at TMT. PEAS-PCS also provides many benefits to Keck. It has provided improvements to Keck in the PCS algorithms and user interface which have already saved observing time, improved reliability, and accuracy. PEAS-PCS has also provided a replacement for the end-of-life PCS software.

Figures 7 and 8 show examples of the web based UI and visualizations implemented using the technologies described in Sec. 5.2. These not only provide a superior interface to the current PCSP software, but have helped to prototype approaches that will be used for APS.

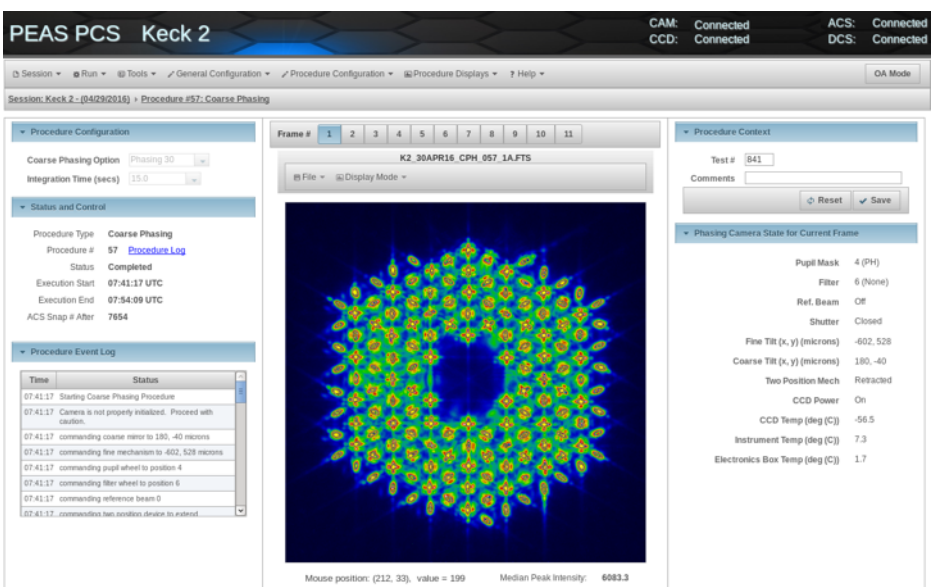

Figure 7. The PEAS-PCS web based UI provides an intuitive way to execute procedures and align the Keck telescope.

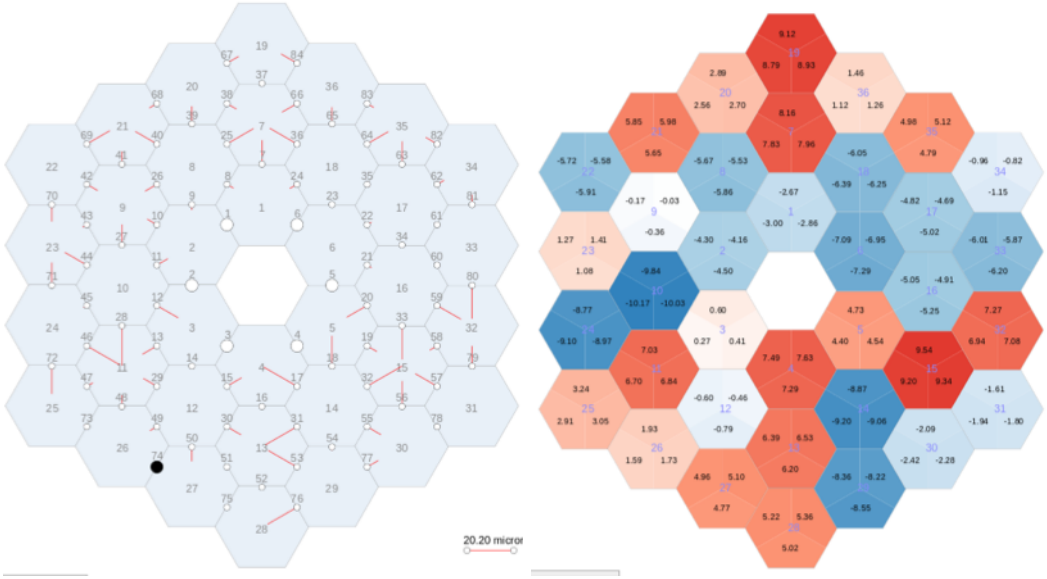

Figure 8. PEAS-PCS edge height display (left) and segment piston display (right) from a phasing procedure on Keck 2.

5.2 PEAS-PCS Design and Implementation

The core design of PEAS-PCS is the use of procedure flows for each alignment use case at Keck. Each procedure flow commands external interfaces (the PCS instrument, Active Control System (ACS) and TCS systems), performs computations, presents data visualizations (general and specific to a procedure), and may prompt users for input at flow decision points.

5.2.1 Fortran Computation Library

The computations that are called by a procedure flow are written in FORTRAN 95 and called by Java using auto-generated Java and C source code. The APS team internally developed the Java to Fortran code auto-generator. The computation code is purely functional and reentrant.

5.2.2 Relational Database

Configuration data is stored in a relational database. This includes instrument configuration, procedure and computation configuration and procedure execution preferences (used to configure the automation of user interaction within procedures). For every computed value and configuration value, a metadata table entry is used to describe that value, including information such as data type, units, and description.

5.2.3 Technologies Used

CCD frame and data visualization displays were implemented using HTML5 and JavaScript. A JBoss application server is used to host PEAS-PCS as a web application. Java Server Faces and Primefaces UI components were used to build the web user interface. Java Enterprise Edition (JEE) technologies were used for database connectivity (Java Persistence API (JPA)) and for building caches and dealing with concurrency. During a procedure flow execution, all computed values are automatically stored in a relational database using JEE method interceptors, which provide aspect-oriented capabilities. The database vendor used was PostgresSQL.

5.2.4 Deployment at Keck

PEAS-PCS is deployed on a single Virtual Machine (VM) for each PCS instrument. The VM has Java 7 and FORTRAN 95 installed as well as PostgreSQL and JBoss. PEAS-PCS uses Remote Procedure Call (RPC) calls to RPC servers hosted on other Keck machines that relay commands and queries to the PCS instrument, and the ACS and TCS systems. A deployment of PEAS-PCS is packaged as a web archive (.war file) and deployed to the JBoss server. The FORTRAN computations are packaged as a single dynamic library (.so file) that is copied to the VM.

5.3 PEAS-PCS Lessons Learned

PEAS-PCS was developed with an eye towards validating design concepts in APS-PEAS. The section details the lessons learned which are directly applicable to the APS-PEAS effort.

Using a relational database for most data enables third-party tools to be employed. For example, Matlab was used extensively for testing and analysis using data from the relational database, and for interfacing with other groups at Keck, such as those requiring PEAS-PCS data as inputs to the warping harness code.

We did not account for data taken in off-nominal conditions, e.g. frames that are currently discarded because they could not be used in subsequent analysis. We would like to save all data and be able to distinguish between data used for analysis and other data.

Keck users need a more directed user interface. Although PCS is used monthly on each of the Keck telescopes it is still often the case that a given user (Observing Assistant) will not have used PCS for 6 months. As a result the PCS users do not gain the experience to handle all situations. More automation is desired and required. The user interface should provide all the information needed for a user to respond to a question or step at the moment they need it.

We did not have access to a reactive push technology like WebSockets for the user interface, and had to use a polling pattern. This resulted in complicated code and timing issues that were difficult to debug.

When considering whether to use a Domain Specific language (DSL) driven workflow approach for APS, the PEAS-PCS project refactoring of PCS procedure flows was used to validate the approach and to develop a prototype set of flows and common sub-flows. The following lessons were learned:

- The majority of procedures mapped well to flows and sub-flows.
- One flow was very complicated and needs to be revisited.
- Asynchronous splits/joins can cross flow/sub-flow boundaries, which had not been considered.

When considering the APS-PEAS requirement for creating ad-hoc procedures, a design goal is to do this without additional code or database tables. In PEAS-PCS we found that new computations would require configuration with default values that might change, and the actual configuration would need to be stored with the completed procedure. This required new code and tables for each new computation.

Creating tables with field metadata (including units) was very important in creating reports and a consistent user interface, as well as having a system of record. This was not previously considered in the APS-PEAS design and could also be used for units validation when passing messages to workflow components.

We developed a simple "one-size-fits-all" approach to procedure reports, which in the end could not handle flow/sub-flow field grouping or multi-dimensional data. When developing APS-PEAS we will investigate Off the Shelf (OTS) reporting tools rather than build out any framework ourselves.

5.4 PEAS-PCS Next Steps

PEAS-PCS development is still in progress. During the coming year, two additional capabilities will be added; Narrowband Phasing[9] and incomplete mirror (the ability to handle missing segments). Both of these capabilities are required for TMT. The speed and accuracy improvements of Narrowband Phasing are required to meet the more stringent TMT wavefront requirements as well as to calibration the M1CS sensors. TMT will often operate without a full complement of segments (an incomplete mirror), so APS needs to be able to handle essentially any configuration of installed/operational segments.

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