TMT-APS DDD

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TMT-APS DDD

1 Introduction

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1.1 The APS and Its Role in TMT

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). 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), 2 degrees of M3 rigid body motion, piston of M2, and either tip/tilt or x/y translation of M2. 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 telescope.
The APS design and concept is based upon that of the Phasing Camera System (PCS), which fulfilled a similar role for the Keck Observatory telescopes. APS will use algorithms similar to those developed and used successfully by PCS at Keck. The resulting APS solutions will be stored as desired sensor readings for M1 or desired actuator settings for M2 and M3. These data can be analyzed as a function of recorded elevation and/or temperature so that look-up tables can be constructed for nominal elevation and temperature corrections. (Note, however, that the construction of such look-up tables from the APS data is not itself an APS responsibility.)

1.2 Purpose

This document will contain the basic Design Description (DDD) for APS. It will describe the system key requirements, system design and operational concepts. The document is meant to be a living document where anyone can find the current state of the APS design.

1.3 Overview

The current APS design is centered mostly around the Logical design prepared in 2007. This document started with that as a baseline and includes the various updates to the requirements, designs, operational concepts, performance predictions, etc since then.
Sections 1 provides an Introduction to the document. Section 2 is a general overview of the APS concept, providing background information, especially heritage from the Keck Observatory, and the ways in which the component elements and subsystems function in relation to one another. The key ad driving requirements are then summarized in Section 3. Section 4 provides the groundwork for the system requirements and specifications by describing in detail the operational concepts, ranging from organizational responsibilities to functional but nondesign- specific operating procedures, and the way the APS interacts with other TMT systems and the operations staff. These sections lead into the design of the APS subsystems in Section 5, which describes the design of the APS opto-mechanical components, including all of the individual optical subsystems, their system configuration, and the mechanical assembly and enclosure. The Instrument Control System (ICS) provides a single control point for all the APS mechanisms and is described in Section 6. Section 7 presents the design of the software required to operate the APS, as well as the data and computation system and related data interfaces that complete the functional APS. Section 8 describes the methodology by which the APS will be assembled and

commissioned; this includes pre-delivery testing at JPL and installation and verification at the telescope site. Section 9 discuss the current APS key issues and risks.

2 System Concept

2.1 Background

The design of the APS is based upon that of the Phasing Camera System (PCS), which fulfilled a similar role for the Keck 1 telescope and later for Keck 2. In particular, PCS was 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 original team of Gary Chanan, Mitchell Troy, and Scott Michaels who designed, built, installed, conducted initial operations, maintained, and eventually upgraded PCS at Keck, is now designing APS as Principal Investigator, Co-Principal Investigator, and Software Architect, respectively. In addition, J. Michael Rodgers of Optical Research Associates, who designed the original PCS collimator, is now designing similar optics for the APS.

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 were 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 is parallelized in APS.

However, there are also some significant differences:

- Due to the difference in instrument location the telescope pupil rotates in the APS instrument, necessitating the need for a K-mirror to de-rotate the pupil.
- APS needs to be able to make off-axis measurements to verify the telescope performance off-axis.
- The required phasing accuracy is higher ~10nm RMS surface vs 30nm for Keck.
- The warping harnesses at TMT will be directly adjusted by APS and as a result APS will need to incorporate the needed control algorithms.
- The M1CS sensors require calibration and multiple Zenith angles after every segment exchange. This drives a requirement (or at least desire) to be able to use multi-wavelength narrow band phasing.
- APS will have an active pupil tracking to stabilize the re-imaged pupil
- APS will need to handle random incomplete mirror configurations.

2.2 System Overview

The Alignment and Phasing System is responsible for the alignment of M1, M2, and M3. Here, the word “alignment” in general encompasses the determination as well as the correction of both rigid body and surface figure degrees of freedom. 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 parameters as required:

- M1 segments in piston, tip, and tilt

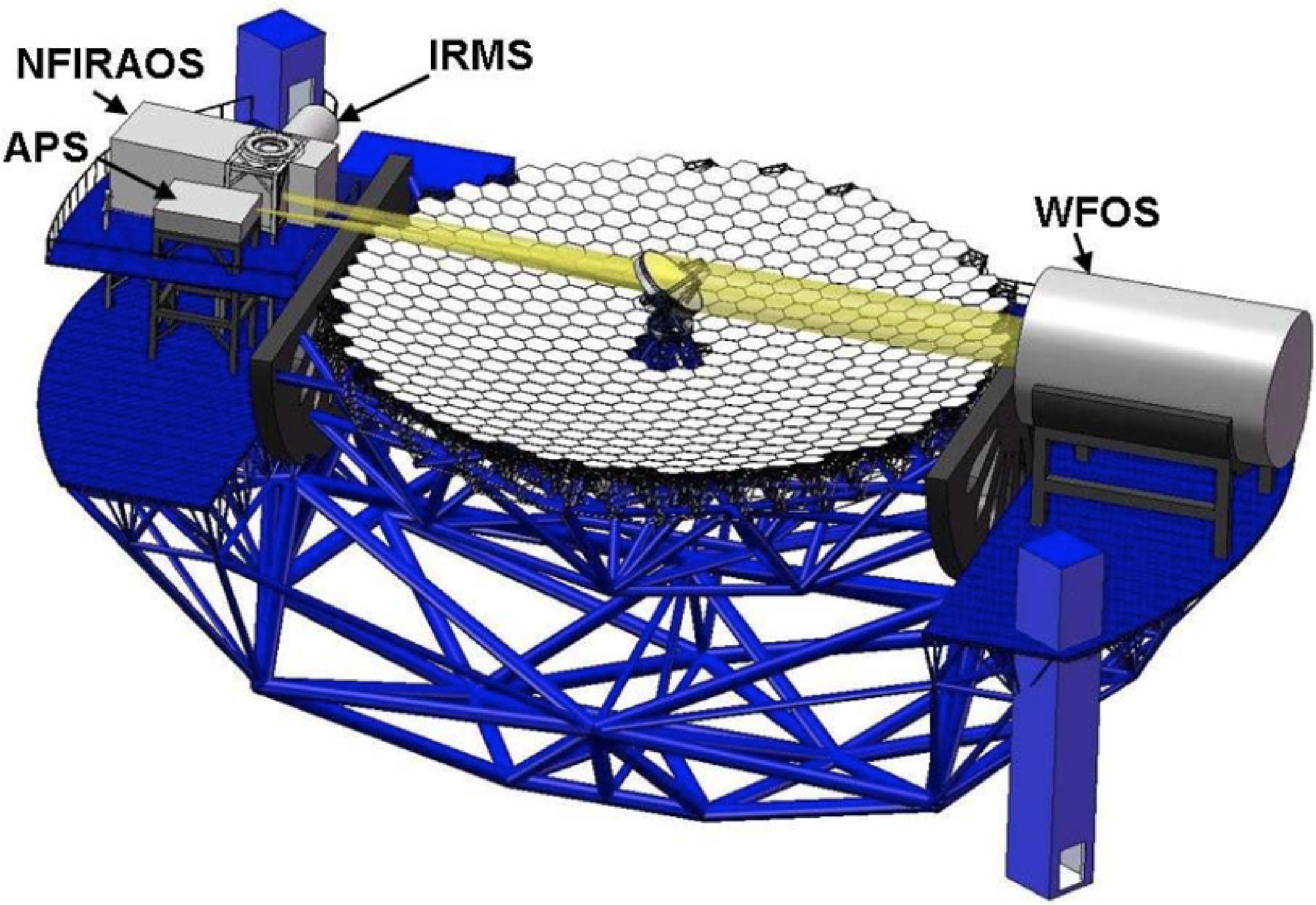
- M1 segment surface figure
- M2 piston and tip/tilt (or x/y-decenter)
- M3 tip and rotation

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. APS will take the necessary data, but the lookup tables will be generated by the TMT optical scientist using a TBD process.

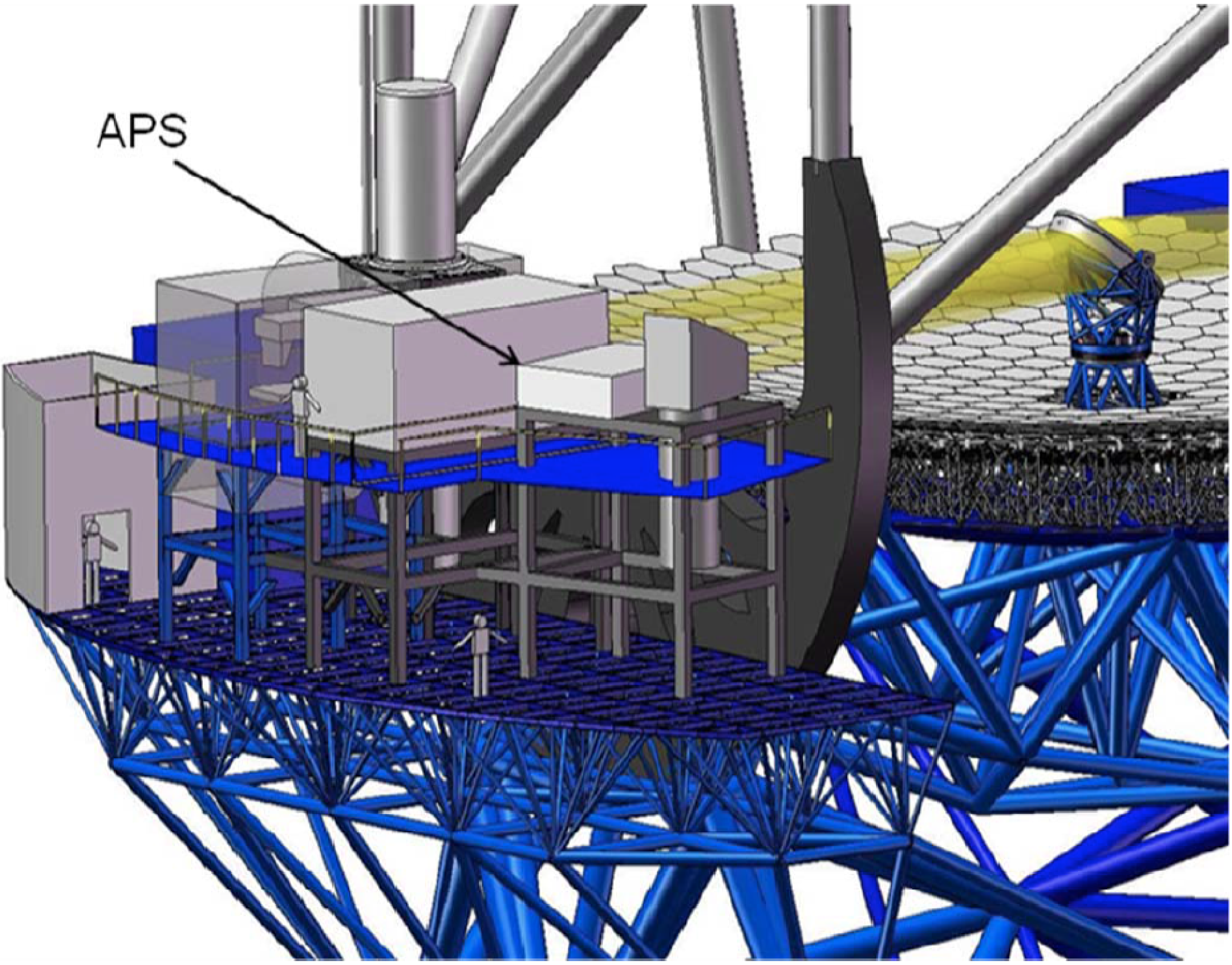
Approximately every two weeks six segments will be exchanged in TMT. APS will then be used to realign these newly installed segments in piston, tip, and tilt, and to correct the segment figures. At the same time APS will adjust three of the secondary rigid body motions. The APS measurements and associated adjustments to the mirrors will take no more than 2 hours of observation time. In general our experience at Keck is 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.

Initial APS operations will be conducted with the APS on the elevation axis of the telescope, as shown in Figure 3-1. However, after early operations the APS might be moved to a position off the elevation axis, such as is shown in Figure 3-2.

APS Location

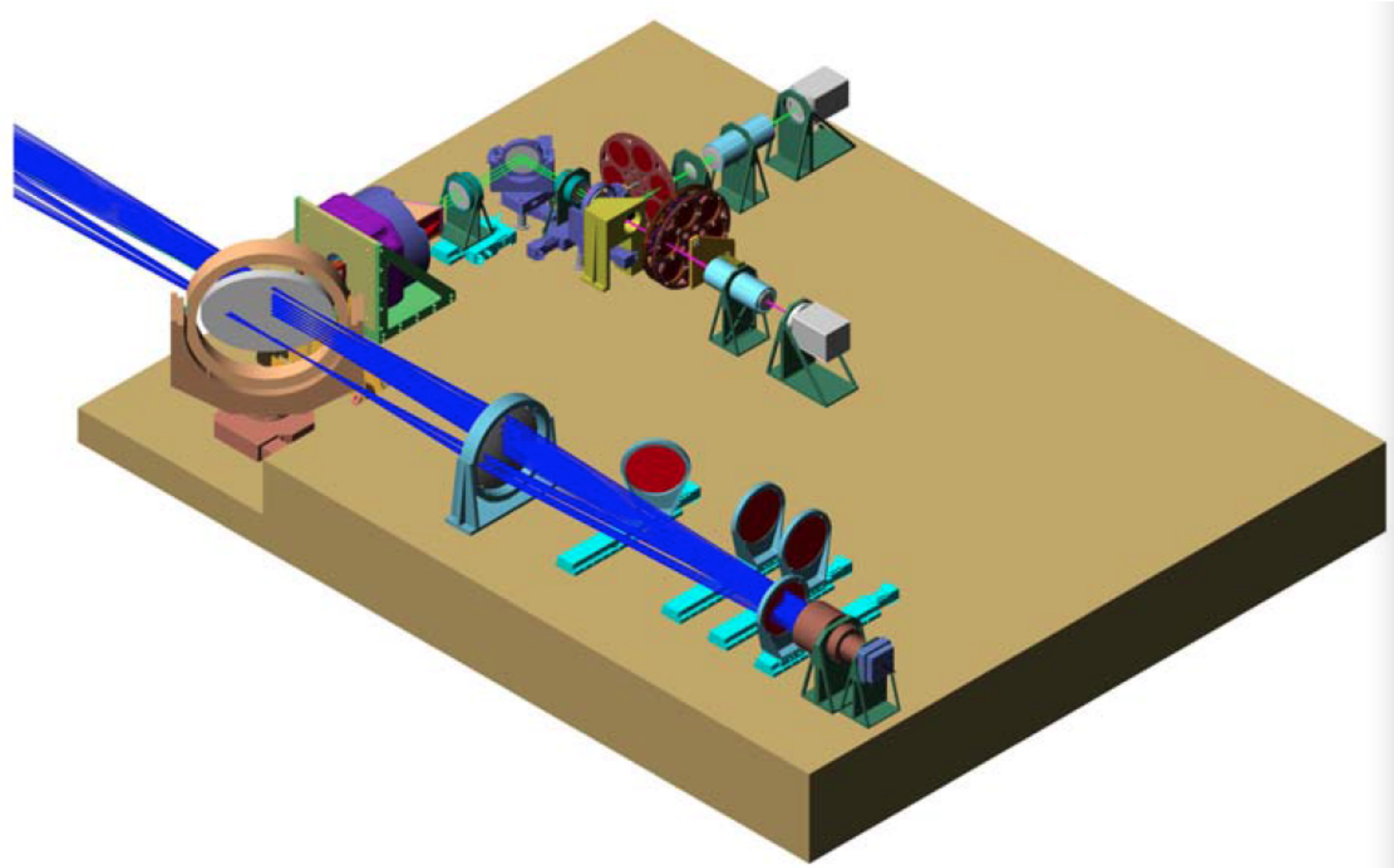


APS Location Side View



A side view of APS located off of the elevation axis.

APS Bench and optics



3 Key and Driving Requirements

The following two tables contain the Key and Driving requirements.

3.1 APS Functional Requirements

3.2 APS Performance Requirements

4 Operations Concept

This section describes the architectural context within with the APS functions, such as the organizational, staffing, and facilities concepts, and then describes typical operational procedures and sequences for operating the APS. This provides a foundation for the detailed requirements and designs of the APS components presented in subsequent sections.

4.1 Responsibilities

This section presents the ways in which the APS will be operated and used by participating organizations and individuals. Much of the operational responsibility is related to use of the APS software, and described in greater detail in Section 7.

4.1.1 APS Development Team

Responsibility for implementation and technical support of the APS will reside with a team led by the Principal Investigator and Co-Investigator, together with a team of engineering specialists, primarily at JPL.

Representatives of this team will be present at the observatory site during the APS Assembly, Integration, and Verification (AIV) phase to ensure that the system is appropriately installed, checked out, and set up in preparation for operations. The TMT construction phase includes the use of APS for alignment of M1 segment piston, tip, and tilt; M1 segment figures; and M2 piston and tip/tilt (or x/y-decenter) and M3 tip and rotation. The APS development team will also train observatory staff in the operation of the APS.

At the conclusion of AIV activities, APS operations for commissioned procedures become the responsibility of the TMT operations crew. For astronomical observing during the operations phase, the APS team will continue in a reduced form to provide technical support. Based on experience at the Keck Observatory, it is expected that this support will gradually become less, but will continue for the operational life of TMT. This operational support will require only occasional part-time activities, and will be served by individuals at their home institutions, such as JPL and UCI, with visits to the observatory site when necessary, probably no more than a couple of times each year when major optical alignment exercises are warranted.

4.1.2 TMT Observatory Staff

Observatory engineering staff are assumed to be available to assist in installation of the APS, e.g., for the movement and positioning of heavy components, and for the connection of utilities such as power, and for preventative maintenance.

Apart from overall engineering responsibilities, observatory staff participation in APS operations centers on the optical scientist and the observing assistants. The observing assistant directly controls the APS during its operation. The optical scientist is that individual responsible for the overall optical performance of the telescope, and is therefore responsible for planning the APS operational exercises, including the analysis and use of data acquired by the APS. As an example, it will be the optical scientist who specifies the APS procedures to run on a particular night and generates the elevation lookup tables from the APS data.

4.2 Facilities

The APS optical bench, located on the telescope's Nasmyth platform, is a fully enclosed unit in order to exclude dust, and requires human access only during maintenance periods. The Instrument Control System, which houses the APS electronics will be adjacent to the APS bench enclosure. The enclosure is normally in a fixed location, although this may change during the course of operations from an on-axis to an off-axis position. For this purpose, the APS bench/enclosure is designed to be moved using the observatory's crane.

For maintenance purposes, the APS enclosure could conceivably be removed temporarily from the Nasmyth platform; however, that is not a normally expected maneuver.

Facilities for storage of spare parts and for component maintenance are assumed to be located on the summit.

The APS computational and data handling facilities consist of workstations and data storage arrays that can be located in the appropriate TMT locations where similar equipment for other observatory systems is located.

The operational model for APS is similar to that of PCS, but with an ultimately higher degree of automation. As with PCS, the APS users will consist of about a dozen people in total including the developers. The APS will support remote operation as well as summit operation, although initial (AIV) operations will be conducted from the summit. During APS operations at the summit, typically a few to several APS staff will need to work with the relevant observatory control rooms, along with the respective telescope staff.

APS will normally be used after a segment exchange. This will occur approximately every week or two. If for some reason the segments are exchanged less frequently, APS will need to be run at least once a month in order to maintain the nominal telescope alignment. In steady state operations at Keck, PCS has been run about once a month per telescope.

4.3 Use Cases

Here we describe each of the top level APS use cases, which in general map directly to APS Level 1 requirements specified in the TMT OAD (RD2) . Each of these use cases is comprised of "High Level Activities" (High Level Activities).

The following list provides a brief overview of the APS use cases:

1. Post Segment-Exchange Alignment (Post Segment-Exchange Alignment): This use case re-aligns the telescope after new segments have been installed or exchanged. The current TMT baseline is that during normal operations ~10 segments will be exchanged, in a single day, every two weeks (RD2). That night, this use case will be run to re-align the telescope. This use case is allocated 2 hours to execute and will be started as soon as possible after sunset. Our current estimate is this procedure could be started 20 minutes after sunset.

2. Calibrate M1CS Edge Sensors (Calibrate M1CS Edge Sensors): After segments are exchanged it will be necessary to perform calibration of the M1CS sensors. This use case will first execute the post segment-exchange alignment at a single elevation angle. After that the telescope is aligned at two additional elevation angles. At each elevation angle the segments are aligned in tip/tilt and piston. The requirement is that the two additional M1CS sensor calibrations take no more than 1 hour.
3. Maintenance Alignment (Maintenance Alignment): This use case is used to re-align the telescope between segment exchanges, as a type of tune-up alignment. The result is the same as the Post Segment-Exchange Alignment use case; however, this use case has a smaller capture range for segment piston and tip and tilt errors. The current TMT baseline calls for the telescope being aligned by APS at least monthly. So, if there are no segments exchanged within the last 30 days then this use case would be executed. In addition, this use case can be used to check/adjust the alignment immediately before specific observations that are very sensitive to wavefront errors. This use case nominally takes 30 minutes to execute.
4. Off-axis Wavefront Measurements (Off-Axis Measurements of WFE): 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.
5. Calibrate Elevation Dependence of M2 and M3 (Calibrate Elevation Dependence of M2 and M3): This use case will align M2 and M3 at multiple elevation angles to provide the data needed for calibration of M2 and M3 motion with telescope elevation angle. Once aligned APS will notify M2 and M3, so that those sub-systems will save the necessary data to generate the needed calibrations.
6. Measurement of Segment Warping Harness Influence Functions (Measurement of Segment Warping Harness Influence Functions): 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 off-line (outside of APS) to generate the control matrix for the warping harness used in the Rigid Body and Segment Figure Correction activity (Rigid Body and Segment Figure Correction). This use case will likely only need to be executed during AIV, troubleshooting and/or periodically (yearly) to confirm the warping harness influence functions are not changing with time.
7. APS Pre-session Calibration (APS pre-session calibration): There are several internal APS calibrations that need to be performed either before or during observing. 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.
8. APS Self Test (APS Self Test): This use case will execute a series of APS tests using internal light sources to confirm that it is functioning correctly. The 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. It will also be executed the day before any planned APS maintenance alignments.
9. APS high-speed telescope diagnostic data: This use case is still in formulation, but the goal is to be able to characterize telescope and segment vibrations, such as the 30Hz vibrations observed at Keck. The current concept is this will be accomplished via high-speed data (~100Hz) in the APT camera with some (or all) of the TMT segments de-stacked. Details of this will be worked out as part of the APS Bench/ICS/MGT PDR.

4.3.1 Post Segment-Exchange Alignment

4.3.1.1 Purpose of Use Case

This use case re-aligns the telescope after new segments have been installed or exchanged. The current TMT baseline is that during normal operations ~10 segments will be exchanged in a single day every two weeks (RD2). That night, this use case will be run by the APS operator (typically the same person as the telescope operator) to re-align the telescope. Assuming the entrance requirements are met (all segments are within tip/tilt and piston capture range) then the time to run this test is independent of the number of "new" segments installed. Thus, this is the same use case that will nominally be used during AIV as new segments are installed and APS is used to align them.

This use case will typically be executed as part of the Calibrate M1CS Edge Sensors use case, but can be executed by itself.

4.3.1.2 Requirements

Prior to executing this use case, all telescope sub-systems should be operating in their nominal modes, including using the standard gravity/temperature look-up/calibration parameters. The use case "APS Self Test" should have been executed the previous day and the use case "APS pre-session calibration" should be executed before sunset.

Requirement REQ-2-APS-0060 defines the capture ranges of the optics that APS is required to handle for this use case.

Requirements REQ-2-APS-0009, REQ-2-APS-0078, REQ-2-APS-0079 and REQ-2-APS-0086 define the APS Optical Performance requirements to be met at the end of the Post-Segment Exchange use case.

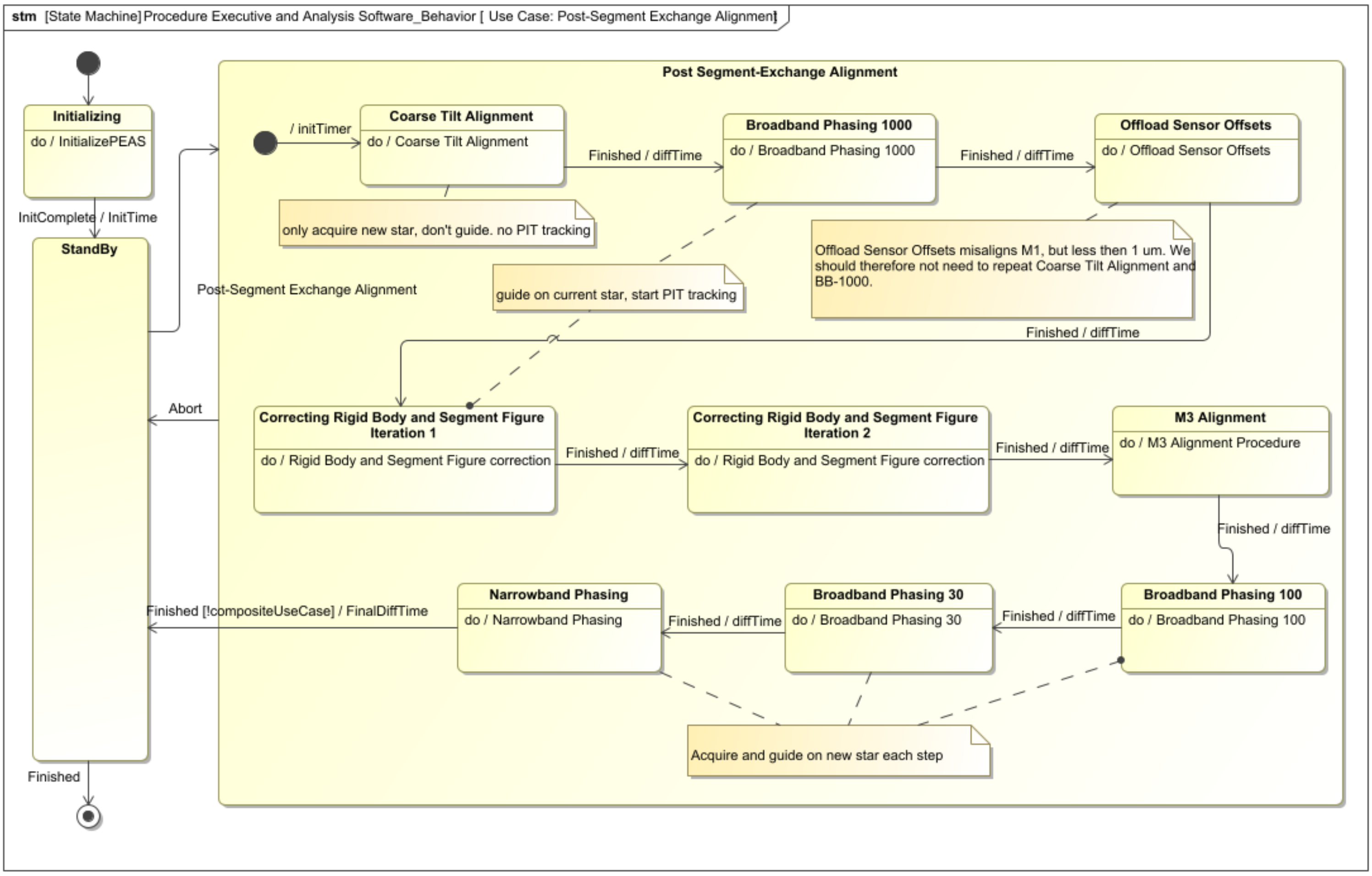
4.3.1.3 Typical Observing Parameters and Operating Conditions

This use case will typically be executed as soon as possible after the segment exchange recovery process has completed, but no sooner then 20 minutes after sunset. The first activity, coarse alignment, uses a 10 nm bandwidth filter and is not very sensitive to sky background compared to the required accuracy of the measurements. Stars are usually selected to be ~1 hour East at a Declination of 0 or 40 degrees to minimize changes in telescope elevation. The typical telescope elevation angle will be 70 degrees and will vary by less than a few degrees over 2 hours. At Keck the required star magnitudes range between 4th and 6th magnitude (depending on the activity) and we expect the values for TMT to be similar (see RD6). In practice we have never had problems finding stars at Keck, so we do not expect any problems with APS at TMT.

4.3.1.4 Use Case Activity

The following figure shows the post-segment exchange alignment use case. It starts with APS in standby mode. A star is acquired, and the Coarse Tilt Alignment activity is executed which will capture and align the segments in tip/tilt. Once this activity has completed, the Broadband Phasing 1000 activity will be executed. As part of this activity the telescope will be requested to start guiding, on the same star used for coarse tilt alignment, --- as we now have a single star image on the Acquisition Pointing Tracking (APT) camera --- and APS will close the Pupil-Image Tracking (PIT) loop. This activity will reduce the initial segment piston errors to ~1 micron. At this point the M1CS will be commanded to offload sensor offsets to ensure 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 harness. Nominally this activity is repeated twice to allow for iteration of the segment figure adjustments. Next the M3 Alignment activity will be executed to measure the M3 tip and rotation, and if needed commands will be sent to align M3, so that the telescope pupil is aligned for other TMT instruments. After this, the segments are aligned to 30 nm RMS surface piston error using first the Broadband Phasing 100 followed by the Broadband Phasing 30 activities. Each of these will require acquisition of new stars of the appropriate magnitude. The final M1 segment piston alignment is executed using the Narrow Band Phasing activity which includes measurements with two or three different filters.T

Use Case: Post-Segment Exchange Alignment



The Post-Segment Exchange Alignment activity will be executed after new segments have been added to the primary mirror.

4.3.1.5 Time to Execute

The table below shows our current bottom-up time estimate for each of the activities that make up this use case. The total time estimate is 83 minutes (4962 seconds), which is to be compared with our requirement of 120 min REQ-2-APS-0016.

At Keck, we routinely perform post-segment exchange alignment in 120 minutes or less. However, at Keck the segment shapes are measured in a separate test, in groups of seven segments, but adjustment of the segment warping harnesses is manual and occurs the next day. We will measure all TMT segment shapes in parallel as part of the rigid body and segment figure activity and immediately adjust the segment shapes during the night via the motorized warping harnesses and iterate the control at least once. Given our bottom-up estimate with a 30% margin and our Keck experience we have a high degree of confidence we can meet the 120 minute requirement.

Post-Segment Exchange Alignment Timing Analysis Results

#	Name	Classifier	postSegXchgTime Limit : second	tFinal : Real	postSegment Exchange : MaxTime Constraint	bBPhasing Stp : Integer	narrowbandFilter Steps : Integer	rigidBody Steps : Integer	RBDit : Integer	Phasing Dit : Integer	tCTA : Real	tBB1000 : Real	tMSR : Real	tRBS F1 : Real	tRBS F2 : Real	tM3 Align : Real	tBB100 : Real	tBB30 : Real	tNB : Real	tAcquisition : Real
1	post- Segment Exchange Duration Scenario at 2023.09.06 09.20	Post-Segment Exchange Duration Scenario																		
2	post- Segment Exchange Duration Scenario .aPS Mission Logical11	APS Mission Logical																		
3	post- Segment Exchange Duration Scenario .aPS Mission Logical11 .usr	APS User																		
4	post- Segment Exchange Duration Scenario .aPS Mission Logical11 .aps operational blackbox	APS Logical																		
5	post- Segment Exchange Duration Scenario .aPS Mission Logical11 .aps operational blackbox.on-axis alignment maximum time for Post Segment Exchange JPL	On-axis alignment maximum time for Post Segment Exchange	7200 second		pass															
6	post- Segment Exchange Duration Scenario .aPS Mission Logical11 .aps operational blackbox .peas	Procedure Executive and Analysis Software		4895		11	2	8	45	20	912	786	30	723	723	26	815	816	64	
7	post- Segment Exchange Duration Scenario .aPS Mission Logical11 .esw	Executive Software																		36
8	post- Segment Exchange Duration Scenario .aPS Mission Logical11 .aps operational blackbox	APS Logical																		
9	post- Segment Exchange Duration Scenario .aPS Mission Logical11 .aps operational blackbox.on-axis alignment maximum time for Post Segment Exchange JPL	On-axis alignment maximum time for Post Segment Exchange	7200 second		pass															
10	post- Segment Exchange Duration Scenario .aPS Mission Logical11 .aps operational blackbox .peas	Procedure Executive and Analysis Software		4895		11	2	8	45	20	912	786	30	723	723	26	815	816	64	

4.3.2 Calibrate M1CS Edge Sensors

4.3.2.1 Purpose of Use Case

This use case performs two functions:

1. It re-aligns the telescope after new segments have been installed or exchanged (via execution of the Post Segment-Exchange Alignment use case)
2. It performs a calibration of the M1CS sensors at two additional telescope elevation angles, providing a total of three calibration angles in order to update the M1CS sensor calibration coefficients.

The current TMT baseline is that during normal operations 10 segments will be exchanged in a single day every two weeks. That night this use case will be run by the APS operator (typically the same person as the telescope operator) to re-align the telescope. Assuming the entrance requirements are met (all segments are within tip/tilt and piston capture range) then the time to run this test is independent of the number of “new” segments installed. Thus, this is the same use case that will nominally be used during AIV as new segments are installed and APS is used to align them.

The initial telescope alignment after the segments are installed occurs at nominally a telescope elevation angle of ~70 degrees and includes all of the steps outlined in Section 3.1 Post Segment-Exchange Alignment. For each additional M1CS sensor calibration telescope zenith angle APS will perform the following alignment procedures:

- Correct segment piston, tip, and tilt
- Broadband phasing 30 (with a 1 micron capture range)
- Narrowband phasing

The results of this use case will be used by the M1CS to update the sensor calibration coefficients. Note that the sensor calibration coefficients are estimated using data from the current APS run, as well as prior runs that include data taken at different telescope temperatures.

4.3.2.2 Requirements

Prior to initiating this use case, all telescope sub-systems should be operating in their nominal modes, including using the standard gravity/temperature look-up/calibration parameters. The use case "APS Self Test" should have been executed the previous day and the use case "APS pre-session calibration" should be executed before sunset.

As in Post Segment-Exchange Alignment the relevant requirements are for the first post-segment exchange alignment are:

1. REQ-2-APS-0060, which defines the capture ranges of the optics required for APS.
2. REQ-2-APS-0009, REQ-2-APS-0078, REQ-2-APS-0079 and REQ-2-APS-0086 define the APS Optical Performance requirements to be met at the end of the Post-Segment Exchange activity.

For the M1CS sensor calibrations at two additional telescope elevation angles the relevant requirements are:

1. REQ-2-M1CS-3200, which defines the capture ranges of the optics required for APS. These are important as they insure that we can use our standard Maintenance Alignment use case.
2. REQ-2-APS-0078 and REQ-2-APS-0079 define the APS Optical Performance requirements to be met at each elevation angle.

4.3.2.3 Typical Observing Parameters and Operating Conditions

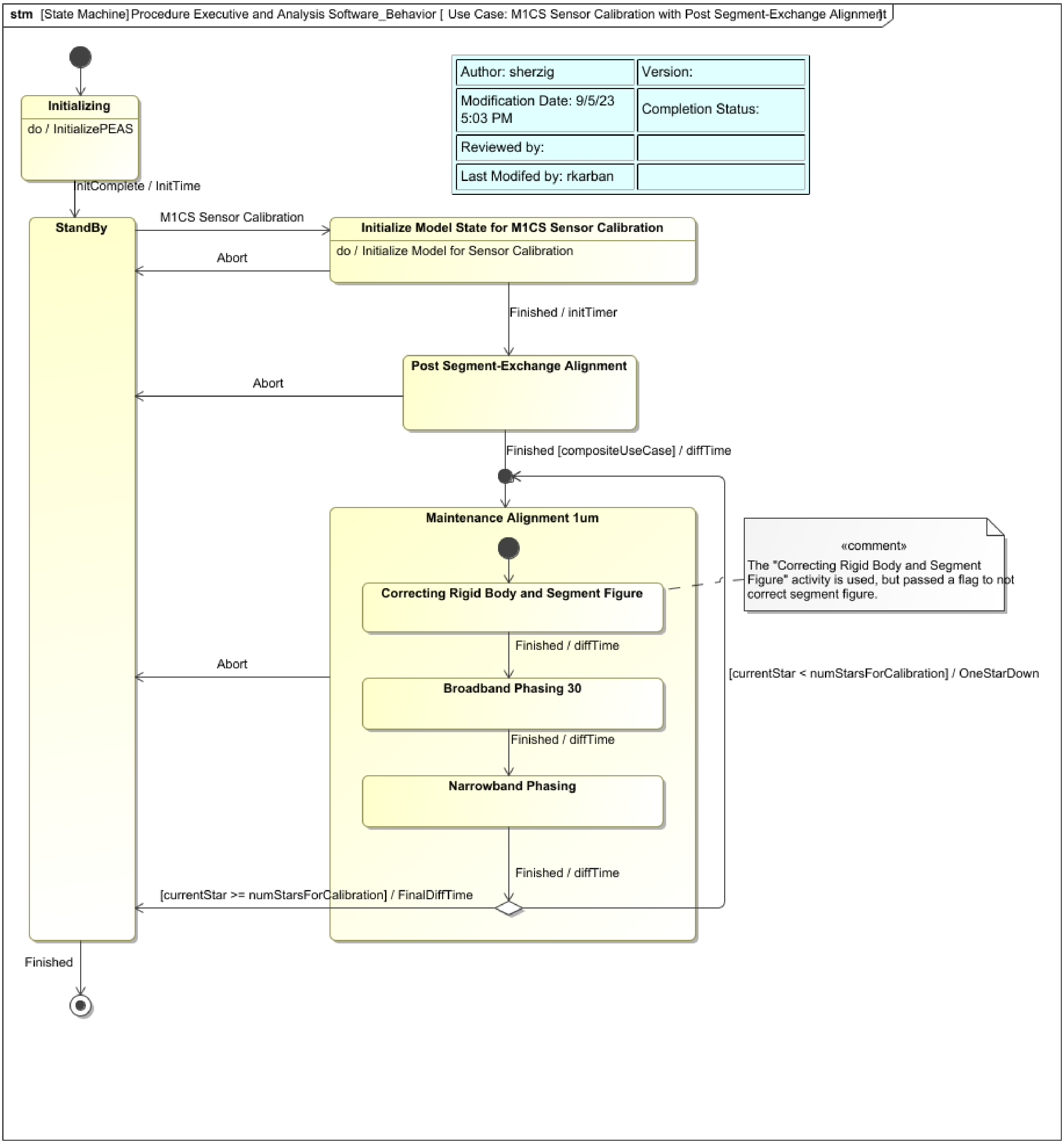
This use case will typically be executed as soon as possible after the segment exchange recovery process has completed, but no sooner then 20 minutes after sunset. The first activity coarse alignment uses a 10 nm bandwidth filter and is not very sensitive to sky background compared to the required accuracy of the measurements. Stars are usually selected to be ~1 hour east at a declination of 0 or 40 degrees to minimize changes in telescope elevation. At Keck the required star magnitudes range between 4th and 6th magnitude (depending on the activity) and we expect the values for TMT to be similar (see RD6). In practice we have never had problems finding stars at Keck, so we do not expect any problems with APS at TMT.

During the initial segment re-alignment the typical telescope elevation angle will be 70 degrees and will vary by less than a few degrees over 2 hours. After the telescope nominal alignment is complete the process of M1CS sensor calibration will start and stars will be acquired at the specified elevation angles.

4.3.2.4 Use Case Activity

The figure below shows the M1CS Sensor Calibration and Post-segment Exchange use case. It starts with APS in standby mode. Then the Post-Segment Exchange Alignment use case is executed (Post Segment-Exchange Alignment) After that the Maintenance alignment use case (Maintenance Alignment) is executed at two different elevation angles. The only difference between this and the "standard" Maintenance alignment use case is that the segment figures/warping harness will not be adjusted.

Use Case: M1CS Sensor Calibration with Post Segment-Exchange Alignment



4.3.2.5 Time to Execute

The table below shows our current bottom-up time estimate for each of the activities that make up this use case. The total time estimate is 137 minutes (8228 seconds), which is to be compared with our requirement of 180 min (REQ-1-OAD-2330) , a 24% margin.

The requirement REQ-1-OAD-2330 flows down to:

1. REQ-2-APS-0016, which states that the APS shall be able to perform on-axis alignment in less than 120 minutes (at a single elevation angle) when the Post-Segment Exchange Alignment specifications in REQ-2-APS-0060 are satisfied.
2. REQ-2-APS-0017, which states that APS shall be able to perform on-axis alignment in less than 30 minutes.
3. REQ-2-M1CS-3224, which states that after replacement of up to 10 non-contiguous segments, and after alignment at a single elevation angle, the alignment of M1 at the required two additional elevation angles will meet REQ-2-M1CS-3200 using calibration coefficients updated after each APS measurement.

M1CS Sensor Calibration Timing Analysis Results

#	Name	Classifier	tFinal : Real	bBPhasing Stp : Integer	narrowbandFilter Steps : Integer	rigidBody Steps : Integer	RBDit : Integer	Phasing Dit : Integer	tCTA : Real	tBB1000 : Real	tMSR : Real	tRBS F1 : Real	tRBS F2 : Real	tBB100 : Real	tBB30 : Real	tNB : Real	tCalibRBS F : Real	tCalibB B1 : Real	tCalibN B : Real	tAcquisition : Real
1	m1CS Sensor Calibration Duration Scenario at 2023.02.01 15.15	M1CS Sensor Calibration Duration Scenario																		
2	m1CS Sensor Calibration Duration Scenario .aPS Mission Logical5	APS Mission Logical																		
3	m1CS Sensor Calibration Duration Scenario .aPS Mission Logical5 .usr	APS User																		
4	m1CS Sensor Calibration Duration Scenario .aPS Mission Logical5 .aps operational blackbox	APS Logical																		
5	m1CS Sensor Calibration Duration Scenario .aPS Mission Logical5 .aps operational blackbox .peas	Procedure Executive and Analysis Software	8228	11	2	8	45	20	912	791	30	728	728	815	816	69	754 754	815 815	69 98	
6	m1CS Sensor Calibration Duration Scenario .aPS Mission Logical5 .esw	Executive Software																		36
7	m1CS Sensor Calibration Duration Scenario .aPS Mission Logical5 .aps operational blackbox	APS Logical																		
8	m1CS Sensor Calibration Duration Scenario .aPS Mission Logical5 .aps operational blackbox .peas	Procedure Executive and Analysis Software	8228	11	2	8	45	20	912	791	30	728	728	815	816	69	754 754	815 815	69 98	
9	m1CS Sensor Calibration Duration Scenario at 2023.09.06 10.48	M1CS Sensor Calibration Duration Scenario																		
10	m1CS Sensor Calibration Duration Scenario .aPS Mission Logical7	APS Mission Logical																		
11	m1CS Sensor Calibration Duration Scenario .aPS Mission Logical7 .usr	APS User																		
12	m1CS Sensor Calibration Duration Scenario .aPS Mission Logical7 .aps operational blackbox	APS Logical																		
13	m1CS Sensor Calibration Duration Scenario .aPS Mission Logical7 .aps operational blackbox .peas	Procedure Executive and Analysis Software	8201	11	2	8	45	20	912	786	30	723	723	815	816	64	759 755	815 815	98 64	
14	m1CS Sensor Calibration Duration Scenario .aPS Mission Logical7 .esw	Executive Software																		35

#	Name	Classifier	tFinal : Real	bBPhasing Stp : Integer	narrowbandFilter Steps : Integer	rigidBody Steps : Integer	RBDit : Integer	Phasing Dit : Integer	tCTA : Real	tBB1000 : Real	tMSR : Real	tRBS F1 : Real	tRBS F2 : Real	tBB100 : Real	tBB30 : Real	tNB : Real	tCalibRBS F : Real	tCalibB B1 : Real	tCalibN B : Real	tAcquisition : Real
15	m1CS Sensor Calibration Duration Scenario .aPS Mission Logical7 .aps operational blackbox	APS Logical																		
16	m1CS Sensor Calibration Duration Scenario .aPS Mission Logical7 .aps operational blackbox .peas	Procedure Executive and Analysis Software	8201	11	2	8	45	20	912	786	30	723	723	815	816	64	759 755	815 815	98 64	

4.3.3 Maintenance Alignment

4.3.3.1 Purpose of Use Case

This use case is used to re-align the telescope in between segment exchanges. The current TMT baseline is that the telescope will be aligned by APS at least monthly; if there is not a segment exchange in the last 30 days then this use case would be executed. As this use case measures (and optionally corrects for) all telescope degrees of freedom that APS can measure, it is also useful for checking and adjusting the alignment immediately before specific observations that are very sensitive to wavefront errors. At Keck this is also used to characterize drifts in telescope alignments as a function of time, elevation angle and/or temperature and will likely be used in a similar fashion at TMT.

4.3.3.2 Requirements

All telescope sub-systems should be operating in their nominal modes, including using the standard gravity/temperature look-up/calibration parameters. The use case "APS Self Test" should have been executed the previous day and the use case "APS pre-session calibration" should be executed before sunset.

Requirement REQ-2-APS-0059 defines the capture ranges of the optics that APS is required to handle for this use case.

Requirements REQ-2-APS-0009, REQ-2-APS-0078, REQ-2-APS-0079 and REQ-2-APS-0086 define the APS Optical Performance requirements to be met at the end of the Maintenance Alignment use case.

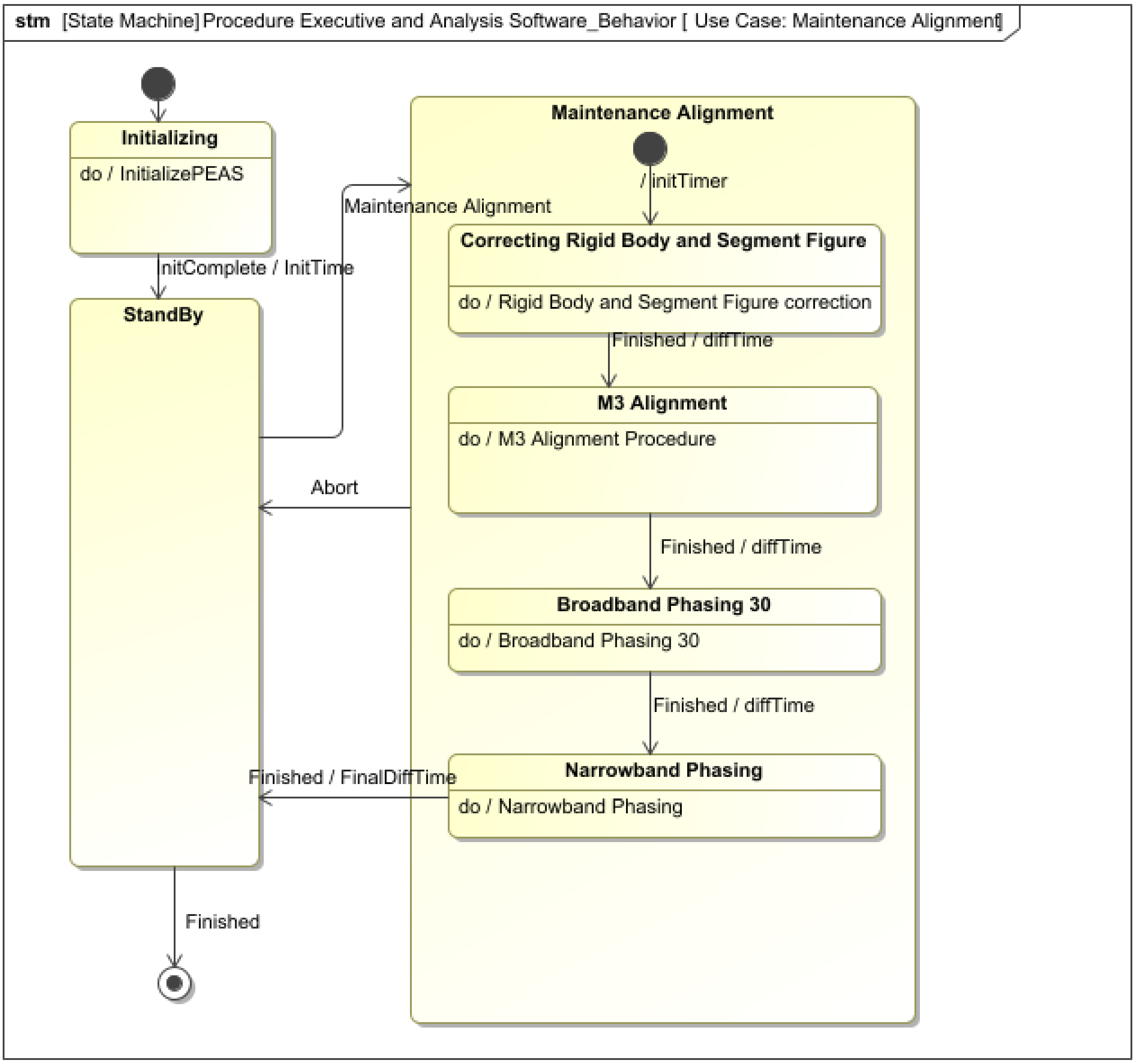
4.3.3.3 Typical Observing Parameters and Operating Conditions

This use case can be executed anytime during the night, but no sooner than ~40 minutes after sunset. Stars are usually selected to be ~1 hour to 30 minutes east at a declination of 0 or 40 degrees to minimize changes in telescope elevation. The typical telescope elevation angle will be 70 degrees and will vary by less than a few degrees over the 30 minutes it takes to execute this use case. If this use case is being used for alignment at an elevation angle other than 70 degrees, then stars should be selected to minimize the change in elevation during the use case execution. The required star magnitudes for this test are between 5th and 6th magnitude (see RD6). In practice we have never had problems finding stars at Keck in this magnitude range, so we do not expect any problems with APS at TMT.

4.3.3.4 Use Case Activity

The figure below shows the maintenance alignment use case. It starts with APS in standby mode. A single iteration of the rigid body and segment figure activity is executed, averaging nominally six 45 second images. This activity aligns M1 segments in tip/tilt, M2 in piston and either tip/tilt or *x*/*y* translation as well as measuring and correcting the segment figures via warping harness. Next the M3 Alignment activity will be executed to measure the M3 tip and rotation and if needed commands will be sent to align M3, so that the telescope pupil is aligned for other TMT instruments. After this, the segments are phased to 30 nm RMS surface piston error using the broadband phasing 30 mode. The final M1 segment piston alignment is executed using the narrowband phasing activity, which includes measurements with two or three different filters. Each of these activities, except the M3 alignment, will require acquisition of new stars of the appropriate magnitude as specified in the description of each activity.

Use Case: Maintenance Alignment



4.3.3.5 Time to Execute

The table below shows our current bottom-up time estimate for each of the activities that make up this use case. The total time estimate is 27.2 minutes (1632 seconds), which is to be compared with our requirement of 30 min REQ-2-APS-0017.

At Keck we routinely perform similar measurements in 30 minutes or less. At Keck the segment shapes are not measured as part of this use case. APS will measure the TMT segment shapes in parallel, as part of the *Rigid Body and Segment Figure* activity, so there is effectively no additional time needed. We will also check and adjust the M3 alignment, but this adds minimal time. Given our bottom-up estimate and our Keck experience we have a high degree of confidence we can meet the 30 minute requirement.

Maintenance Alignment Timing Analysis Results

#	maintenanceAlignmentTime Limit : second	tFinal : Real	tRBS F1 : Real	offAxisMeasurement Steps : Integer	RBDit : Integer	tM3 Align : Real	tBB30 : Real	tNB : Real	Phasing Dit : Integer	tAcquisition : Real
1										
2	1800 second									
3		1687	742	6	45	63	818	64	20	
4										38
5										
6										37

4.3.4 Off-Axis Measurements of WFE

4.3.4.1 Purpose of Use Case

The baseline TMT alignment scenario is that the global metrology system (GMS) will be used to build look-up tables as a function of gravity for M2 and M3. With on-axis measurements M2 tip/tilt cannot be distinguished from M2 *x*/*y* translation. The expected GMS measurement error is sufficient to constrain the M2 positions and associated off-axis errors and as a result APS needs only adjust M2 tip/tilt or M2 decenter. The APS alignment of M2 is done as part of the "Rigid Body and Segment Figure Correction" activity. Analysis (RD3) has shown that a 100 micron M2 translation error corrected with M2 tip/tilt introduces a negligible amount of off-axis telescope aberrations. Specifically, at 7.5 arcmins off-axis correction of a 100 micron M2 translation error with M2 tip/tilt results in:

- A PSSN (worst case) of ~0.993 versus a requirement of ~0.96
- An 80% enclosed energy after removal of the telescope design error of less than 15 milli-arcseconds.
- An RMS WFE after removal of the telescope design error (~2,250 nm) of less than 75 nm.

The current GMS accuracy requirement is to measure the M2 position to better than 33 microns (REQ-2-TINS-1920). Additional analysis of the alignment procedure for M2 is provided in RD4 and RD5.

This use case provides a method to measure the off-axis wavefront errors using APS and characterize them by Zernike polynomials. This is mainly intended as a verification of the telescope alignment. APS will characterize, but not attempt to calculate M2 commands to correct the off-axis error. In addition, APS will not attempt to reconstruct the surface of M3. We expect that these measurements will mainly be performed during the AIV phase of the project or for trouble-shooting purposes. PCS had no off-axis capability and thus was unable to diagnose off-axis performance problems experienced by some Keck instruments.

Off-axis wavefront characterization requires a sequence of four to six off-axis measurements made with the SH-2 lenslet array. In order to define a "baseline" use case we have assumed six off-axis measurements as shown in Figure 6, which cover 93% of M3.

4.3.4.2 Requirements

Prior to initiating this use case, all telescope sub-systems should be operating in their nominal modes, including using the standard gravity/temperature look-up/calibration parameters. The use case "APS Self Test" should have been executed the previous day and the use case "APS pre-session calibration" should be executed before sunset. There are currently no L1 requirements on how well aligned the telescope needs to be before this use case is executed. However, it is assumed that the telescope is aligned to the level specified at the end of the post segment-exchange/maintenance alignment use cases. Both use cases have the same optical performance requirements. Refer to the "Optical Performance Requirements" section under "Post Segment-Exchange Alignment" use case for the details.

The driving requirement for this use case is to make off-axis measurements at any point in the telescope field of view, and to measure 15 Zernike terms (excluding focus) to an accuracy of 1.5 times the atmospheric-imposed limit (REQ-2-APS-0084). The measurement error of focus may be larger due to the need to refocus the telescope as part of the off-axis measurement process. This APS L2 requirement is flowed down from the L1 OAD requirement to measure across the whole field of view and to characterize the wavefront in terms of Zernike polynomials (REQ-1-OAD-2245).

Recent investigations indicate that it might be possible to use the measurements from the off-axis field points to control all five M2 DOFs (RD5). While this is not an APS requirement it could be very beneficial to TMT. In future phases of APS development, we plan to investigate this further.

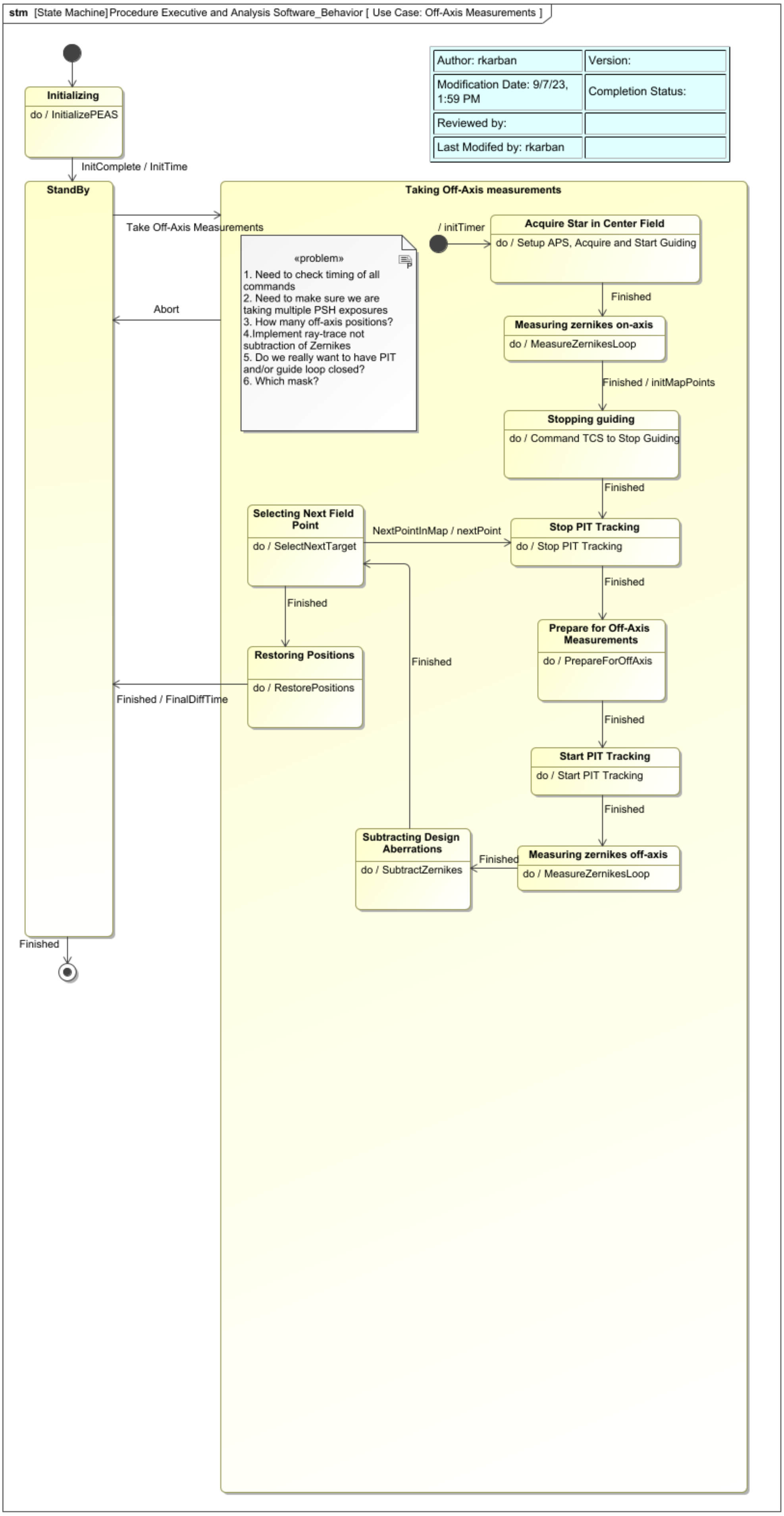
4.3.4.3 Typical Observing Parameters and Operating Conditions

This use case can be executed any time during the night, but no sooner than ~40 minutes after sunset. Stars are usually selected to be ~1 hour to 30 minutes East at a declination of 0 or 40 degrees to minimize changes in telescope elevation. The typical telescope elevation angle will be 70 degrees and will vary by less than a few degrees over the ~45 minutes it takes to execute this use case. If this use case is being used for alignment at an elevation angle other then 70 degrees, then stars should be selected to minimize the change in elevation during the use case execution. The required star magnitudes for this test are between 5th and 6th magnitude (see RD6). In practice we have never had problems finding stars at Keck in this magnitude range, so we do not expect any problems with APS at TMT.

4.3.4.4 Use Case Activity

Figure 6 shows the off-axis measurement use case. It starts with APS in standby mode. The "Acquire Star in Center Field" performs the standard activity to acquire and guide on a star. After this a measurement activity to determine the global Zernikes will be executed. This will be a measurement with a Shack-Hartmann that has 19 subapertures per segment. In preparation for measuring off-axis the guiding and PIT tracking are stopped. Given an off-axis field point the system is "prepared for off-axis measurements", as described in Prepare for Off-Axis. Once complete APS will restart the PIT tracking and execute the measurement activity to measure the global Zernikes. The design aberrations are subtracted from these measured Zernikes and both the raw and corrected Zernikes saved by APS. If requested, the next off-axis field point is measured. Once all field points have been measured, the telescope and APS optics are restored to their nominal positions.

Use Case: Off-Axis Measurements



4.3.4.5 Time to Execute

The current estimated total time for measurement of the on-axis and six off-axis field points is 50 minutes (3018 seconds). There are no requirements on the duration of this use case.

Off-Axis Measurements Timing Analysis Results

#	Name	tFinal : Real	offAxisMeasurement Steps : Integer	offAxisMap Points : Integer	RBDit : Integer	tAcquisition : Real
1	off- Axis Acquisition Duration Scenario at 2023.01.30 16.42					
2	off- Axis Acquisition Duration Scenario .aPS Mission Logical6					
3	off- Axis Acquisition Duration Scenario .aPS Mission Logical6 .usr					
4	off- Axis Acquisition Duration Scenario .aPS Mission Logical6 .aps operational blackbox					
5	off- Axis Acquisition Duration Scenario .aPS Mission Logical6 .aps operational blackbox .peas	3018	6	7	45	
6	off- Axis Acquisition Duration Scenario .aPS Mission Logical6 .esw					38
7	off- Axis Acquisition Duration Scenario .aPS Mission Logical6 .aps operational blackbox					
8	off- Axis Acquisition Duration Scenario .aPS Mission Logical6 .aps operational blackbox .peas	3018	6	7	45	
9	off- Axis Acquisition Duration Scenario at 2023.09.06 10.23					
10	off- Axis Acquisition Duration Scenario .aPS Mission Logical10					
11	off- Axis Acquisition Duration Scenario .aPS Mission Logical10 .aps operational blackbox					
12	off- Axis Acquisition Duration Scenario .aPS Mission Logical10 .aps operational blackbox .peas	3018	6	7	45	
13	off- Axis Acquisition Duration Scenario .aPS Mission Logical10 .esw					38
14	off- Axis Acquisition Duration Scenario .aPS Mission Logical10 .usr					
15	off- Axis Acquisition Duration Scenario .aPS Mission Logical10 .aps operational blackbox					
16	off- Axis Acquisition Duration Scenario .aPS Mission Logical10 .aps operational blackbox .peas	3018	6	7	45	

4.3.5 Calibrate Elevation Dependence of M2 and M3

4.3.5.1 Purpose of Use Case

This use case is used to align the M2 (piston and either tip/tilt or *x*/*y* decenter) and M3 rigid body degrees of freedom at multiple elevation angles. The data is then used by TCS to build gravity look up tables to ensure M2 and M3 stay aligned as the telescope tracks stars.

This use case will be executed during AIV, likely multiple times. It should also be re-executed on a routine bases (~1/yr) to ensure proper telescope alignment and as a diagnostic for other potential telescope problems.

4.3.5.2 Requirements

Prior to initiating this use case, all telescope sub-systems should be operating in their nominal modes, including using the standard gravity/temperature look-up/calibration parameters. The use case "APS Self Test" should have been executed the previous day and the use case "APS pre-session calibration" should be executed before sunset.

The entrance requirements for this use case are the same as that for Maintenance Alignment, REQ-2-APS-0059. Requirements REQ-2-APS-0079 and REQ-2-APS-0086 define the APS Optical Performance requirements to be met after alignment at each desired telescope elevation angle.

4.3.5.3 Typical Observing Parameters and Operating Conditions

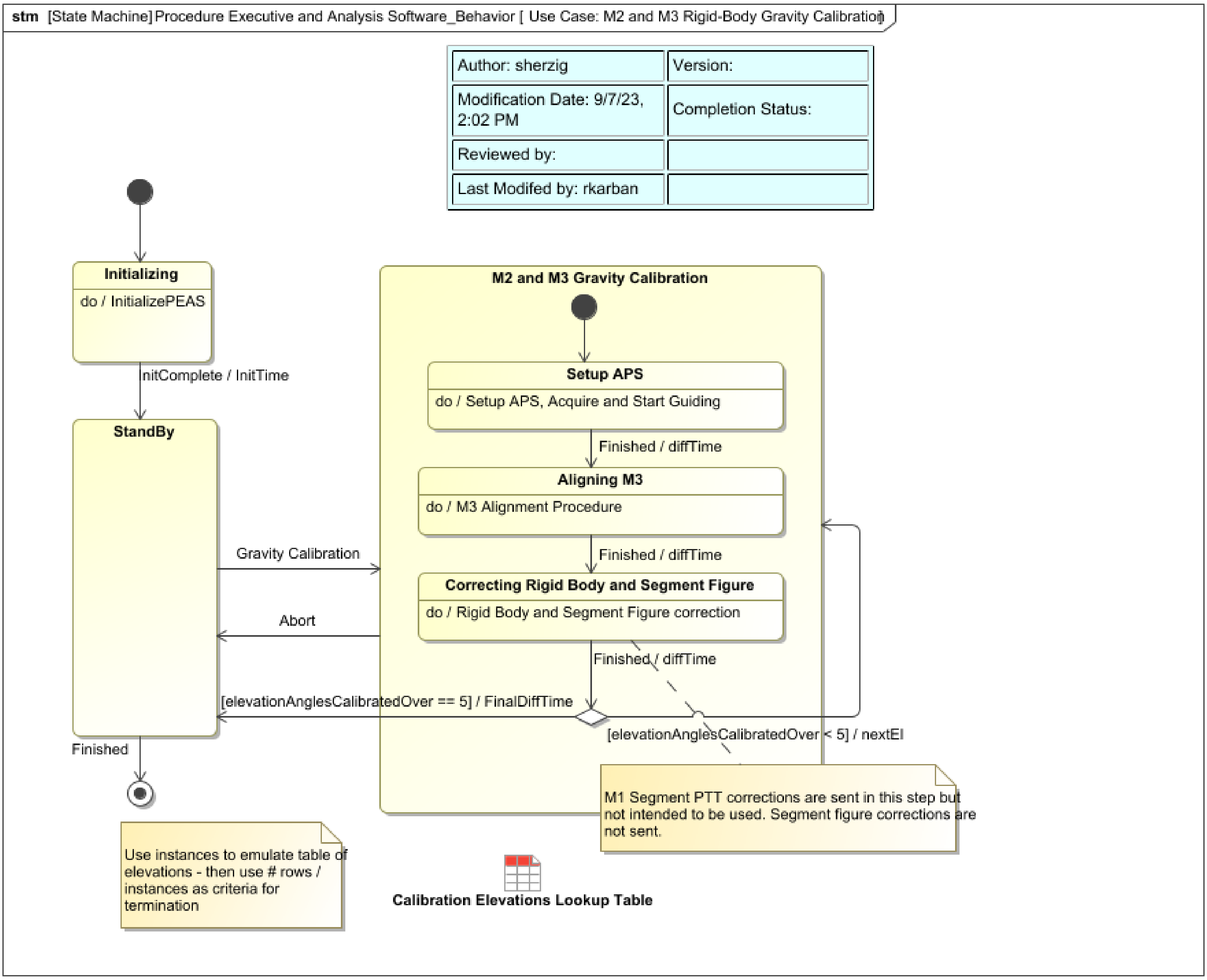
This use case can be executed any time during the night, but no sooner than ~40 minutes after sunset. Stars are usually selected to be ~1 hour to 30 minutes East at a declination of 0 or 40 degrees to minimize changes in telescope elevation. Stars will be acquired at specified telescope elevation angles, elevation and will vary by less than a few degrees over the 30 minutes it takes to execute this use case. The required star magnitudes for this test are between 5th and 6th magnitude (see RD6). In practice we have never had problems finding stars at Keck in this magnitude range, so we do not expect any problems with APS at TMT.

4.3.5.4 Use Case Activity

The figure below shows the use case activity state machine. It starts with APS in standby mode. A star at the specified elevation angle is acquired and tracking started. Then the high level activity M3 Alignment Procedure is executed to align M3 as part of this activity the "saveM3Position" command is sent to TCS. Next the Rigid Body and Segment Figure Correction is executed, during this process commands are calculated to align M2 and M1 segments in tip/tilt and nominally sent. Commands to the warping harness to correct the M1 segment figures are calculated, but nominally not sent. At the end of Rigid Body and Segment Figure Correction the command "saveM2Position" is sent to TCS and "SaveCurrentSensorCalibCoef" is sent to M1CS. If an additional elevation angle is specified, a new star will be acquired, and the previous process repeated.

The above procedure is repeated for each elevation angle specified in the Calibration Elevation Lookup Table. The current assumption is six stars at elevation angles between 30 and 80 Deg. TCS will use the saved M2 and M3 configurations at the various elevation angles to check and/or update the needed elevation corrections.

Use Case: M2 and M3 Rigid-Body Gravity Calibration



Calibration Elevations Lookup Table

#	Name	elevation Angle : Rea l
1	row1	80
2	row2	70
3	row3	60
4	row4	50
5	row5	40
6	row6	30

4.3.5.5 Time to Execute

The table below shows our current bottom-up time estimate of (4965 seconds) of 83 minutes for all six elevation angles. There is currently no requirement that directly maps to this use case.

Gravity Calibration Timing Analysis Results

#	Name	Classifier	tFinal : Real	tCalibAlign M3 : Real	tCalibRBS F : Real	tAcquisition : Real
1	gravity Calibration Duration Scenario at 2023.04.14 22.01	Gravity Calibration Duration Scenario				
2	gravity Calibration Duration Scenario .aPS Mission Logical	APS Mission Logical				
3	gravity Calibration Duration Scenario .aPS Mission Logical .usr	APS User				
4	gravity Calibration Duration Scenario .aPS Mission Logical .aps operational blackbox	APS Logical				
5	gravity Calibration Duration Scenario .aPS Mission Logical .aps operational blackbox .peas	Procedure Executive and Analysis Software	5095	64 66 66 66 66 64	733 734 733 734 734 733	
6	gravity Calibration Duration Scenario .aPS Mission Logical .esw	Executive Software				0
7	gravity Calibration Duration Scenario .aPS Mission Logical .aps operational blackbox	APS Logical				
8	gravity Calibration Duration Scenario .aPS Mission Logical .aps operational blackbox .peas	Procedure Executive and Analysis Software	5095	64 66 66 66 66 64	733 734 733 734 734 733	
9	gravity Calibration Duration Scenario at 2023.09.06 11.14	Gravity Calibration Duration Scenario				
10	gravity Calibration Duration Scenario .aPS Mission Logical47	APS Mission Logical				
11	gravity Calibration Duration Scenario .aPS Mission Logical47 .usr	APS User				
12	gravity Calibration Duration Scenario .aPS Mission Logical47 .aps operational blackbox	APS Logical				
13	gravity Calibration Duration Scenario .aPS Mission Logical47 .aps operational blackbox .peas	Procedure Executive and Analysis Software	5222	114 81 114 114 81 81	723 723 723 723 723 723	
14	gravity Calibration Duration Scenario .aPS Mission Logical47 .esw	Executive Software				37
15	gravity Calibration Duration Scenario .aPS Mission Logical47 .aps operational blackbox	APS Logical				

#	Name	Classifier	tFinal : Real	tCalibAlign M3 : Real	tCalibRBS F : Real	tAcquisition : Real
16	gravity Calibration Duration Scenario .aPS Mission Logical47 .aps operational blackbox .peas	Procedure Executive and Analysis Software	5222	114 81 114 114 81 81	723 723 723 723 723 723	

4.3.6 Measurement of Segment Warping Harness Influence Functions

4.3.6.1 Purpose of Use Case

The baseline plan is to use theoretical warping harness influence function in the control of the segment surface shapes. However, due to manufacturing tolerances, etc. these may differ from the actual influence functions. This use case is designed to measure the warping harness influence functions on-sky. Details are discussed in RD6. This procedure will certainly be executed during AIV and may be re-executed to check warping harness influence functions as well as troubleshoot any problems. We envision this procedure being executed on the order of once per year once the telescope is in normal operation. This use case just covers collection of the data. The analysis of the collected data is currently planned to be executed off-line.

4.3.6.2 Requirements

Prior to initiating this use case, all telescope sub-systems should be operating in their nominal modes, including using the standard gravity/temperature look-up/calibration parameters. The use case "APS Self Test" should have been executed the previous day and the use case "APS pre-session calibration" should be executed before sunset.

This use case has no optical performance requirements as it does not change the alignment of the telescope

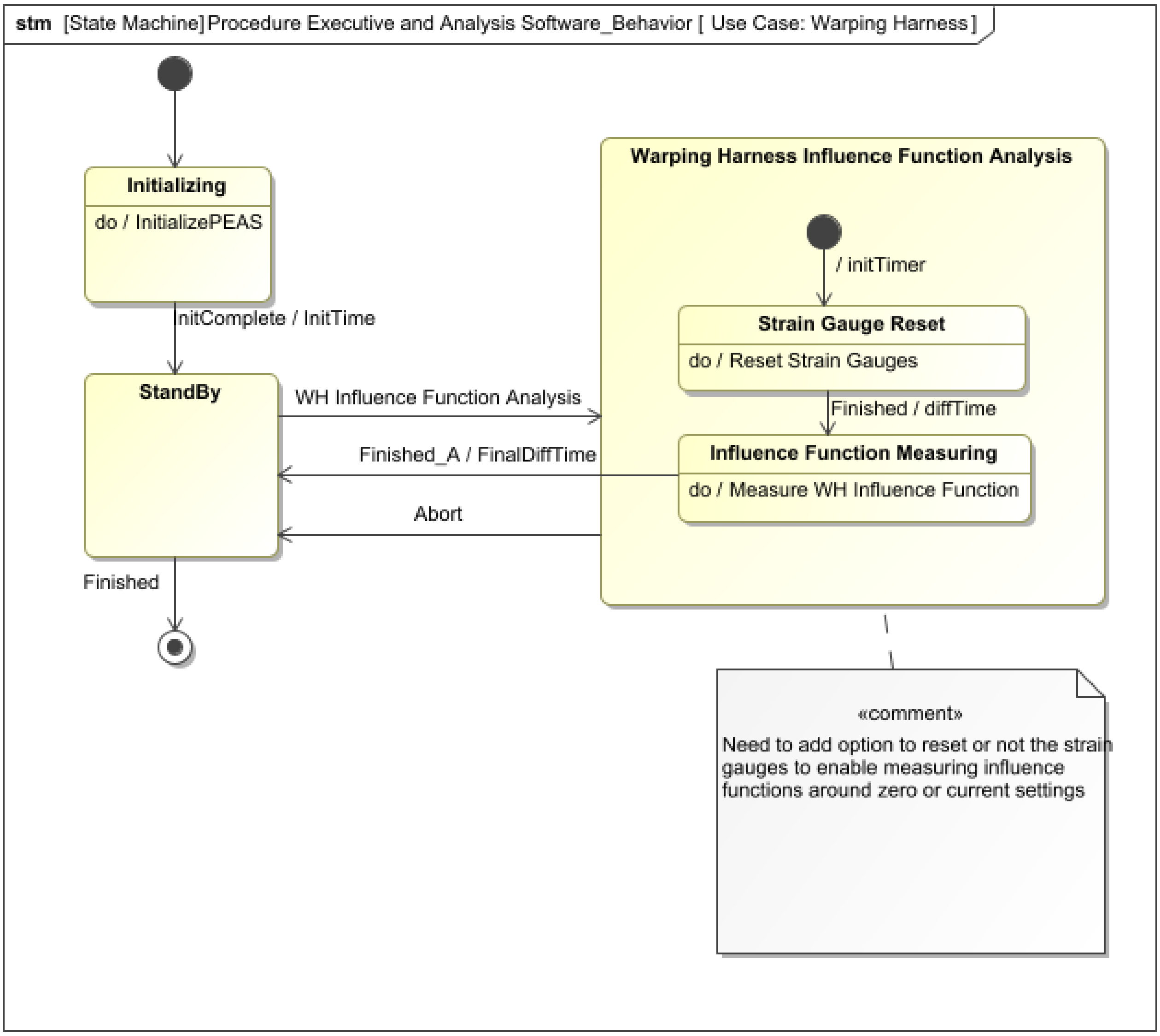
4.3.6.3 Typical Observing Parameters and Operating Conditions

The total time to collect data on all warping harness motors is ~10 hours. However, this can be broken down into three groups (~3.5 hours each), and data collected on different nights if required. The use case can be started as soon as ~40 minutes after sunset. Stars should be selected to be ~2 hours east at a declination of 0 or 40 degrees to minimize changes in telescope elevation. The required star magnitude is between 5th and 6th magnitude (see RD6). In practice we have never had problems finding stars at Keck, so we do not expect any problems with APS at TMT.

4.3.6.4 Use Case Activity

The figure below describes this use case. Once the use case starts, the "Strain Gauge Reset" activity sends a command to M1CS to move the warping harness motors to set all warping harness strains to a value of zero. This optional step allows measurements of the warping harness influence functions about the nominal zero point. If desired, it can be skipped, and measurements made around the current strain gauge settings for each segment. Then, the process of measuring the warping harness influence functions starts. The details of this activity are described in this document under "High Level Activities" Measure Warping Harness Influence Functions . Once the use case is complete the strain values from the start of the use case are restored.

Use Case: Warping Harness



4.3.6.5 Time to Execute

The table below shows our current bottom-up time estimate. The total time estimate is 10.2 hours (36667 seconds), which could be split into multiple nights. There is currently no explicit OAD requirement on how long this takes and as discussed above it will be executed on the order of once per year.

Warping Harness Influence Function Analysis Timing Analysis Results

#	Name	Classifier	tFinal : Real	tSG : Real	tAcquisition : Real
1	warping Harness Influence Function Analysis Duration Scenario at 2023.02.17 12.40	Warping Harness Influence Function Analysis Duration Scenario			
2	warping Harness Influence Function Analysis Duration Scenario .aPS Mission Logical68	APS Mission Logical			
3	warping Harness Influence Function Analysis Duration Scenario .aPS Mission Logical68 .usr	APS User			
4	warping Harness Influence Function Analysis Duration Scenario .aPS Mission Logical68 .aps operational blackbox	APS Logical			
5	warping Harness Influence Function Analysis Duration Scenario .aPS Mission Logical68 .aps operational blackbox . peas	Procedure Executive and Analysis Software	36667	600	
6	warping Harness Influence Function Analysis Duration Scenario .aPS Mission Logical68 .esw	Executive Software			38

#	Name	Classifier	tFinal : Real	tSG : Real	tAcquisition : Real
7	warping Harness Influence Function Analysis Duration Scenario .aPS Mission Logical68 .aps operational blackbox	APS Logical			
8	warping Harness Influence Function Analysis Duration Scenario .aPS Mission Logical68 .aps operational blackbox .peas	Procedure Executive and Analysis Software	36667	600	
9	warping Harness Influence Function Analysis Duration Scenario at 2023.09.06 11.51	Warping Harness Influence Function Analysis Duration Scenario			
10	warping Harness Influence Function Analysis Duration Scenario .aPS Mission Logical	APS Mission Logical			
11	warping Harness Influence Function Analysis Duration Scenario .aPS Mission Logical .usr	APS User			
12	warping Harness Influence Function Analysis Duration Scenario .aPS Mission Logical .aps operational blackbox	APS Logical			
13	warping Harness Influence Function Analysis Duration Scenario .aPS Mission Logical .aps operational blackbox .peas	Procedure Executive and Analysis Software	36666	600	

#	Name	Classifier	tFinal : Real	tSG : Real	tAcquisition : Real
14	warping Harness Influence Function Analysis Duration Scenario .aPS Mission Logical .esw	Executive Software			38
15	warping Harness Influence Function Analysis Duration Scenario .aPS Mission Logical .aps operational blackbox	APS Logical			
16	warping Harness Influence Function Analysis Duration Scenario .aPS Mission Logical .aps operational blackbox .peas	Procedure Executive and Analysis Software	36666	600	

4.3.7 APS pre-session calibration

4.3.7.1 Purpose of Use Case

This use case will be executed before sunset on any night APS observations are planned. Its purpose is to perform all needed internal calibrations before the start of observing in order to minimize the APS use of dark time and maximize the time for TMT science operations. At Keck, the PCS internal calibrations are taken as needed, which adds ~5 mins to the 120 mins of time needed for recovery from a segment exchange (a ~4% overhead). If we did not do this for APS, the additional needed time would be similar.

4.3.7.2 Requirements

Prior to initiating this use case, APS-PEAS and APS-ICS should be operating in their nominal modes. The use case "APS Self Test" should have been executed prior to executing this use case. The time taken to execute this use case is not included in the calculations of the time to perform any of the on-sky use cases.

4.3.7.3 Typical Observing Parameters and Operating Conditions

This use case will typically be executed during the day. APS will be designed so that it can operate with exterior (such as dome) lights on. The PCS pre-calibrations are routinely run at Keck during the daytime, so this should not be an issue for APS. APS should be in its normal operating configuration with all detectors already cooled.

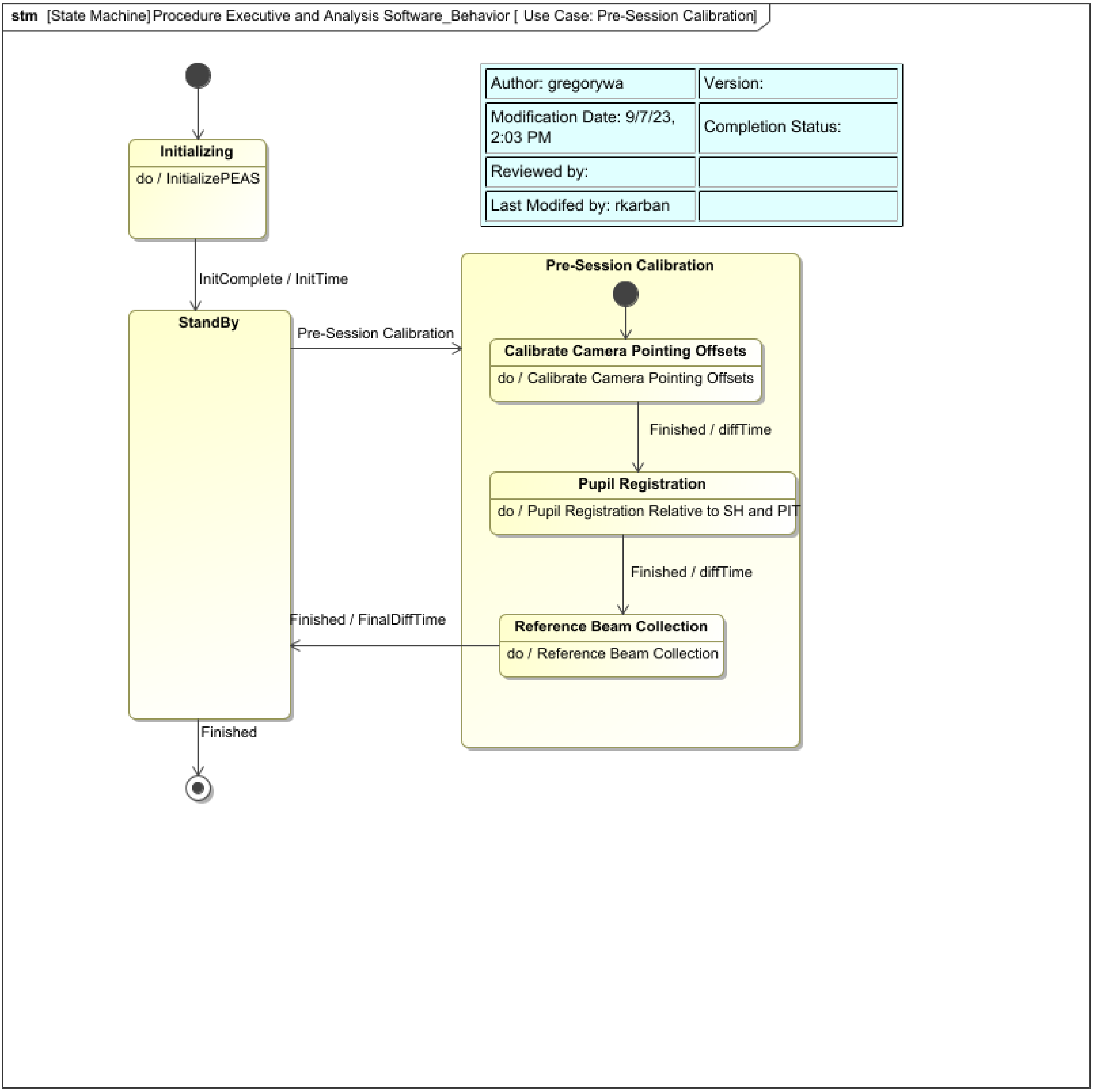
4.3.7.4 Use Case Activity

The figure below shows the Pre-Session Calibration use case. It starts with APS in standby mode. A series of Lower Level Activities are executed:

1. Calibrate Camera Pointing Offsets: This determines the pixel on the 3 APS detectors (APT, PIT and main Shack-Hartmann) on which an on-axis star will land. This information is used during acquisition/guiding with the APT and PIT operation.
2. Pupil Registration: This activity aligns a simulated telescope pupil in the main Shack-Hartmann camera and then determines the location (*x*/*y* translation, rotation, and scale) in the PIT camera. These are then the values that the PIT loop will maintain when observing on-sky to insure a correctly aligned pupil in the main Shack-Hartmann camera.
3. Get Reference Beam: This procedure uses an internal light source at the telescope focus within APS to measure the desired centroid positions of the sub-images in the main Shack-Hartmann camera for each SH mask and filter.

All calibrations are currently planned to be executed before each APS night. As we characterize and understand the system they can be conducted less often. The software supports execution of the calibrations based on changes since the last calibration as a function of time, temperature, K-mirror rotation, and shear plate position.

Use Case: Pre-Session Calibration



4.3.7.5 Time to Execute

The table below shows our current bottom-up time estimate. The total time estimate is (5423 seconds) 90 minutes. There is no explicit requirement on time for execution as it is done during the day. This estimate is a "worst case" as it includes 10 different filter/SH mask combinations taken at 12 different K-mirror rotation angles for a total of 120 images in the Get Reference Beam Activity.

Pre-Session Calibration Timing Analysis Results

#	Name	Classifier	tFinal : Real	tCalCam Point : Real	tCalPup Reg : Real	tColRef Beam : Real
1	pre- Session Calibration Duration Scenario at 2023.02.21 12.41	Pre-Session Calibration Duration Scenario				
2	pre- Session Calibration Duration Scenario .aPS Mission Logical12	APS Mission Logical				
3	pre- Session Calibration Duration Scenario .aPS Mission Logical12 .usr	APS User				
4	pre- Session Calibration Duration Scenario .aPS Mission Logical12 .aps operational blackbox	APS Logical				
5	pre- Session Calibration Duration Scenario .aPS Mission Logical12 .aps operational blackbox .peas	Procedure Executive and Analysis Software	5423	360	109	4954
6	pre- Session Calibration Duration Scenario .aPS Mission Logical12 .esw	Executive Software				
7	pre- Session Calibration Duration Scenario .aPS Mission Logical12 .aps operational blackbox	APS Logical				
8	pre- Session Calibration Duration Scenario .aPS Mission Logical12 .aps operational blackbox .peas	Procedure Executive and Analysis Software	5423	360	109	4954
9	pre- Session Calibration Duration Scenario .aPS Mission Logical	APS Mission Logical				
10	pre- Session Calibration Duration Scenario .aPS Mission Logical .usr	APS User				
11	pre- Session Calibration Duration Scenario .aPS Mission Logical .aps operational blackbox	APS Logical				
12	pre- Session Calibration Duration Scenario .aPS Mission Logical .aps operational blackbox .peas	Procedure Executive and Analysis Software	5423	360	109	4954
13	pre- Session Calibration Duration Scenario .aPS Mission Logical .esw	Executive Software				
14	pre- Session Calibration Duration Scenario .aPS Mission Logical .aps operational blackbox	APS Logical				
15	pre- Session Calibration Duration Scenario .aPS Mission Logical .aps operational blackbox .peas	Procedure Executive and Analysis Software	5423	360	109	4954
16	pre- Session Calibration Duration Scenario at 2023.09.06 10.51	Pre-Session Calibration Duration Scenario				
17	pre- Session Calibration Duration Scenario .aPS Mission Logical13	APS Mission Logical				
18	pre- Session Calibration Duration Scenario .aPS Mission Logical13 .usr	APS User				

#	Name	Classifier	tFinal : Real	tCalCam Point : Real	tCalPup Reg : Real	tColRef Beam : Real
19	pre- Session Calibration Duration Scenario .aPS Mission Logical13 .aps operational blackbox	APS Logical				
20	pre- Session Calibration Duration Scenario .aPS Mission Logical13 .aps operational blackbox .peas	Procedure Executive and Analysis Software	5423	360	109	4954
21	pre- Session Calibration Duration Scenario .aPS Mission Logical13 .esw	Executive Software				
22	pre- Session Calibration Duration Scenario .aPS Mission Logical13 .aps operational blackbox	APS Logical				
23	pre- Session Calibration Duration Scenario .aPS Mission Logical13 .aps operational blackbox .peas	Procedure Executive and Analysis Software	5423	360	109	4954

4.3.8 APS Self Test

4.3.8.1 Purpose of Use Case

This use case will execute a series of APS tests using internal light sources to confirm that it is functioning correctly and able to support observing.

4.3.8.2 Requirements

REQ-2-APS-0051 specifies the APS reliability requirement, which allows for 0.6 hours of down time per year.

As discussed in the requirement APS will implement a self test:

- To minimize what would be significant down-time to the observatory this test shall be executed the day before any planned segment exchange. If APS cannot be repaired before the end of day, then the segment exchange will be delayed until APS is repaired.
- In the case of a planned APS maintenance alignment this test shall be executed the day before the planned observing. If APS cannot be repaired before the end of the day, then the maintenance alignment will be delayed until APS is repaired.

4.3.8.3 Typical Observing Parameters and Operating Conditions

This use case will typically be executed during the day. APS will be designed so that it can operate with exterior (such as dome) lights on. The PCS self-test is routinely run at Keck during the daytime, so this should not be an issue for APS. APS should be in its normal operating configuration with all detectors already cooled.

On completion of this use case APS will either report that it passed the self test and is ready to observe, or that an error occurred and provide a description of the error.

<style type="text/css">p {padding:0px; margin:0px;}
</style>
<p>This use case will typically be executed during the day. APS will be designed so that it can operate with exterior (such as dome) lights on. The PCS self-test is routinely run at Keck during the daytime, so this should not be an issue for APS. APS should be in its normal operating configuration with all detectors already cooled.</p>

<p> </p>

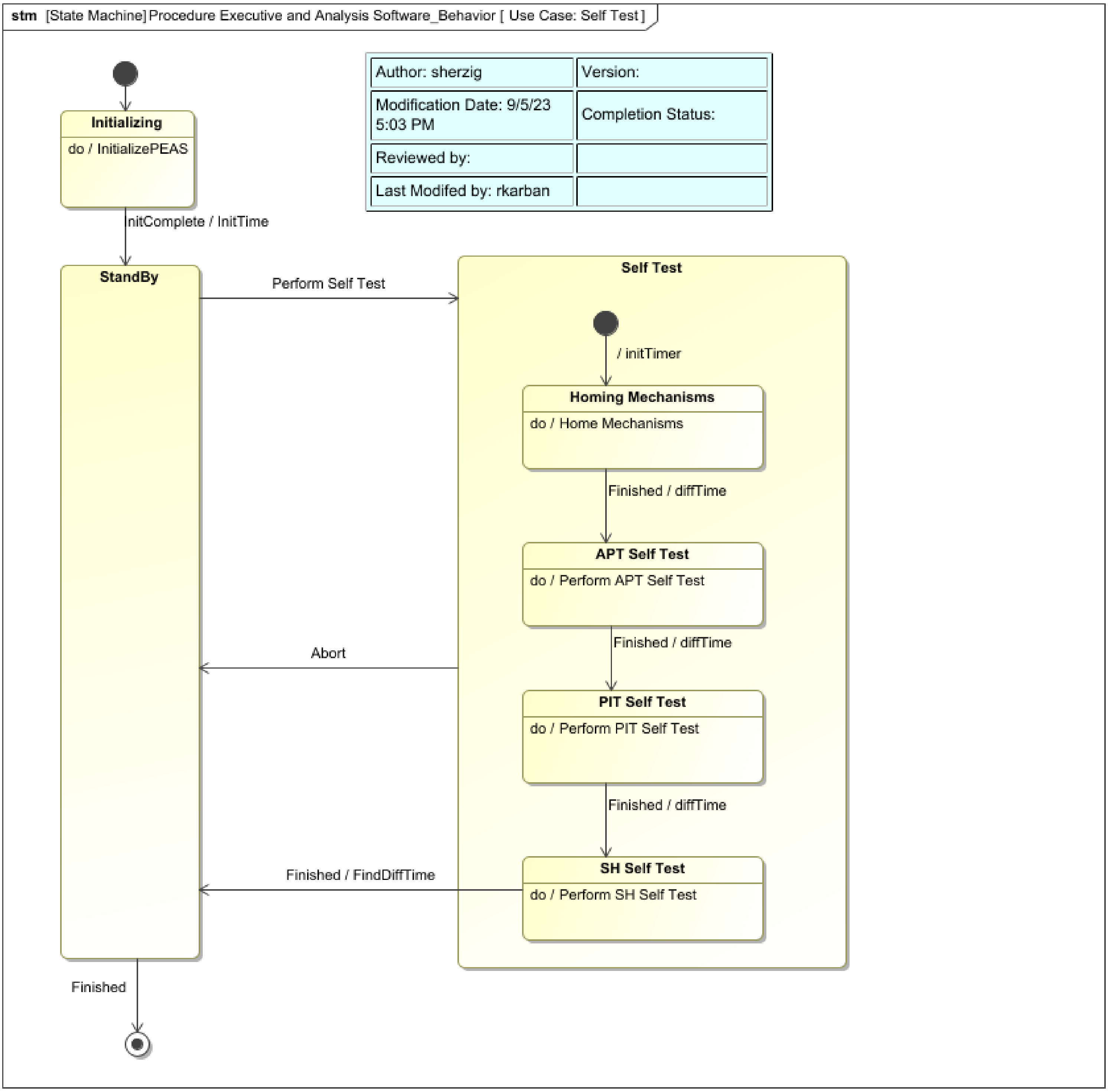
<p>On completion of this use case APS will either report that it passed the self test and is ready to observe, or that an error occurred and provide a description of the error.</p>

4.3.8.4 Use Case Activity

The figure below describes this use case. The use case starts by homing all APS mechanisms and then proceeds to test each of the APS optical paths and detectors: APT, PIT and SH.

1. Home Mechanisms: Homes all mechanisms in APS to ensure proper operation.
2. Perform APS Self Test: This test turns on the stimulus, configures the APT camera, takes two APT images, each with a different filter and then compares the two images to insure proper APT operation.
3. Perform PIT Self Test:
    1. This test turns on the stimulus
    2. Takes PIT images
        1. With the shear plate and K-Mirror at a nominal position
        2. With the shear plate positioned to move the pupil 20 mm
        3. With the shear plate moved back to it's nominal position and the K-mirror rotated -1 deg
    3. Moves the K-mirror back to it's nominal position.
    4. Compares the 3 images to ensure the proper pupil motion is measured.
    5. Turns off the stimulus.
4. Perform SH Self Test: Using a table of for each Shack-Hartman mask, filter, integration time and reference beam this test:
    1. Turns on the associated reference beam.
    2. Configured the APS PSH camera.
    3. Takes an exposure.
    4. Turns off the reference beam.
    5. Calls find and identify (to ensure all sub images can be found).

Use Case: Self Test



4.3.8.5 Time to Execute

The table below shows our current bottom-up time estimate. The total time estimate is (484 seconds) 8 minutes. There is currently no OAD requirement on how long this takes.

Self Test Timing Analysis Results

#	Name	Classifier	tFinal : Real	tSelfTest Homing : Real	tSelfTestAP T : Real	tSelfTestPI T : Real	tSelfTestS H : Real	tAcquisition : Real
1	self Test Duration Scenario at 2023.02.01 15.23	Self Test Duration Scenario						
2	self Test Duration Scenario .aPS Mission Logical1	APS Mission Logical						
3	self Test Duration Scenario .aPS Mission Logical1 .usr	APS User						
4	self Test Duration Scenario .aPS Mission Logical1 .aps operational blackbox	APS Logical						
5	self Test Duration Scenario .aPS Mission Logical1 .aps operational blackbox .peas	Procedure Executive and Analysis Software	484	122	160	132	70	
6	self Test Duration Scenario .aPS Mission Logical1 .esw	Executive Software						0
7	self Test Duration Scenario .aPS Mission Logical1 .aps operational blackbox	APS Logical						
8	self Test Duration Scenario .aPS Mission Logical1 .aps operational blackbox .peas	Procedure Executive and Analysis Software	484	122	160	132	70	
9	self Test Duration Scenario at 2023.09.06 11.23	Self Test Duration Scenario						
10	self Test Duration Scenario .aPS Mission Logical	APS Mission Logical						
11	self Test Duration Scenario .aPS Mission Logical .usr	APS User						
12	self Test Duration Scenario .aPS Mission Logical .aps operational blackbox	APS Logical						
13	self Test Duration Scenario .aPS Mission Logical .aps operational blackbox .peas	Procedure Executive and Analysis Software	483	121	160	132	70	
14	self Test Duration Scenario .aPS Mission Logical .esw	Executive Software						0
15	self Test Duration Scenario .aPS Mission Logical .aps operational blackbox	APS Logical						
16	self Test Duration Scenario .aPS Mission Logical .aps operational blackbox .peas	Procedure Executive and Analysis Software	483	121	160	132	70	

4.4 High Level Activities

This chapter describes high level APS activities. High level activities are those that are called from the use cases.

4.4.1 Coarse Tilt Alignment

4.4.1.1 Overview of Activity

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 segment installation requirements for TMT are that the one-dimensional tip/tilt errors on the sky shall be less than ±20 arcseconds (maximum, not RMS) (REQ-2-APS-0060) . The APS field of view in the Shack-Hartman channels is 25 arcsec in diameter, set by vignetting in the K-mirror and enforced via a field stop at the telescope focus. Thus, the APS tip/tilt capture range is nominally only ±12.5 arcsec. Below we describe how APS is able to met and exceed the required capture range.

This test uses the SH-0 mask which has a single sub-aperture per segment. This mask has a nominal subimage spacing at the detector of 78 arcseconds, much greater than the field of view radius. As a result, if the segment subimages are within the 25 arcsec FoV, there is never any question of which subimage corresponds to which segment. That is, as a subimage moves away from its nominal position, it will disappear before it can cross into a region of the CCD that is assigned to another segment. This test does not need a very well aligned telescope pupil; in principle the single subaperture just needs to be within ±~0.6m so that it is on the correct segment. This tolerance, along with the unlikeliness of subimage confusion means that there are no segment edge subapertures on the SH-0 mask, so telescope closed loop guiding and the pupil image tracking loop (PIT) are not needed.

The effective capture range of the coarse alignment activity will be increased by performing a search via re-pointing the mirror segments. Our proposed approach is to:

1. Take an image with the SH-0 mask. If all segments are found, continue as normal to analyze the image and send commands to M1CS.
2. If not all segments are found then send commands to M1CS to tilt those segments not found by 20 arcseconds on-sky and repeat step 1. A raster search pattern with 9 images will be used to provide a ±30 arcsecond on-sky capture range. This provides a capture range that is 1.5 times larger than the requirement and if needed can easily be increased by extending the raster search pattern.

The coarse tilt alignment procedure will correct the segment image tip/tilts to within 0.2 arcseconds (one dimension, RMS), which is within the capture range of the *rigid body and segment figure* alignment activity. The specific details of the coarse tilt alignment algorithms are described in RD5. During AIV we can confirm this activity is working as expected by executing it twice in a row and looking at the RMS and maximum segment tip/tilt. During normal operations we will likely execute this activity once and move on to the next activity. If this activity fails to reach the needed exit condition and it is not caught by the APS software, then it will be obvious in the next activity as subimages will be overlapping. At Keck, the equivalent activity (passive tilt) has been successfully executed many hundreds of times without any failures, so we do not expect any problems.

4.4.1.2 Activity Parameters

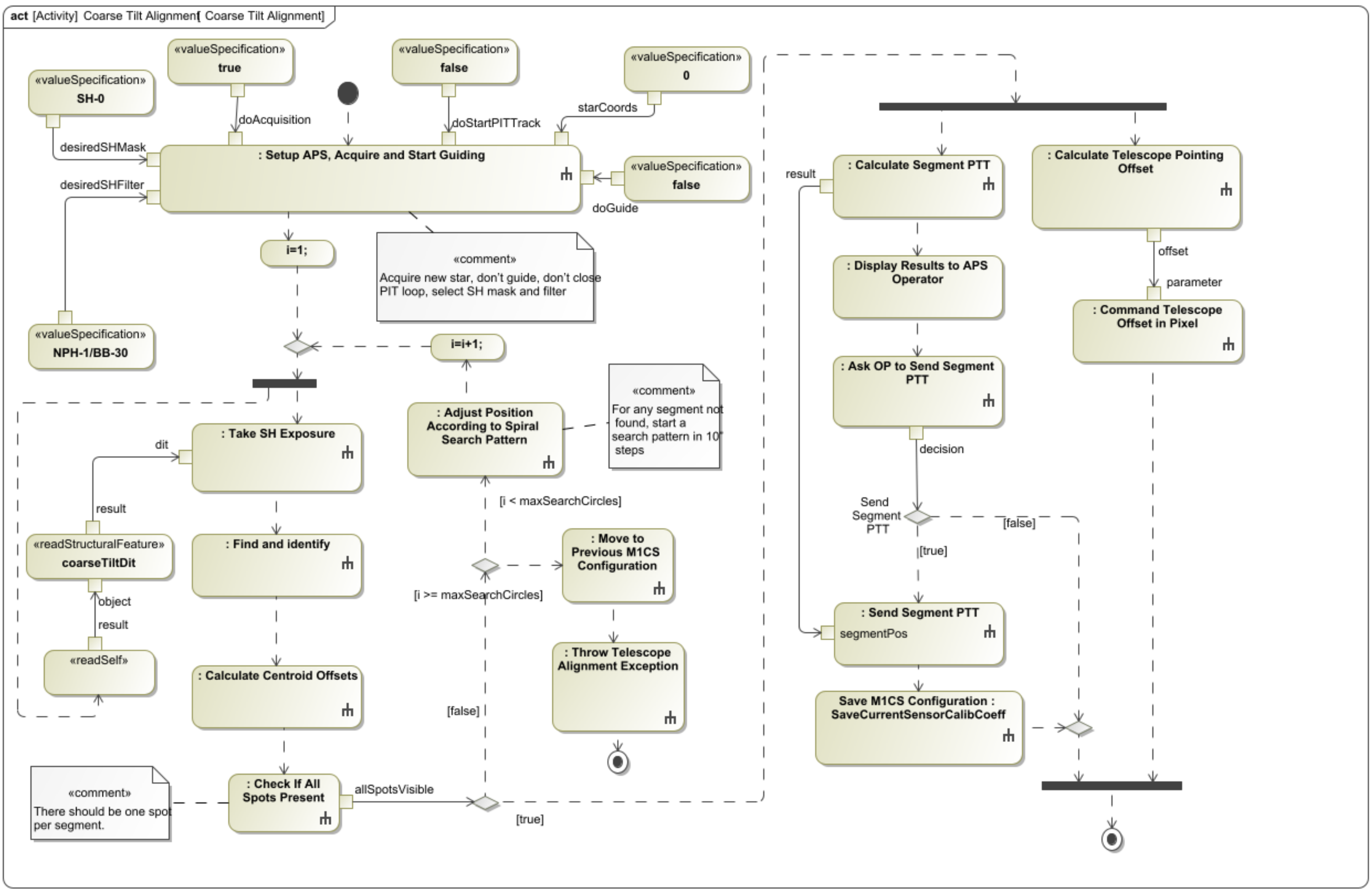
Relevant activity parameters are:

- Entrance requirement: segment tip/tilt errors less than ±20 arcseconds (one-dimensional, maximum, not RMS) on the sky (REQ-2-APS-0060) .
- Exit condition: segment tip/tilt errors within the capture range of the rigid body and segment figure alignment activity, which is estimated to be ±~ +/-1.28 arcseconds (RD5) on the sky. We expect the coarse tilt alignment errors to be similar to those at Keck which are ~+/- 0.2 arcseconds.
- Filter: 611 nm with a bandpass of 10 nm
- Pupil Mask: SH-0, which has one subaperture per segment
- APT/telescope guiding status: open loop telescope tracking
- PIT loop status: open (not used)
- Star magnitude: 5-6
- Star spectral type: nominally K, but not critical
- Integration time for a single frame: ~20 seconds
- Number of frames used per measurement: 1
- Number of frames used per activity: 9

4.4.1.3 Activity Description

The following figure shows the coarse tilt alignment activity. APS first executes the "Setup APS, Acquire and Start Guiding" activity. In this case the required PSH mask and filter are requested and if requested a star is acquired. At this point the telescope segments will not be stacked. Neither guiding nor the PIT loop is started; neither is required.
An image is taken in the PSH, find and identify is called to find the sub-images, and the centroid offsets are calculated. A check is then made to determine if there was a sub-image found for each segment installed in the telescope. If there are missing segment sub-images then those segments are commanded in a raster pattern, another PSH images is taken, and the process iterates until all segment sub-images are found or the maximum search radius is exceeded. If the maximum search radius is exceeded the user is presented with an error message.
Once all the segment sub-images are found the segment tip/tilt values and telescope pointing offsets are calculated (in parallel). The telescope pointing offset is sent to TCS. The segment tip/tilt value are displayed to the APS user along with the associated statistics. If the user desires, the commands are sent to M1CS and the M1CS configuration is saved via the command SaveCurrentSensorCalibCoef (the equivalent of a snapshot at Keck).

Coarse Tilt Alignment



4.4.2 Rigid Body and Segment Figure Correction

4.4.2.1 Overview of Activity

The Rigid body and Segment Figure Correction activity will align the segment tip/tilts and M2 Piston as well as either M2 tip/tilt or M2 *x*/*y* decenter. The software will have a configuration parameter to select between control of M2 tip/tilt or decenters. This activity will also adjust the 21 warping harness strains on each segment to minimize the segment shape errors; control will be done using warping harness modes. Control of the segment surface errors is described in more details in RD4 and RD5. The warping harness control modes are the singular value decompensation modes from the warping harness influence functions. Based on simulations we expect to control the first 10 modes, but this will be a user configurable parameter in the software when the on-sky activity is executed. To achieve the required alignment accuracy, we will need to average over several different realizations of atmospheric turbulence; a typical exposure sequence will consist of eight integrations of 40 to 60 seconds each. Shack-Hartmann measurements only determine the segment tip/tilts, not segment pistons. APS-PEAS will normally constrain the segment pistons so that the changes to the RMS inter-segment edge height are minimized.

4.4.2.2 Activity Parameters

Relevant activity parameters are:

- Entrance requirement: segment tip/tilt errors less than +/-1.28 arcseconds (RD5) on the sky, which is met by the coarse tilt alignment activity with a factor of 6 margin.
- Exit conditions: are defined by requirements REQ-2-APS-0009 and REQ-2-APS-0079.
- Filter: 611 nm with a bandpass of 10 nm
- Pupil Mask: SH-5 or SH-6 (91 or 127 subapertures per segment).
- APT/telescope guiding status: closed
- PIT loop status: closed
- Star magnitude: 5-6
- Star spectral type: nominally K, but not critical
- Integration time for a single frame: ~40-60 seconds
- Number of frames used per measurement: 8

4.4.2.3 Activity Description

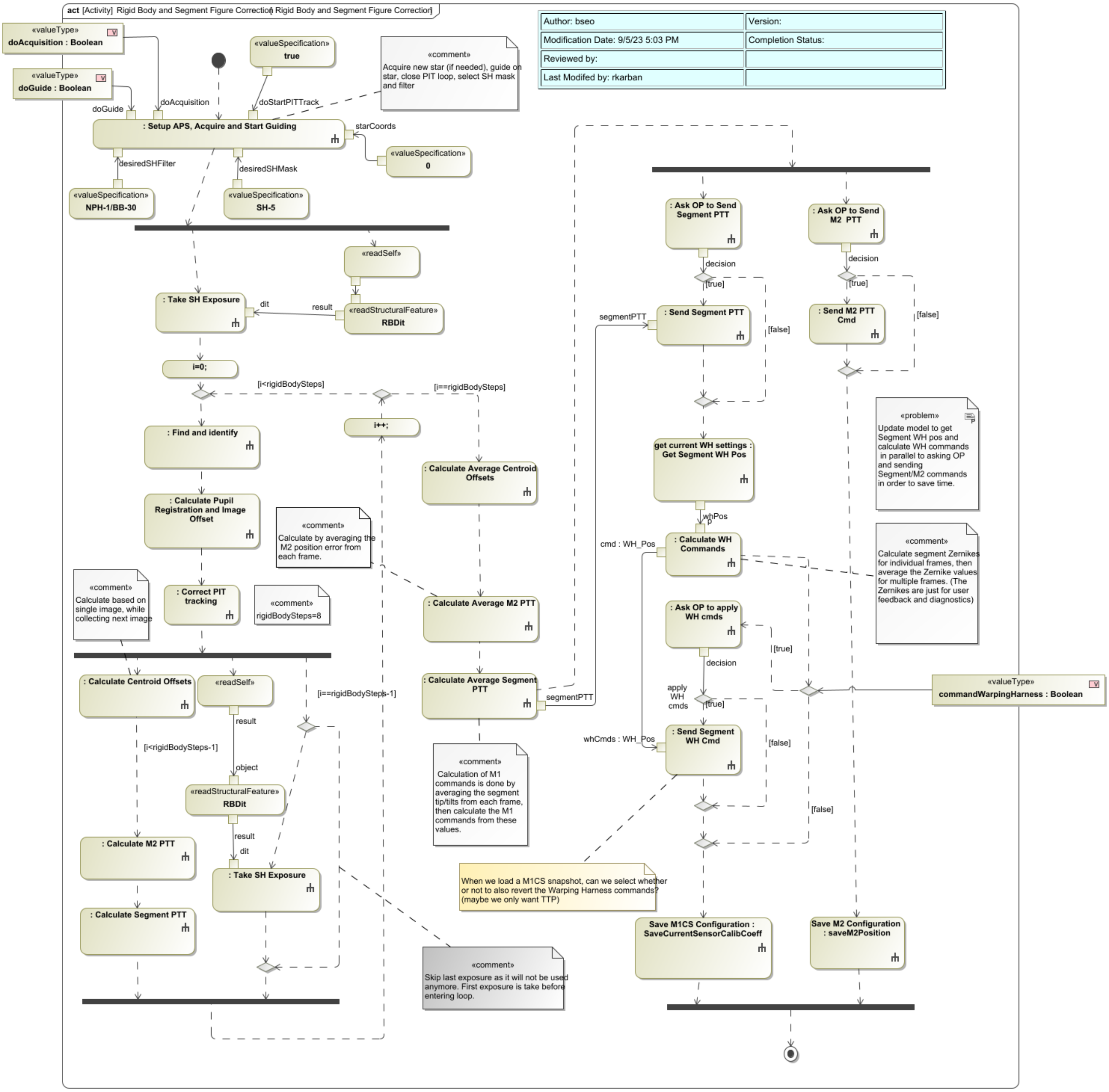
The following figure shows the rigid body and segment figure correction activity. APS first executes the "Setup APS, Acquire and Start Guiding" activity. In this case, the required PSH mask and filter are requested and if requested a star is acquired. The telescope will start guiding, and then the PIT loop will close and stabilize the M1 pupil position and the correct location within APS.

An image is taken with the PSH mask, the *Find and Identify* computational routine is called in order to find the sub-images and pupil registration (*x*, *y*, rotation and scale) and the image offset is calculated. These are then sent to the PIT loop to correct the errors. The activity shows the nominal flow, but if the pupil registration and/or image offsets exceed pre-defined acceptable values, then after "correct PIT tracking" is called, the image will automatically be re-taken.

After this, APS will take the next PSH image, while calculating the centroid offsets as well as M1 and M2 errors and commands. This loop continues until the desired number of images is collected, nominally eight, but this is run-time configurable. Next the average values for the centroid offsets (over frames), and M1 and M2 errors and commands are calculated. The calculation of the commands for each frame provides statistics on the APS measurement errors for these quantities.

The APS user is then presented with the M1 and M2 results and if desired, commands are sent. Currently the diagram shows that after the M1 commands are complete, the warping harness commands are calculated by first requesting from M1CS the WH strain readings for all segments and then calculating the desired strains (Calculate WH commands). After this, the results are displayed to the APS user and if desired, the WH commands are sent. As noted on the diagram we can save a little time (~1 minute) by starting the request for the WH strains and then calculating the WH commands in parallel with sending M1 and M2 commands. Both M1 and M2 configurations are saved via the commands SaveCurrentSensorCalibCoef and saveM2Position before exiting the activity.

Rigid Body and Segment Figure Correction



4.4.3 Broadband Phasing

4.4.3.1 Overview of Activity

Broadband phasing is described in detail in RD5. In summary broadband phasing is a physical optics generalization of the Shack-Hartmann test and measures the intersegment edge height in two places along each intersegment edge. Broadband phasing measures the edge heights against a "length standard" of the coherence length of the filter: where Δλ is the FWHM of the wavelength filter. This is to be contrasted with the actual (or central) filter wavelength used in narrowband phasing. The broadband and narrowband phasing algorithms differ in several other fundamental respects. While narrowband phasing maximizes the overlap of the diffraction pattern against a series of templates for different phase errors, broadband phasing maximizes the "coherence" of the diffraction pattern as the primary mirror is stepped through a series of (typically 11) different configurations [The total number of configurations must be odd.]. Thus, while narrowband phasing requires only a single exposure (per filter), broadband phasing requires multiple exposures. In general, the broadband phasing procedure has a larger capture range but a lower accuracy than the narrowband phasing procedure. In addition to the larger capture range, broadband phasing has the major advantage that it cannot fail in the sense of producing significantly incorrect result. Narrowband phasing with a single wavelength, on the other hand, produces an infinite number of solutions and it is impossible to say which one is the correct edge height if it cannot be guaranteed to be below

(see Section 4.4 and RD5). The same is true for a subset of wavelength combinations in multi-filter narrowband phasing, albeit with a much larger capture range. By contrast, if the maximum possible piston error is larger than is appropriate for the given coherence length in broadband phasing, this is readily apparent.

In addition, multi-wavelength narrowband phasing in the presence of measurement errors can produce significantly incorrect results even for edge heights well within its capture range, although knowledge of the measurement noise and post-processing of the solution help reduce the occurrence rate of this type of error to a very small fraction of measurements. Broadband phasing does not have this problem either, at the expense of somewhat lesser accuracy compared to narrowband phasing.

This fail-safe feature of broadband phasing is particularly important during early operations.

4.4.3.2 Activity Parameters

Relevant activity parameters are:

- Entrance requirement: M1 segment piston of +/- 30 microns (surface, not to exceed value) REQ-2-APS-0060.
- Exit conditions: M1 segment edges are within the capture range of narrowband phasing, ~+/- 200 nm (surface)
- Filter: see table below
- Pupil Mask: phasing, which has two 120 mm (at M1) phasing sub-apertures per segment edge.
- APT/telescope guiding status: closed
- PIT loop status: closed
- Star magnitude: see table below
- Star spectral type: nominally K (particularly important for BB-30)
- Integration time for a single frame: ~20 seconds
- Number of frames used per measurement: 11

Filter Central Wavelength (nm)	Filter FWHM (nm)	Capture Range (um, surface)	Accuracy (nm, RMS piston)	Typical Star Magnitude	Operational Mode Name	Notes
890	3	+/- 100	3000	2-3	Broadband Phasing 3000/BB-3000	This mode is a "backup" in case the entrance requirements are not met.
890	10	+/- 30	1000	4	Broadband Phasing 1000/BB-1000	
870	100	+/- 3	100	6	Broadband Phasing 100 /BB-100	
No filter	~200	+/- 1	30	7	Broadband Phasing 30/BB-30	

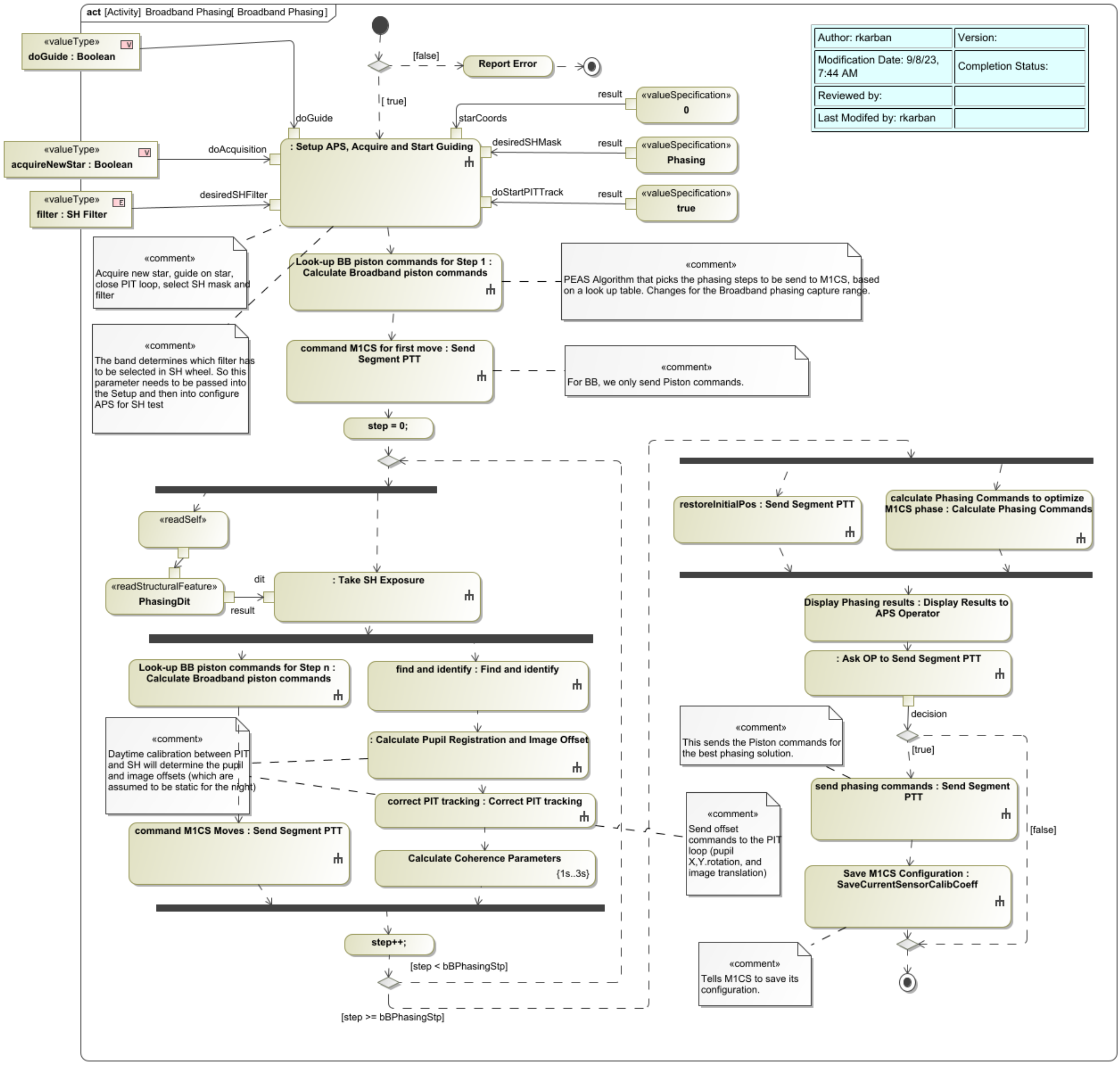
4.4.3.3 Activity Description

The following figure shows the broadband phasing activity. APS first executes the "Setup APS, Acquire and Start Guiding" activity in this case the required PSH mask and filter are requested and if requested, a star is acquired. The telescope will start guiding and then the PIT loop will close and stabilize the M1 pupil position at the correct location within APS.

Broadband phasing utilizes a series of M1CS commands to generate the required segment edge steps. After setup these are calculated, and the first set of commands is sent. Note, that while there are typically 11 broadband phasing steps this value can be altered in software by an appropriately authorized APS user. After the M1CS commands have been completed a PSH image is taken, the *Find and Identify* routine is called to find the sub-images and pupil registration (*x*, *y*, rotation and scale) and image offset is calculated. These are then sent to the PIT loop to correct the errors. The activity shows the nominal flow, but if the pupil registration and/or image offsets exceed pre-defined acceptable values, then after "correct PIT tracking" is called, the image will automatically be re-taken. Next the coherence parameters for the segment edges are calculated. To minimize on-sky time, while all calculations are going on the next set of M1CS commands will be sent. Once the calculations and M1CS commands have completed the next PSH image is taken.

When all "broadband phasing step" images have been taken (typically 11) the 492 phasing commands are calculated and at the same time one last command is sent to M1CS to re-configure the mirror to its initial, nominally aligned state. During the calculation of phasing commands, the algorithm will test for unconstrained segments or disconnected “islands” of segments. Once both have completed the phasing results are displayed to the user and if desired, commands sent to phase M1CS. If commands are sent, the M1 configuration is saved via the command SaveCurrentSensorCalibCoef before exiting the activity.

Broadband Phasing



4.4.4 Narrowband Phasing

4.4.4.1 Overview of Activity

Narrowband phasing works by a physical optics generalization of the usual geometrical optics Shack-Hartmann test. It exploits the fact that details of the diffraction pattern formed by the two halves of a circular subaperture straddling two segments are sensitive to the relative piston error of the segments. For this purpose, each of the 1386 intersegment edges will be sampled in two places. Because this procedure utilizes high order information in the diffraction pattern, and not just the centroid location used in the traditional Shack-Hartmann test, the optical quality of the sub images is critical. PCS used prisms instead of lenslets for this reason. As part of risk reduction efforts, we have demonstrated that for APS we can use Fresnel Phasing (no lenslets and just a mask in the re-imaged pupil). APS will use Fresnel phasing for both narrow and broadband phasing.

Since in narrowband phasing the light is essentially monochromatic, the phasing measurements do not determine the actual (surface) edge heights h, but rather an aliased height h′,

where n is an integer such that:

. Since the uncertainty in h′ approaches λ/2 (independent of the formal measurement errors) as h′ approaches ±λ/4, narrowband phasing using a single wavelength filter is effectively limited to the situation where the edge height (including the contributions both from residual piston errors and from segment aberrations) is well below λ/4, typically within about 100 nm of zero. See RD5 for details.

The capture range can be extended with the use of multiple filters when the wavelengths are correctly selected, see RD5 for more details. However, there are several limitations which can result in the algorithm calculating the wrong edge height. A more robust means of extending the capture range is provided by the separate broadband phasing routine. Roughly speaking, then, the broadband algorithm is used for coarse phasing and the narrowband algorithm is used for fine phasing, although in practice there may be significant overlap. As APS can meet all requirements using narrowband phasing with a single filter, that is the current baseline.

The APS team is activity pursuing multi-filter narrowband phasing via experiments at Keck and simulations. The increased capture range could significantly decrease the needed on-sky time post segment exchange, potentially from 137 mins to 96 min, a reduction of ~30% that would save ~18 hours of observing per year. See RD5 for details on both single and multi-filter narrowband phasing.

4.4.4.2 Activity Parameters

Relevant activity parameters for single filter narrowband phasing are:

- Entrance requirement: M1 segment edges are within the capture range of narrowband phasing, ~+/- 200 nm (surface)
- Exit conditions: The APS measurement error of the M1 segment pistons shall be less than 13.6 nm RMS WFE REQ-2-APS-0078).
- Filter: 890 nm with a bandpass of 10 nm, other filters will be added if multi-filter wavelength phasing is implemented
- Pupil Mask: Phasing, which has two 120 mm (at M1) phasing sub-apertures per segment edge.
- APT/telescope Guiding status: closed
- PIT loop status: closed
- Star magnitude: ~4-5
- Star spectral type: nominally K
- Integration time for a single frame: ~20 seconds
- Number of frames used per measurement: 1

4.4.4.3 Activity Description

The following figure shows the narrowband phasing activity. APS first executes the "Setup APS, Acquire and Start Guiding" activity in this case the required PSH mask and filter are requested and if requested a star acquired. The telescope will start guiding and then the PIT loop will close and stabilize the M1 pupil position at the correct location within APS.

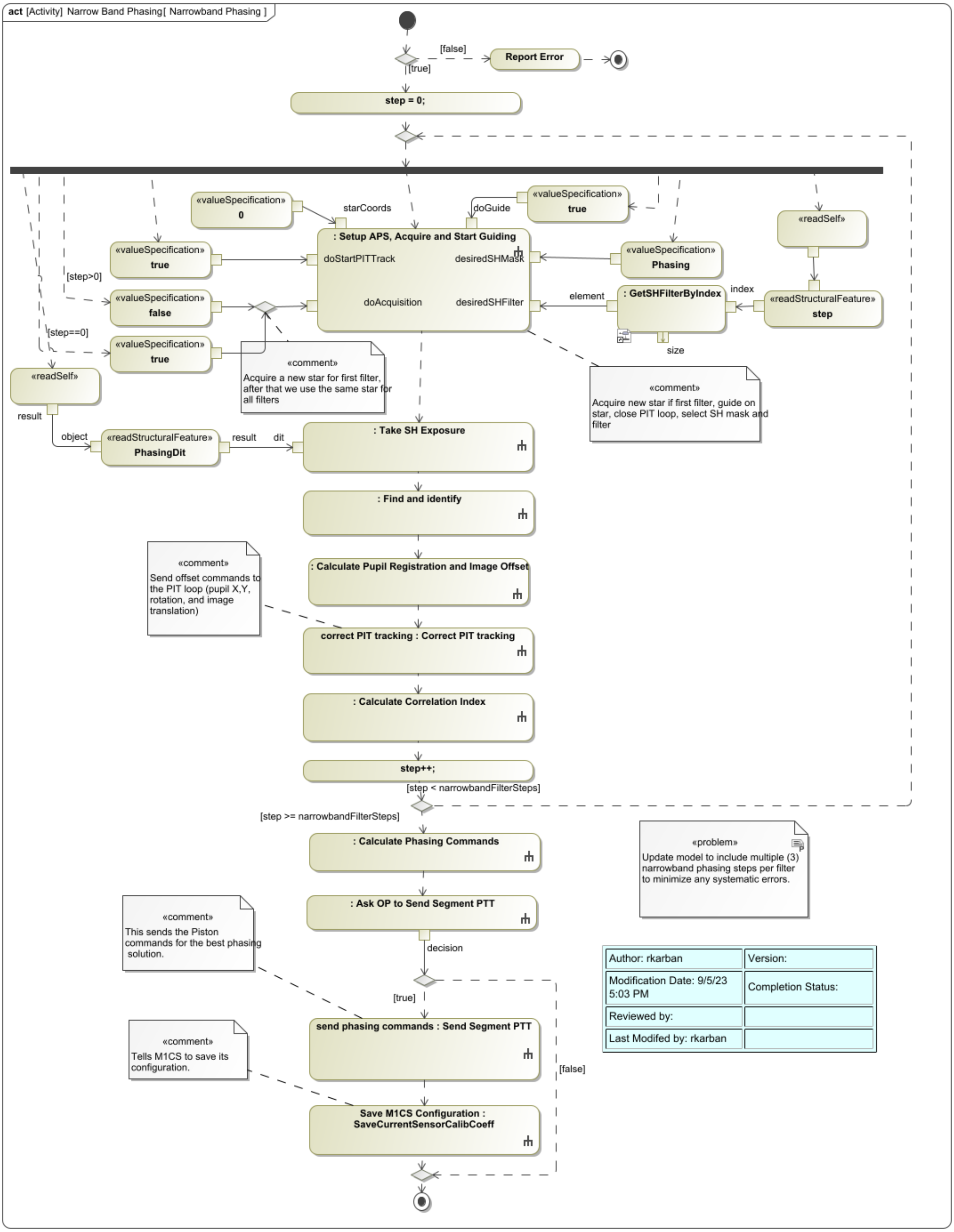
A PSH image is taken, the *Find and Identify* computational routine is called to find the sub-images and pupil registration (*x*, *y*, rotation and scale) and image offset is calculated. These are then sent to the PIT loop to correct the errors. The activity shows the nominal flow, but if the pupil registration and/or image offsets exceed pre-defined acceptable values, then after "correct PIT tracking" is called and the image will automatically be re-taken. Next the correlation indexes for the segment edges are calculated. If multi-filter narrowband phasing is implemented, then the next filter is selected (no new star is required) and this process is repeated.

After all filters have been collected, the 492 phasing commands are calculated. During the calculation of phasing commands, the algorithm will test for unconstrained segments or disconnected “islands” of segments. Then the phasing results are displayed to the user and if desired, commands are sent to phase M1CS. If commands are sent, the M1 configuration is saved via the SaveCurrentSensorCalibCoef command before exiting the activity.

Notes:

1. As mentioned above, the APS team is actively investigating multi-filter narrowband phasing to reduce the required APS on-sky time.
2. The APS team is also investigating if multiple (3) narrowband phasing steps per filter can minimize any systematic errors.

Narrowband Phasing



4.4.5 Measure Warping Harness Influence Functions

4.4.5.1 Overview of Activity

The baseline plan is to use theoretical warping harness influence functions in the control of the segment surface shapes. However, due to manufacturing tolerances, etc. these may be different than the actual influence functions. This activity is designed to measure the warping harness influence function on-sky. Details and analysis are presented in RD7. This procedure will certainly be executed during AIV and may be re-executed to check warping harness influence functions as well as troubleshoot any problems. We envision this procedure being executed on the order of once per year once the telescope is in normal operation. This activity description just covers collection of the data. The analysis of the collected data is currently planned to be executed off-line.

4.4.5.2 Activity Parameters

Relevant activity parameters are:

- Entrance requirement: telescope segments are well aligned in rigid body degrees of freedom (REQ-2-APS-0078 and REQ-2-APS-0079.
- Exit conditions: no change in telescope alignment or segment figures
- Filter: 611 nm with a bandpass of 10 nm
- Pupil Mask: SH-5 or SH-6 (91 or 127 subapertures per segment)
- APT/telescope guiding status: closed
- PIT loop status: closed
- Star magnitude: 5-6
- Star spectral type: nominally K, but not critical
- Integration time for a single frame: ~40-60 seconds
- Number of frames used per measurement: 8
- Number of frames used per activity: 504 (21 strain gauges per segment, 3 WH settings per strain gauge, 8 frames per measurement)

4.4.5.3 Activity Description

This activity takes ~10 hours total to measure all warping harness influence functions; all segments are measured in parallel. The nominal plan is to measure the influence functions using three (3) different stars and measure seven (7) warping harness influence functions per star which will take ~3.5 hours per star.

The following figure shows the WH influence function measurement activity. For each group of warping harness influence functions to be measured on a specific star the following procedure is followed:

1. APS executes the "Setup APS, Acquire and Start Guiding" activity in this case the required PSH mask and filter are requested and if requested a star acquired. The telescope will start guiding and then the PIT loop will close and stabilize the M1 pupil position at the correct location within APS.
2. For each warping harness influence function to be measured on the current star:
    1. 8 frames of Shack-Hartmann data are collected
    2. The current warping harness influence function to be measured is set to +45% of its stroke limit for all segments
    3. 8 frames of Shack-Hartmann data are collected
    4. The current warping harness influence function to be measured is set to -45% of its stroke limit for all segments
    5. 8 frames of Shack-Hartmann data are collected
    6. The current warping harness influence function to be measured is set to zero for all segments

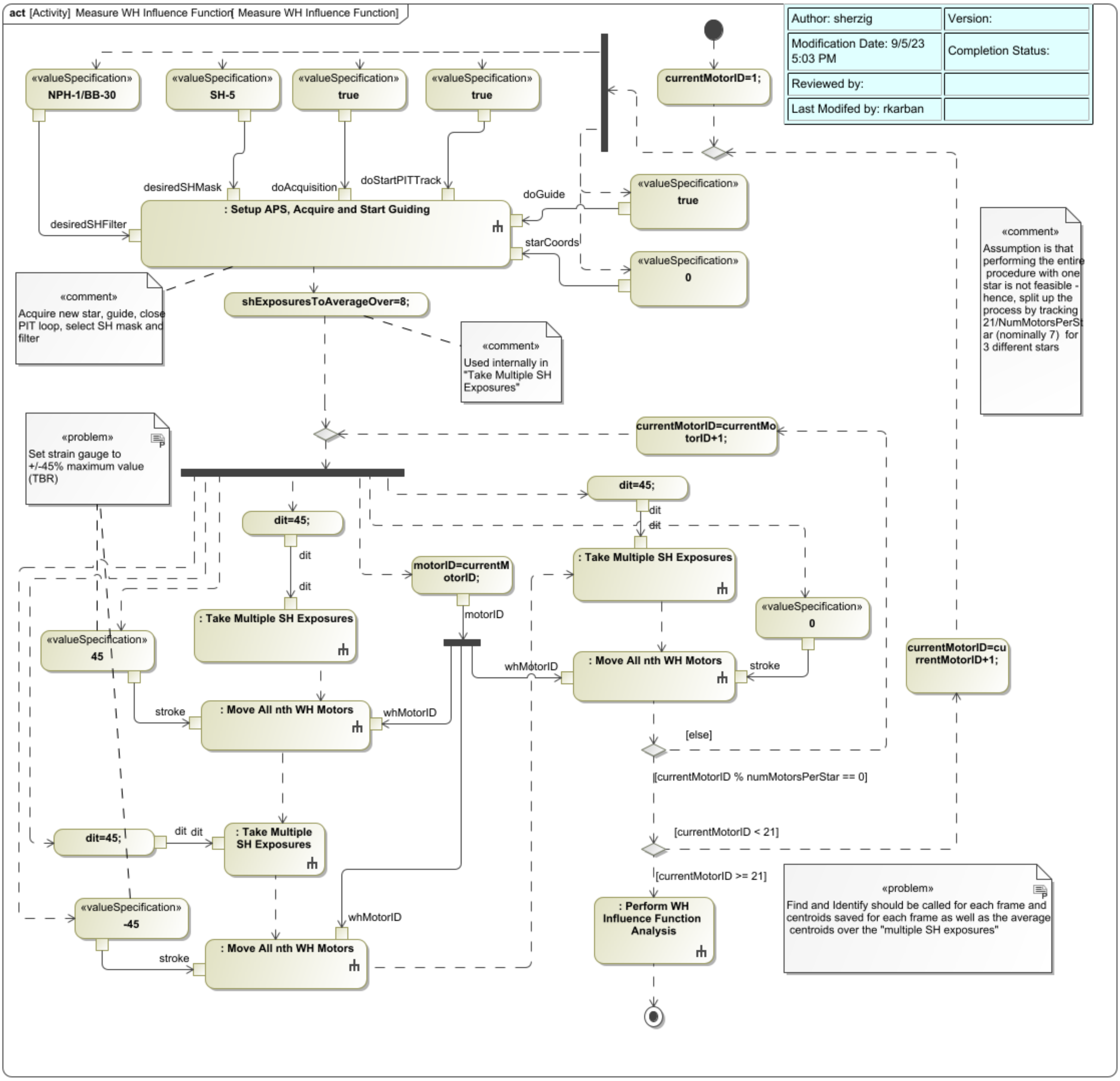
As currently written once all the data has been collected, perform WH Influence function analysis will calculate the centroid offsets for each segment and each set of Shack-Hartmann frames (8 frame average), and store this data in the APS-PEAS database. As noted in the figure this should occur as we collect the data, the activity will be updated to reflect this as part of the final design phase.

The remaining data analysis will be performed off-line and cannot be defined and/or developed until the first set of data is collected. However, the data analysis will likely include the following:

- Comparing the on-sky measured influence functions to the theoretical influence functions.
- Comparing and/or combining the on-sky measured influence functions among segments of the same type.
- Comparison of the measured influence functions over the lifetime of the telescope.
- Blending the on-sky and theoretical influence functions to generate a better estimate of the influence functions.

As currently written the influence functions are measured about zero strain. If needed, measurements about the nominal (non-zero) strains settings will also be made. The influence functions are predicted to be linear so such measurements are assumed (at this point) not to be required.

Measure WH Influence Function



4.4.6 M3 Alignment Procedure

This activity is nominally executed as part of the Post Segment-Exchange Alignment and/or Maintenance Alignment use cases. This activity's objective is to make corrections to the M3 look-up table so that it will be aligned for all TMT instruments. This is accomplished by adjusting the M3 rigid-body position such that the telescope pupil (M1) is positioned correctly with respect to the SMRs within APS.

4.4.6.1 Overview of Activity

4.4.6.2 Activity Parameters

Relevant activity parameters are:

- Entrance requirement: telescope segments are well aligned in tip/tilt (REQ-2-APS-0079).
- Exit conditions: the APS shall determine the telescope pupil position to an accuracy of 0.05% the diameter of the pupil relative to the APS SMRs (REQ-2-APS-0086).
- PIT Filter: standard PIT filter, nominally 700 nm with a bandpass of 200 nm
- Pupil Mask: SH-0 (one subaperture at center of segment and 1 subaperture on each segment edge)
- APT/telescope guiding status: closed
- PIT loop status: closed
- Star magnitude: 5-6
- Star spectral type: nominally K, but not critical
- Integration time for a single frame: ~10 seconds
- Number of frames used per measurement: 1
- Number of frames used per activity: estimate 3 PIT iterations

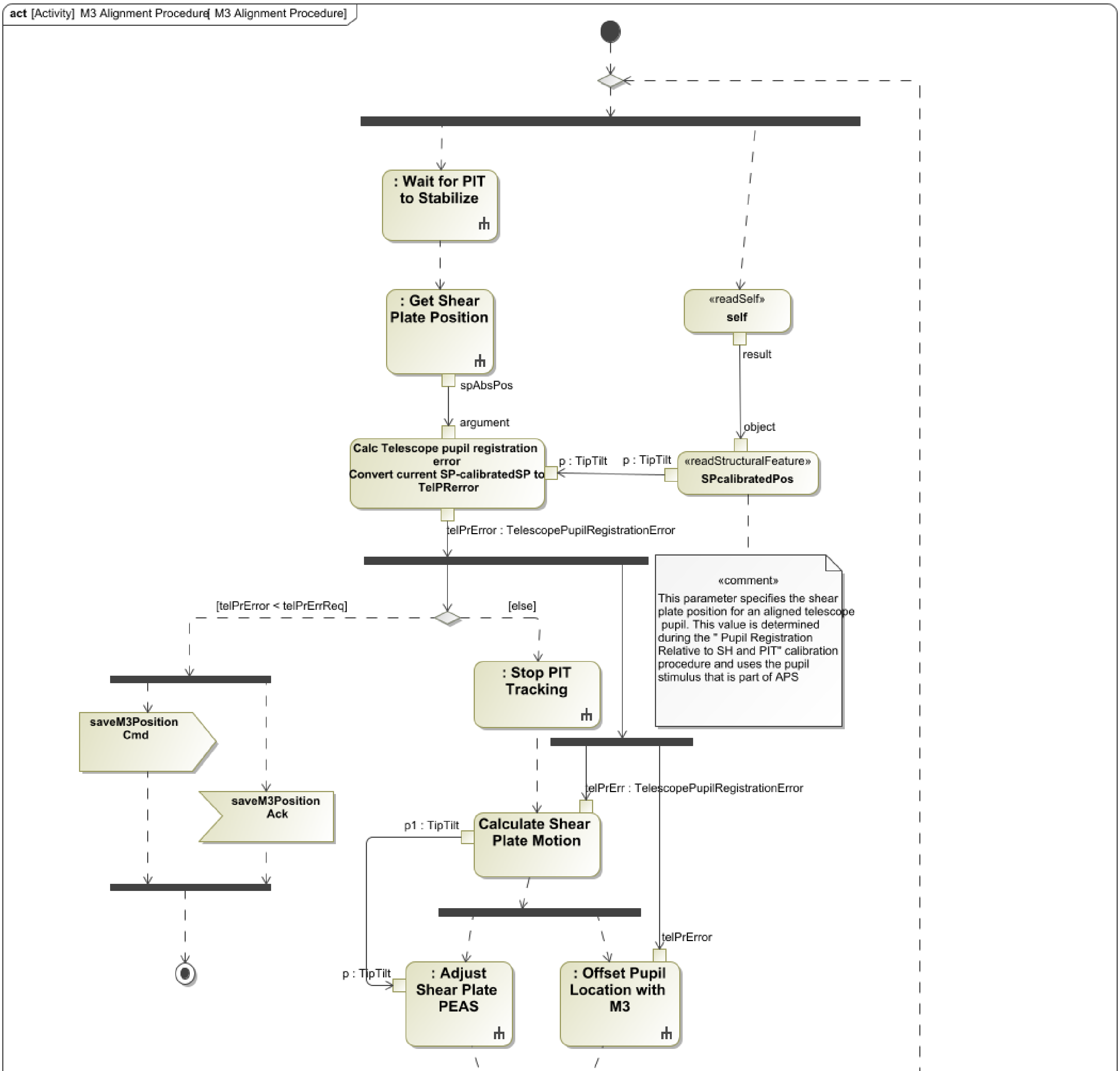
4.4.6.3 Activity Description

This activity uses the PIT loop to adjust the M3 location to center the telescope pupil at the correct location within APS. This activity is called with the telescope already tracking a star and the PIT loop closed.

The activity uses the results from Pupil Registration Calibration which contain the desired shear plate location for an aligned M3.

This activity waits for the PIT loop to stabilize the pupil in *x*, *y*, rotation, and scale, then gets the current APS shear plate location. Next the telescope pupil registration error (*x*, *y* in meters at M1) is calculated by comparing the current APS shear plate to the desired/calibrated location. If the registration error is less than the required value of 150 mm (at M1) then the M3 position is saved via the saveM3Position command. If the registration error is not within requirements, then the PIT loop is stopped and the desired shear plate motion calculated. Then in parallel, the shear plate is commanded to the calibrated location for an aligned M3 and the corresponding offset is also sent to M3. The result should be that the pupil stays aligned in the PIT arm. The PIT loop is then closed, and this process iterates.

M3 Alignment Procedure



Author: sherzig	Version:
Modification Date: 9/5/23 5:03 PM	Completion Status:
Reviewed by:	
Last Modifed by: rkarban	

4.4.7 Prepare for Off-Axis

4.4.7.1 Overview of Activity

This activity is called from the Off-Axis Measurements of WFE use case. Given a field point to look at (in Az, El) it configures the telescope to steer to that off-axis field point and then it re-configures the telescope and APS such that the star enters APS on-axis. This allows APS to measure the WFE across the FoV of TMT without APS needing to have that same FoV. The details of which telescope and APS optics need to move, the amounts, and the ray traces are in RD5 and other documents referenced in RD5.

4.4.7.2 Activity Parameters

Relevant activity parameters are:

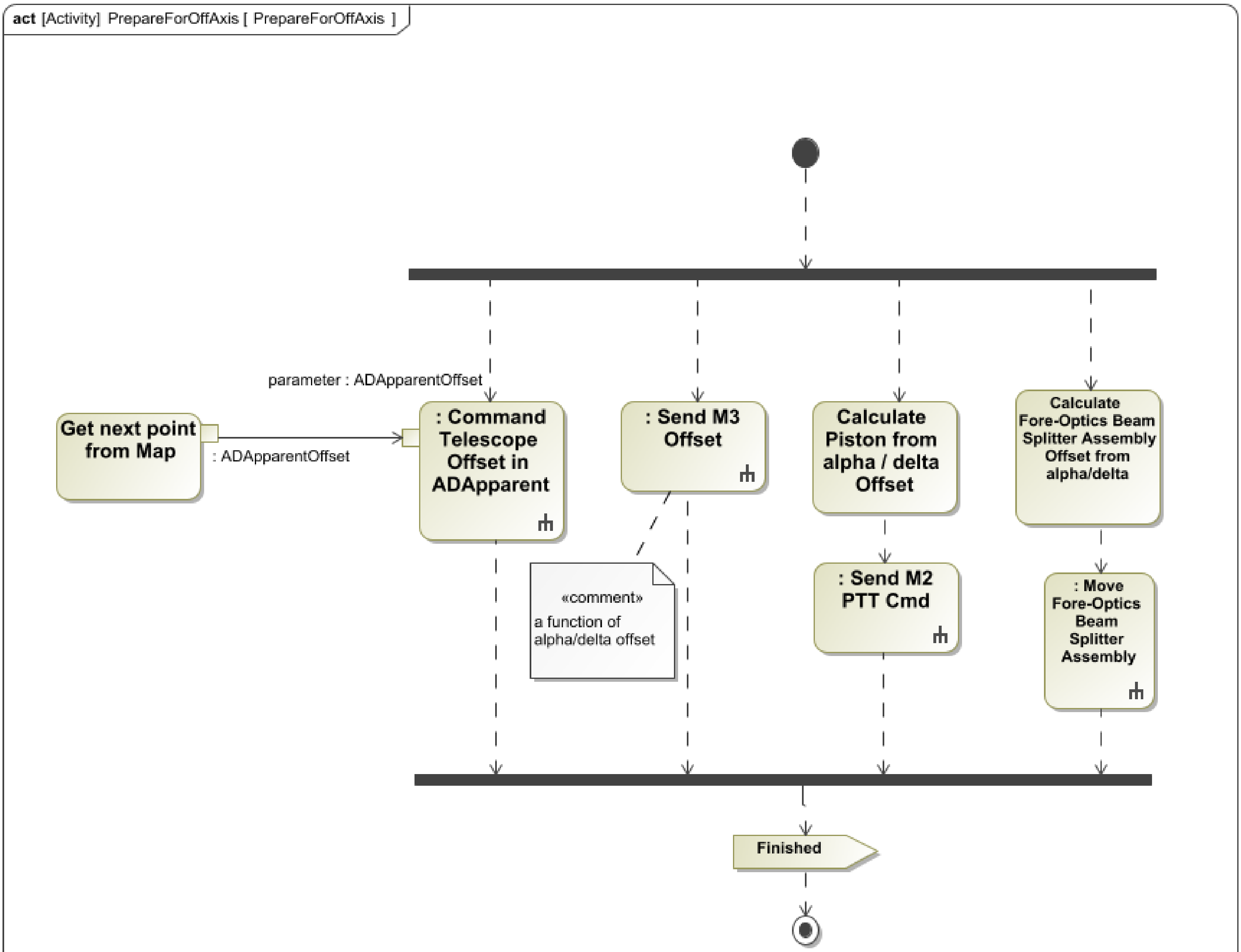
- Entrance requirement: PIT and APT loop should be open
- Exit conditions: The telescope (M1, M2, M3) optics and APS are reconfigured to point at the desired off-axis position.

4.4.7.3 Activity Description

Given an Az, EL offset this activity:

1. Offsets the telescope using the offsetTelescopePosAzEl command to TCS. At this point the star that was on-axis is now off-axis, but outside the APS field of view (assuming the offset command is larger than the APS FoV).
2. Tilts M3 to bring the star back on-axis using the command offsetImageLocationWithM3 to TCS, at this point the star is on-axis in APS, but the M1 pupil will be mis-registered and the star out of focus, both due to moving M3.
3. Pistons M2 to bring the star back in focus using the command offsetM2Position to TCS.
4. Tilts the first optics in APS (FM1, a beam splitter, near the telescope focus) to move the M1 pupil back into alignment.

PrepareForOffAxis



Author: gregorywa	Version:
Modification Date: 9/5/23 5:03 PM	Completion Status:
Reviewed by:	
Last Modifed by: rkarban	

4.4.8 Reference Beam Collection

4.4.8.1 Overview of Activity

The Reference Beam Collection Activity is called from APS pre-session calibration use case, which is typically executed during the day before the night that APS will be used. As with any Shack-Hartmann camera it is critical to calibrate the sub-image positions of a perfect wavefront (zero wavefront error). In APS this will be done via a reference beam that can be inserted at the telescope focus in APS, which is just after the first optic in APS. Then the desired Shack-Hartmann sub-images can be measured for the various filters, Shack-Hartmann masks, and optics positions.

The critical measurements are those for the Rigid Body and Segment Figure Correction activity, which uses the PSH camera and SH-5 or SH6 mask and the nominal 611 nm filter. We will also measure the sub-image locations for the other masks, but these do not need to be updated as often as they are just used in phasing to find the approximate locations of the phasing sub-images. As we collect data in the PSH camera, we will collect similar data in the PIT camera.

All calibrations are currently planned to be executed before each APS night. As we characterize and understand the system they can be conducted less often.

4.4.8.2 Activity Parameters

The table below shows the various configurations that are currently defined for measurements in this activity:

- ReferenceBeamType refers to the nominal wavelength of the reference beam. In PCS at Keck, we used fiber-coupled LED sources, which have a limited bandwidth. Here we assume the same. If we find a broadband source that can work, then we will update the table accordingly.
- SH Mask is the SH mask in the PSH.
- SH Filter is the filter in the PSH.
- PIT mask is the SH mask in the PIT.
- IntegrationTimeSH is our estimate (based on experience at Keck) for the integration time (in seconds) in the PSH.
- IntegrationTimePIT is our estimate (based on experience at Keck) for the integration time (in seconds) in the PIT.

Notes:

1. In the table below the SH masks are labeled as SH-<# of rings>
    1. The SH-0 mask has one subaperture at the center of the segment
    2. SH-2 has two rings, so 19 subapertures
2. The naming convention for the filters will be improved in the next iteration and are just place holders in this document. The filter specifications are currently captured in RD1.

Wavefront Calibration Lookup Table Data

#	Name	reference Beam : ReferenceBeam Type	shMask : SH Mask	shFilter : SH Filter	pit Mask : PIT Mask	pit Filter : PIT Filter	integrationTimeSH : Real	integrationTimePIT : Real
1	entry001	650mm	SH-0	NPH-2/SH	SH-0	BB-1	30	15
2	entry002	650mm	SH-5	NPH-2/SH	SH-0	BB-3	30	10
3	entry003	650mm	SH-6	NPH-2/SH	SH-2	BB-1	30	15
4	entry004	650mm	Phasing	NPH-2/SH	SH-2	BB-3	30	10
5	entry005	650mm	SH-2	NPH-2/SH			30	0
6	entry006	890nm	Phasing	BB-100	SH-2	BB-10	6	7
7	entry007	890nm	Phasing	NPH-1/BB-30	SH-0	BB-10	2	7
8	entry008	890nm	Phasing	BB-3			1	0
9	entry009	700mm	Phasing	BB-1			4	0
10	entry010	650mm	Phasing	Open			4	0

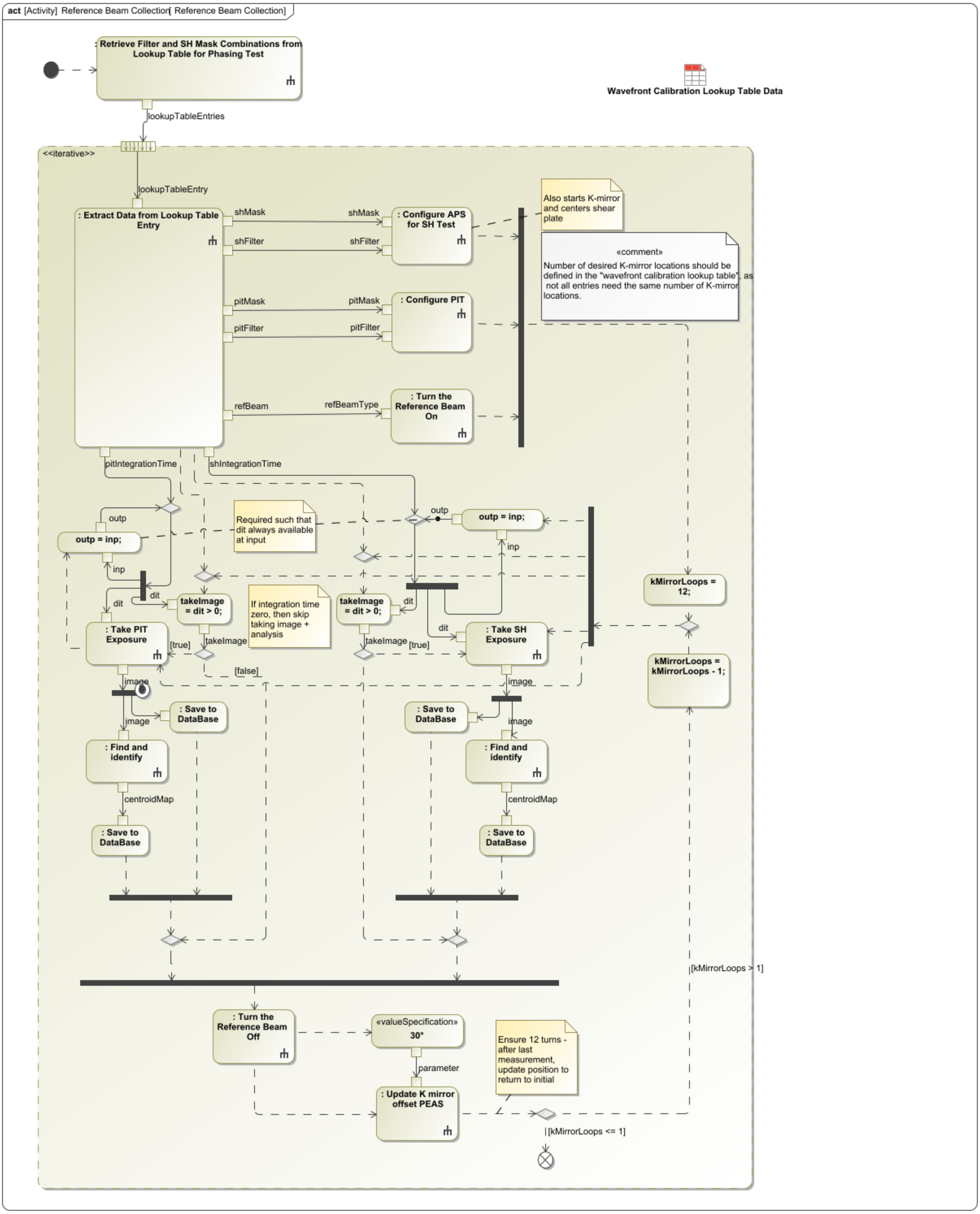
4.4.8.3 Activity Description

The figure below shows the reference beam collection activity. The activity is executed as follows:

1. Extract data from lookup table entry, extract a row from the above table and configure the PSH, PIT cameras, turn on the reference beam, rotate the K-mirror to zero degrees.
2. In parallel, exposures are taken in the PSH and PIT cameras, the centroids found, and the results saved to the database.
3. The reference beam is turned off.
4. The K-mirror is rotated by 30 deg.
5. Steps 2-4 are repeated until data has been taken at all desired (12) K-mirror locations.
6. Steps 1-5 are then repeated for the next entry in the table.

One improvement to this will be to allow specification of the K-mirror rotation angles for each row in the table. We expect that the phasing, SH-0 and SH-2 masks will not need multiple K-mirror measurements, whereas to meet the stringent WFE requirements, the SH-5 and SH-6 masks will.

Reference Beam Collection



4.4.9 Pupil Registration Calibration

4.4.9.1 Overview of Activity

The Pupil Registration Calibration Activity is called from the APS pre-session calibration use case, which is typically executed the during the day before the night that APS will be used. This activity is needed for:

1. The calibrations in the M3 Alignment Procedure activity, which aligns M3 in rotation and tilt in order to satisfy the requirement to measure the telescope pupil position to an accuracy of 0.05% of the diameter of the pupil relative to the APS SMRs (REQ-2-APS-0086). To accomplish this, we need to determine where a well aligned telescope pupil will appear in either the PIT or PSH cameras. This is not trivial, as the pupil will translate and rotate both as the APS K-mirror rotates and as a function of the APS shear plate position. To have a stable, well aligned, pupil reference APS will use the pupil in the APS stimulus. The pupil in the APS stimulus will be aligned with respect to the APS SMRs. This activity will determine both the shear plate location and K-mirror rotation offset that provides a well-aligned pupil in the PIT and PSH for the reference pupil in the APS stimulus.
2. The calibration of the offset between the PSH and PIT pupil masks. During closed loop PIT control (PIT Loop) the pupil is adjusted every ~10 seconds to keep it well aligned on the PSH masks. However, there will likely be an offset between the PIT and PSH masks. This calibration will measure that difference which will then be the set point for the PIT loop.

4.4.9.2 Activity Parameters

As discussed in Activity Description this activity will be updated to allow the specification of multiple configurations. The values that will be specified are:

- SH mask in the PSH
- Filter in the PSH
- SH mask in the PIT
- Filter in the PIT
- Integration time for the PSH
- Integration time for the PIT
- Allowable registration tolerances for the pupil tip/tilt, rotation and scale

4.4.9.3 Activity Description

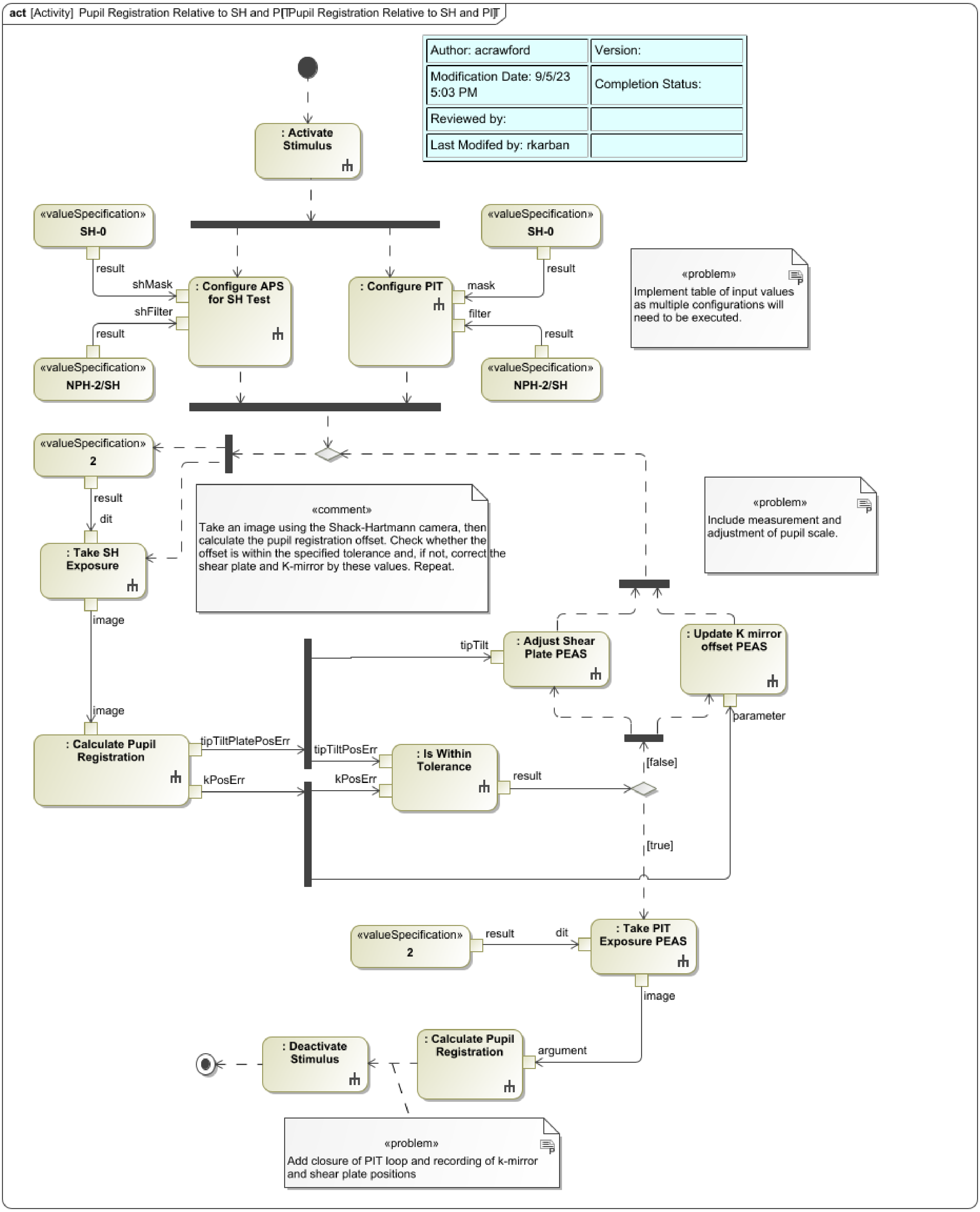
The figure below shows the pupil registration calibration activity:

1. The APS stimulus is activated, which includes turning on the source and moving a stage with a mirror, so that the stimulus light is injected into APS.
2. In parallel the PIT and PSH cameras are configured with the specified SH mask, filter and integration times.
3. A PSH image is taken, and the pupil registration error is calculated.
4. If the errors in tip/tilt, rotation and scale are not all within defined tolerances, then an adjustment to the K-mirror and shear plate is made, and step 3 repeated until within tolerances.
5. Once the pupil is well aligned in the PSH a PIT image is taken, the pupil registration error is calculated, and these offsets are saved for later use.
6. Close the PIT loop and, once stabilized, the locations of the K-mirror and shear plate will be saved for use in M3 Alignment Procedure . The M3 Alignment Procedure adjusts the M3 position to match the PIT closed loop positions of the K-mirror and shear plate measured in this step. (This step is currently not represented in the activity diagram, but will be added.)
7. The stimulus is then deactivated by turning off the stimulus light source and moving the stage with the mirror so that APS can now observe star light from the telescope.

Note: This activity needs to be updated to:

1. Allow specification of a table that will contain the activity parameters defined in Activity Parameters .
2. Include measurement and control of the pupil scale.
3. Add step 6 above.

Pupil Registration Relative to SH and PIT



4.4.10 Calibrate Camera Pointing Offsets

4.4.10.1 Overview of Activity

During Setup APS, Acquire, and Start Guiding guiding and acquisition of stars occurs using the APT camera and the star is located at a pixel location defined by APS. This activity will determine this APT camera pixel location that will result in the star being centered in the PSH. If this location is off by more than ~12 arcseconds, the star would not enter the PIT/PSH camera. If the star is within +/- ~12 arcseconds then the PIT loop, once closed, would offset the telescope. We want to minimize this offset to minimize APS on-sky time.

4.4.10.2 Activity Parameters

This activity's values that will be specified are:

- SH-5 mask in the PSH
- Filter-TBD in the PSH
- SH-1 mask in the PIT
- Filter-TBD in the PIT
- Filter-TBD in the APT
- Integration times for the PSH, PIT and APT

It's sufficient to execute this for a single combination of PSH, PIT and APT configurations as any pointing offsets between masks within the PSH or PIT will be small and static.

4.4.10.3 Activity Description

We have not yet developed an activity diagram for this activity. However, this activity will:

1. Activate the APS stimulus, which includes turning on the source and moving a stage with a mirror, so that the stimulus light is injected into APS.
2. In parallel:
    - The PSH and PIT cameras are configured with the specified SH mask, filter, and integration times.
    - The APT camera is configured with the specified filter and integration time
3. In parallel:
    - An image is taken in the APT camera, the centroid location found and saved
    - An image is taken in the PSH and PIT cameras, the *Find and Identify* routine is called, and the center of the image calculated and saved.
4. The stimulus is then deactivated by turning off the stimulus light source and moving the stage with the mirror so that APS can now observe star light from the telescope.

4.5 Lower Level Activities

4.5.1 Setup APS, Acquire, and Start Guiding

This activity is used at the start of most of the APS high level activities. It is used to:

- Acquire a new star
- Start guiding (if desired)
- Close the PIT loop
- Configure the PSH camera for the alignment activity

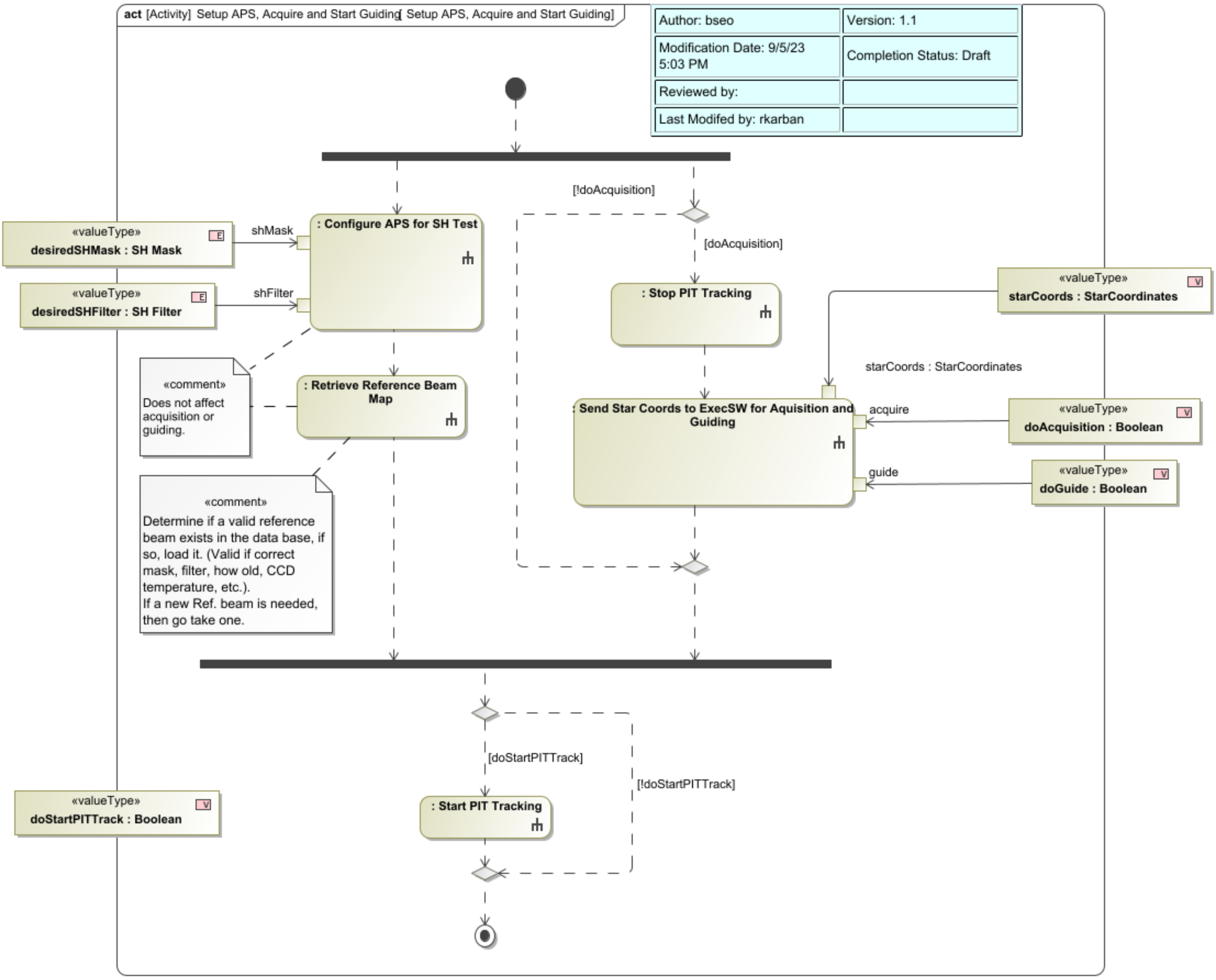
At the end of execution of this activity APS is ready to start data collection and execution of the alignment activity that called this activity.

This performs the following two activities in parallel.

1. "Configure APS for SH test" configures the APS PSH with the correct SH mask and filter. "Retrieve Reference Beam Map" will retrieve the appropriate reference beam map. If a valid reference beam map does not exist, one will be taken using Calibrate Single Reference Beam .
2. If acquisition of a new star is requested, the PIT loop is stopped, and the activity "Send Star Coords to ExecSW for Acquisition and Guiding" is called to acquire, and if desired start guiding on, the specified star. See RD9 for additional details.

Once both above activities are completed, the PIT loop will start, if desired.

Setup APS, Acquire and Start Guiding



4.5.2 PIT Loop

The pupil image and tracking (PIT) loop actively measures and corrects both the pupil position (translation, rotation, and scale) as well as the image position (telescope position). This mode does not exist at Keck. This procedure is different than most APS procedures as it runs concurrently with all alignment procedures. The telescope pupil must be correctly positioned to ~10 mm referred to M1, which is 0.03% of the TMT diameter.

Once the PIT procedure starts running it will continue to run until either APS selects a new star or APS observations are completed for the night. The PIT camera will take an image and determine the pupil translation, pupil rotation and image location. These values are compared to the desired values and the pupil shear plate, K-mirror and telescope pointing are commanded as needed. Then another image is taken and this loop repeats at a rate of once every ~10 seconds.

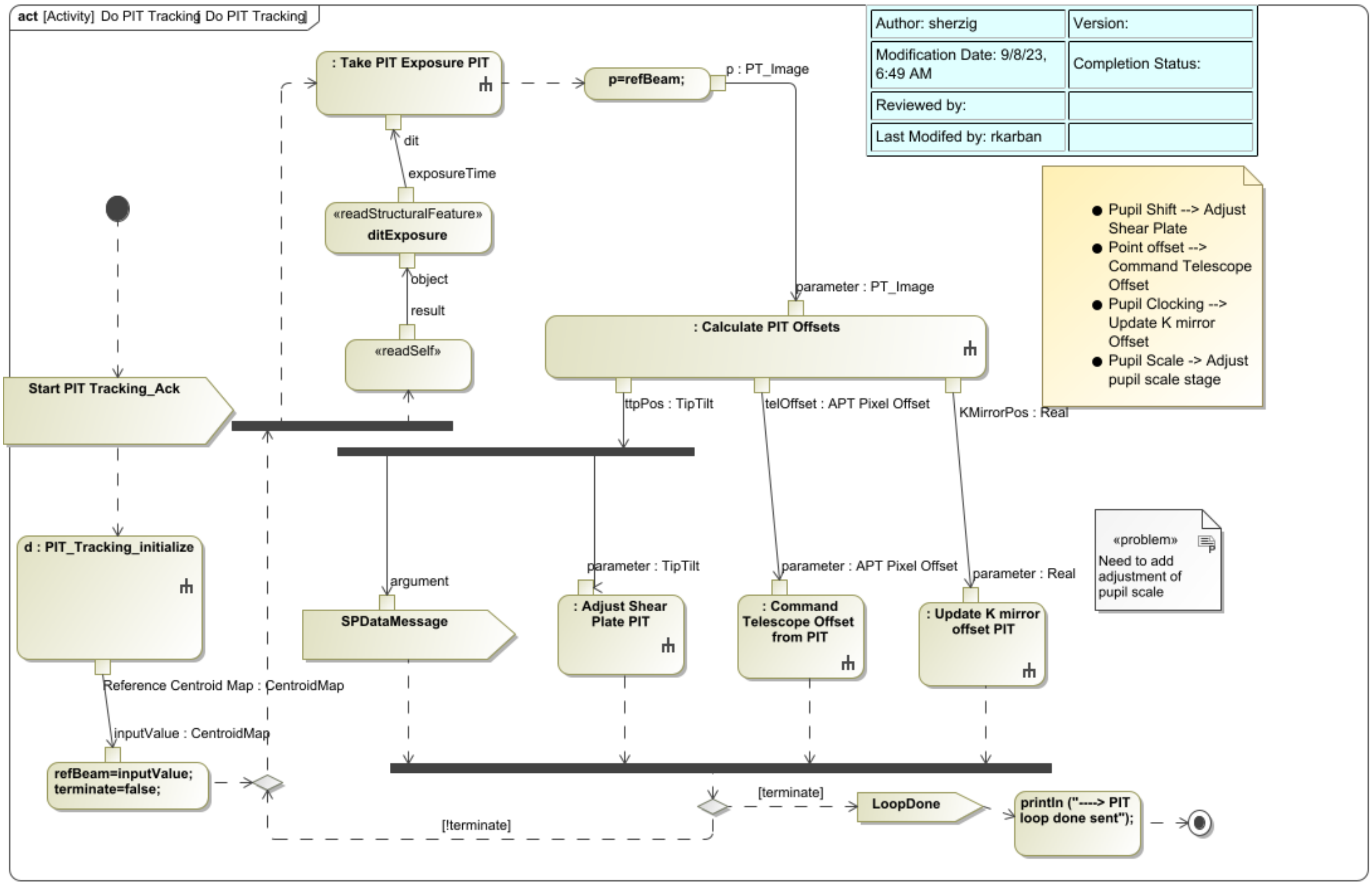
In the figure below we show an activity diagram that describes the baseline activity. The activity starts with the assumption that the telescope is tracking or guiding, and the star has been acquired on the APT CCD within ~5 arcseconds of the desired APS tracking point. This activity will work with the telescope open loop tracking or guiding. The PIT CCD takes an exposure ("Take PIT Exposure PIT") of the specified duration and publishes the pixel data. The activity "Calculate PIT Offsets" will execute a series of algorithms which will result in the calculation of the error in the desired star location, pupil translation, rotation, and scale. This activity returns the desired new positions (or offsets as appropriate) of the shear plate, K-mirror, pupil scale stage, and APT pixel offset.

In parallel, commands are sent to:

1. Adjust the shear plate position
2. Update the K-mirror rotation offset. The K-mirror tracks the telescope pupil rotation, so it is always rotating. The K-mirror offset does not change this tracking (or tracking rate), but does change the reference rotation between the static telescope pupil orientation and the internal APS pupil rotation.
3. Adjust the pupil scale stage. Note: This step is not shown in the diagram, and will be added in a future revision.
4. Update the APT pixel guide point.

Then a new PIT image is taken and the process continues until requested to stop.

Do PIT Tracking

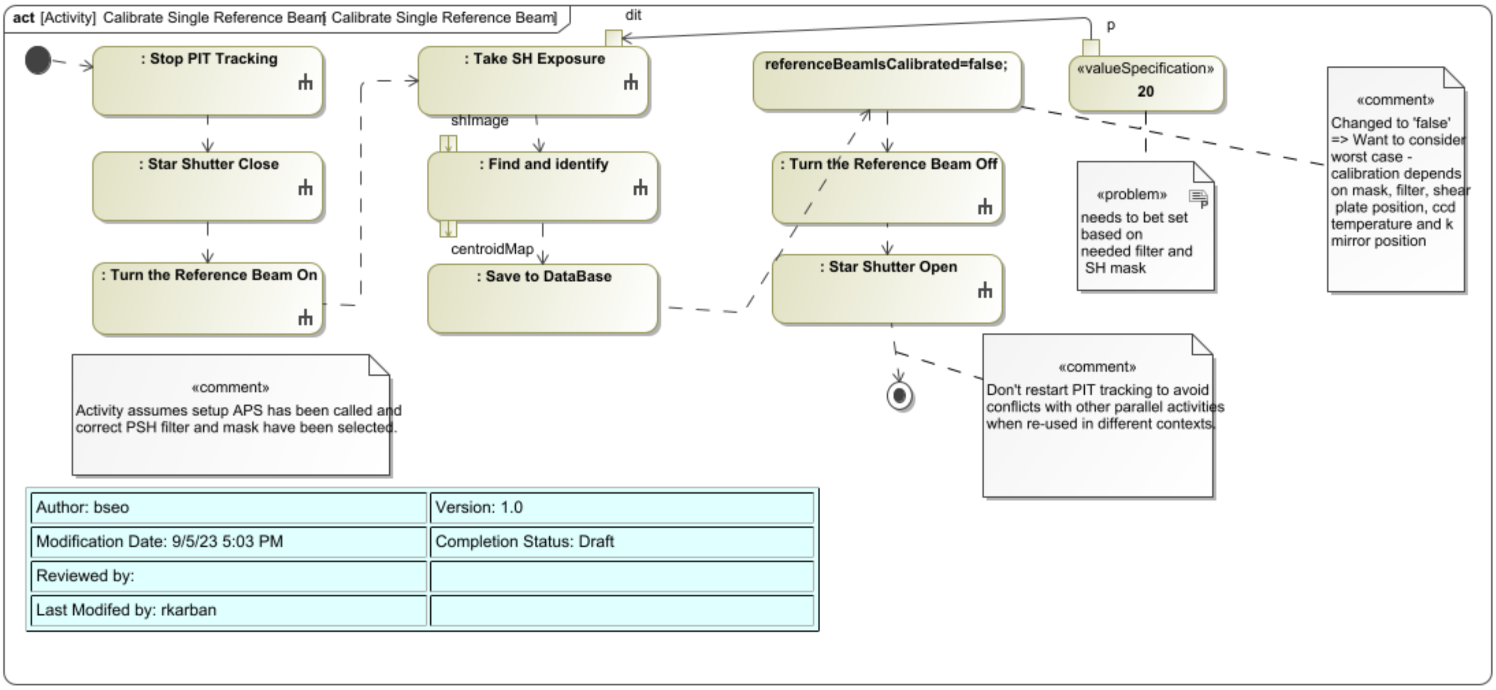


4.5.3 Calibrate Single Reference Beam

This activity is used to take a single reference beam in the PSH. The reference beams taken during the [APS pre-session calibration] should, in general, meet the criteria for all reference beams needed for observing. However, if the currently-saved reference beam maps do not meet the current criteria (shear plate position, K-Mirror, pupil scale stage, CCD temperature), then this activity will be automatically called to take a reference beam map. We will monitor how often this activity is called and, if needed, adjust the parameters in the [APS pre-session calibration]

This activity will stop the PIT tracking loop, block star light from entering the Shack-Hartmann arm of APS and turn on a reference beam. Then a PSH exposure will be taken, the *Find and Identify* routine is called, and the centroids/reference beam map saved to the APS database. Once complete the reference beam will be turned off and APS configured to allow star light back into the Shack-Hartmann arm. Currently the PIT loop is not re-started, but we will re-evaluate this as part of the FD phase.

Calibrate Single Reference Beam



4.5.4 APT Loop

The APS Acquisition Pointing and Tracking (APT) portion of APS provides a 1 arcmin diameter FoV that among other things is used for acquisition and closed loop tracking of stars during APS operations (RD1). The APT will publish the needed CCD/pixel data for acquisition and guiding and TCS will subscribe to these data and perform the needed functions for guiding (RD9 and RD10).

RD9 describes the Acquisition, Start Guiding, and Guiding Loop activities. These have not yet been integrated into the SysML activity diagrams, but this will be done as part of the APS Bench/ICS/MGT PDR.

5 Opto-Mechanical Design

5.1 APS Bench Overview

The APS instrument will reside on the TMT “–X” Nasmyth platform. APS has two nominal positions, on the telescope elevation axis [cf:APS Location.name] (Figure 2-1), and off the telescope elevation axis [cf:APS Location Side View.name] (Figure 2-2). The APS bench is broken down into five assemblies:

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

Figure 6-1 shows the optical bench layout with the various assemblies labeled. Sections 5.2 to 5.6 describe the function, elements, requirements and Logical design of each assembly. All optics were designed with sufficient detail to ensure they could meet the requirements and to allow us to obtain cost estimates for the optics and opto-mechanical assemblies (mounts, stages, etc.). The one exception is the collimator design, generated by Optical Research Associates, which has been completed at a preliminary design level. This was done to ensure APS could meet the tight requirement on image quality of the re-imaged primary mirror pupil. The entire optical design has been integrated in ZEMAX and exported to a mechanical design program.

A mechanical design of APS was created that incorporated the optical prescription in the layout of the optics, as well as the optical mounts and mechanisms, on the optical bench. Where possible, off-the-shelf components were used in the design. APS contains two rather complex mechanical assemblies: a K-mirror and a prism/filter wheel. We performed detailed mechanical designs of both of these devices (see Sections 5.2.5 and 5.5.3.5 for more details) to ensure they would fit in APS and to obtain an accurate estimate of the cost to build them.

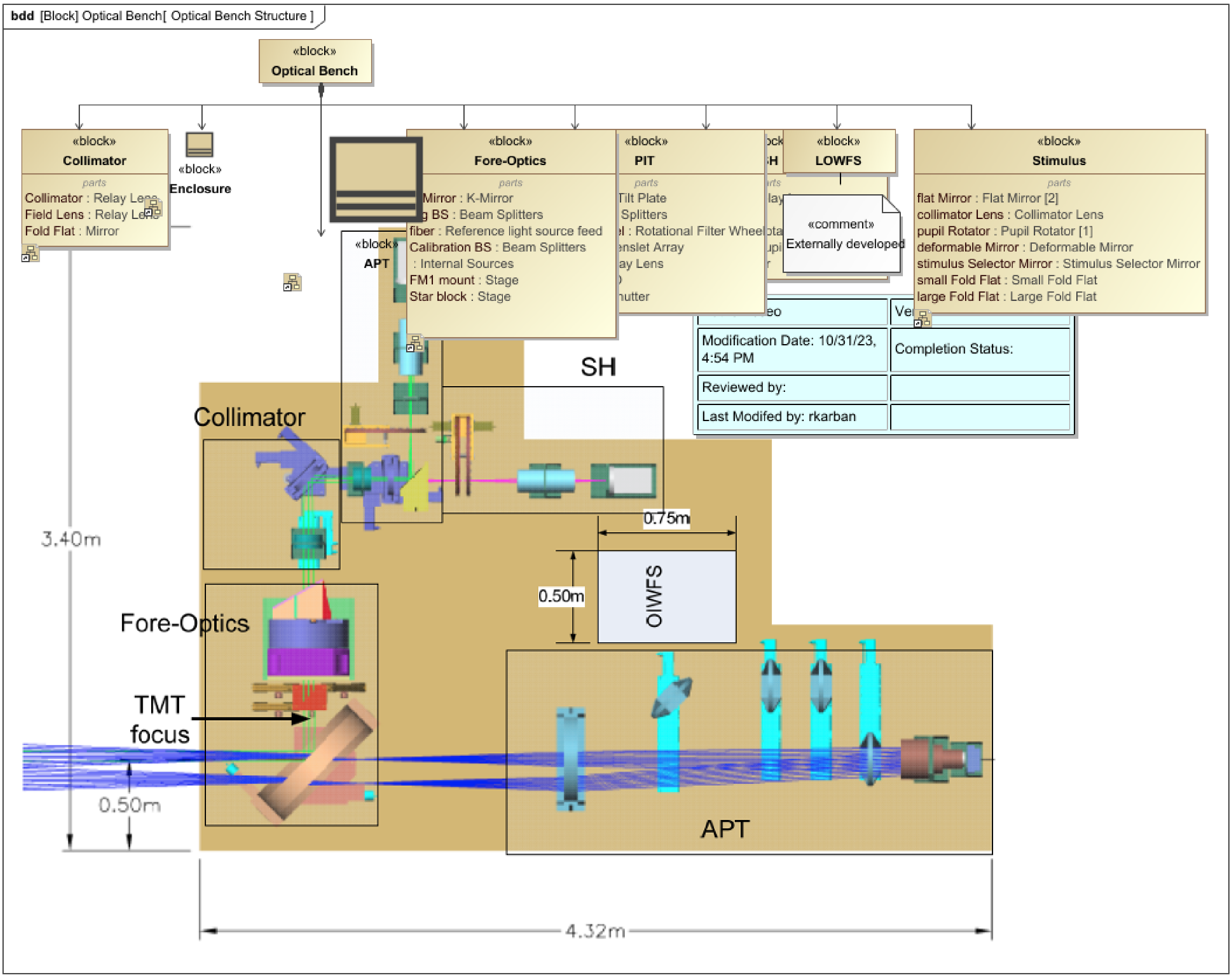
For the design of APS, we selected a 75-mm pupil (1/400 demagnification). The requirement for good pupil image quality (Section 5.4) specified a pupil larger than 50 mm. However, most lenslet manufacturers can only handle 100-mm substrates, so this placed a hard upper limit on the size. Cost also increases 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 re-imaged primary mirror. As can be seen in Figure 5-1, the available space between the TMT focus and collimator assembly is very crowded.

In initial designs, the first APS optic was a fold mirror followed by a beam splitter that fed the APT assembly. This had the benefit that all reference sources were seen by all cameras, and the APT camera could see the pupil motion from tilts in the first APS fold flat. In order to fit all the necessary components, we modified this initial layout to the one shown in Figure 5-1. We will insert a calibration source upstream of the first APS optic so that all cameras can see the same light source. It was a goal (rather than a requirement) for the APT camera to see the pupil motion from tilts in the first APS fold flat. Therefore, the current design does not suffer any loss of functionality. We will need to be careful about the size of optics and mounts to ensure we can accommodate all of the mechanisms. If this proves to be impossible, we will be forced to reduce the FOV of the PIT and SH assemblies from their current 25-arcsec diameters. The only mode of APS this would impact is the capture of segment tip/tilts after segment exchanges; however, we are currently investigating a method by which we scan around for the missing segments by tip/tilting the missing segments.

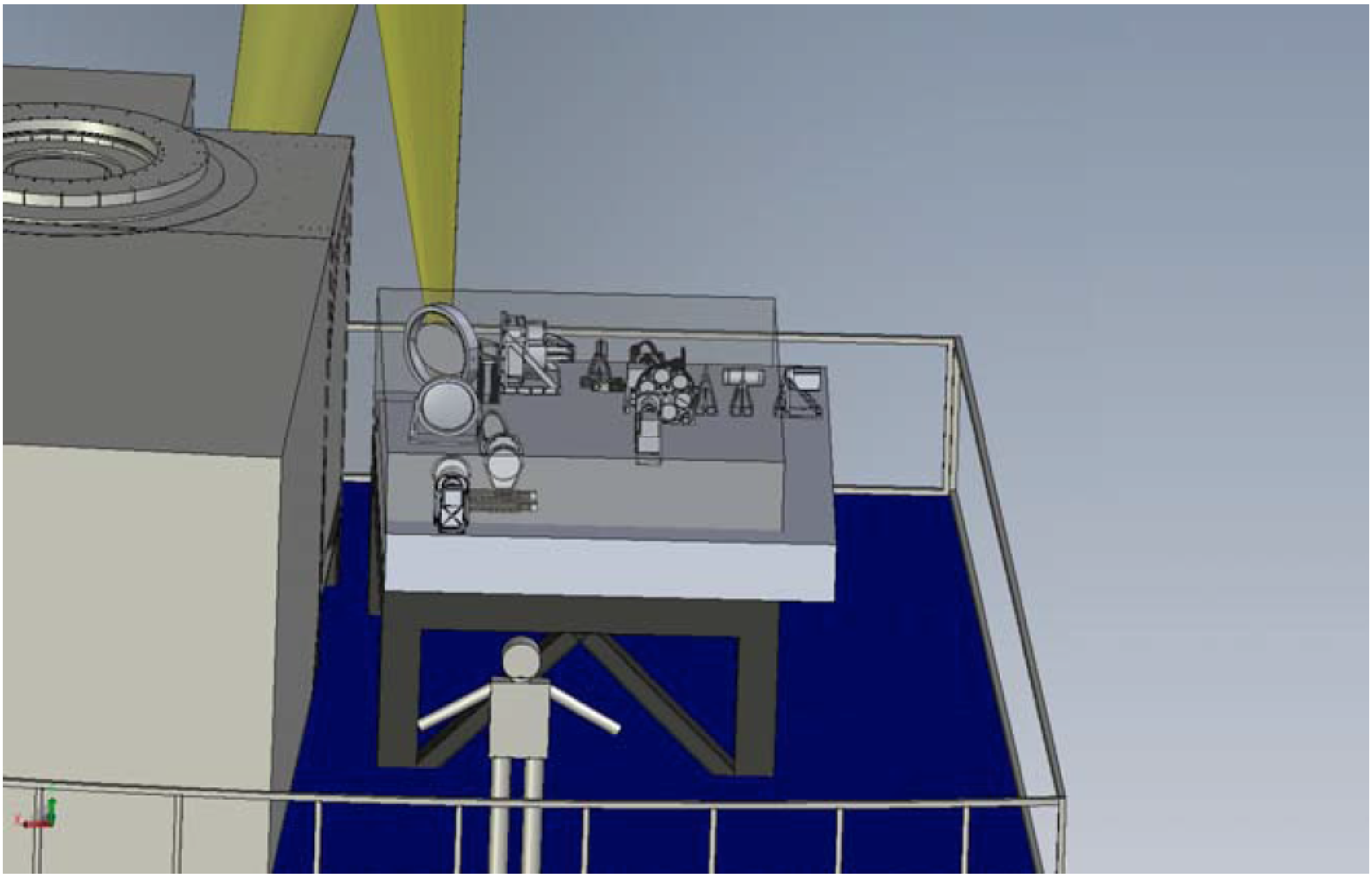
Figure 5-1 shows the APS bench with its current nominal dimensions (4.32 X 3.40 m) which exceed the currently allocated dimensions of (4.0 X 3.0 m) by about 15 percent; see Section 9 for more details. We have removed some unused areas of the optical bench in order to make it easier to access, install and troubleshoot the various optical-mechanical assemblies. Figure 5-2 shows the APS installed on the telescope elevation axis next to the NFIRAOS. The transparent box indicates the original APS space allocation. The larger size of the current APS design does not appear to cause any interference problems. There is ample room on three sides of the APS for access. The space between the NFIRAOS and APS ranges between ~0.25 m and ~0.60 m. Note that Figure 5-2 represent the APS bench as a rectangle, not the irregular shape shown in Figure 5-1.

Figure 2-2 and Figure 2-2 show the APS installed off the telescope elevation axis with the TMT first decade instruments installed. We will remove the interference with HROS (the instrument to the right of APS) in the next design phase, but access to the APS optics may still be a problem.

Optical Bench Structure



APS Back view



A back view of APS located on the elevation axis. The transparent box shows the allocated space and the solid box the current design. Note that the increased size of APS does not interfere with any of the first-light instruments

5.2 Fore-Optics Assembly

5.2.1 Fore-optics Overview

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 +/-7 degrees.
3. Pass a 60-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.

Figure 5-6 shows the optical-mechanical design and layout of the fore-optics. The large imaging/SH beamsplitter satisfies functions 2 and 3 above. The K-mirror provides a way to de-rotate the telescope pupil. The artificial telescope light sources to associated with functions 1 and 4 above are not pictured because they have not yet been fully designed. In the current plan, the small calibration beamsplitter 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 imaging/SH beamsplitter (function 1).

5.2.2 Calibration Beamsplitter

The calibration beamsplitter allows one to insert calibration sources into the optical path of the SH and PIT cameras. These calibration sources will be used to determine the desired locations of the Shack-Hartmann subimages when aligning the telescope. As a result, it is important that the calibration sources themselves have minimal wavefront errors. This will be accomplished using single-mode fibers placed at the telescope focus. The focus of TMT is ~50 mm in front of the calibration beamsplitter, which will allow the insertion of multiple sources at various wavelengths. The detailed specifications for this optic are shown in Table 5-2.

5.2.3 K-mirror and Rotation Mechanism

The K-mirror is included as part of the TMT APS subsystem to de-rotate the telescope pupil as the telescope tracks stars. The derotation of the telescope pupil is accomplished by mounting the K-mirror to a precision rotation stage and controlling the position of the rotation stage as a function of telescope pointing coordinates.

5.2.3.1 K-mirror Design

The design proposed for implementing the K-mirror and the rotation mechanism is shown in the following figures. The Logical design selected for the K-mirror and rotation mechanism is based on two basic design philosophies that are expected to reduce technical, cost, and schedule risk.

The first design philosophy is to fabricate the K-mirror optic assembly as a single-material (Zerodur), monolithic-bonded subassembly. A monolithic-bonded subassembly fabricated from Zerodur is expected to provide a long-term, thermally stable alignment of the K-mirror component mirrors due to the low CTE and high-stability properties of Zerodur. Long-term structural stability is expected to be provided by this design since it is a bonded design that cannot change over time. There are no joints that can slip or adjustments that can creep or be changed inadvertently.

5.2.3.2 K-mirror Requirements

The optical requirements, developed on the basis of preliminary APS system engineering analysis for the K-mirror, are presented in Table 5-3.

The structural and mechanical requirements for the K-mirror, mounting, and rotation mechanism, developed on the basis of preliminary APS system engineering analysis, are presented in Table 5-4.

5.2.4 Imaging/SH beamsplitter

This is a large beamsplitter with dimensions of ~0.30 m x 0.30 m. The size of this optic is set by the requirement to feed a 1 arcminute field of view to the APT camera. The transmitted optical quality does not need to be exceptional (as it feeds a seeing-limited camera); the reflected quality, however, must be superb. This optic is before the calibration source for the SH camera and, as a result, any aberrations in the center 25 arcseconds (the FOV of the SH camera) of this optic will be mistaken for telescope aberrations. This will result in these aberrations being introduced into the alignment of the telescope. The mirror specification over the center 25 arcseconds is lambda/100 RMS surface (at 633 nm) to minimize these non-common path aberrations. Detailed specifications for this optic are shown in the following table.

5.2.5 Sources

In the current design, there will be two artificial light sources to fulfill the various requirements of the system. A source with a defined pupil will be inserted into the beam prior to the imaging/SH beamsplitter in order to provide an image and pupil to all the detectors in the system. The source can be inserted and removed from the beam path via a motorized stage. This source will only be used on-axis, so the optics can be relatively small. A second source will be used for calibration of the PIT and SH cameras which minimizes noncommon path wavefront error to the sensors. This source will also be used to test the PIT and SH over their entire FOV. The second source will be inserted into the path by the calibration beamsplitter, which is fixed, so light from the source and the telescope will be available simultaneously. It may be possible to combine the functionality of the two sources if the optical system that creates a pupil can be made with sufficiently low wavefront error over the full field of the SH. This would reduce the reflected wavefront requirements on the imaging/SH beamsplitter because that optic would then be in the common path for the calibration source and starlight. In addition this solution would eliminate the need for the calibration beamsplitter.

5.2.5.1 Telescope simulator

5.2.5.2 Calibration Sources

5.2.5.3 Imaging/SH Beamsplitter

5.3 Acquisition Pointing and Tracking Assembly

5.3.1 APT Overview

The APS Acquisition Pointing and Tracking (APT) assembly (Figure 6 10) has several functions. It provides the following:
1. A large (60 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 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 a wavefront sensor for commissioning (CAGS LOWFS) or similar device to validate that the telescope active-optics loops work as required.

In the list above, only item 1 is necessary for APS operation. However, the TMT project has decided that since it involves only a modest increase in scope and cost, the other four items should also be provided by the APS. APS will not be responsible for demonstrating that the telescope meets any of the above requirements. APS will provide the hardware and a software interface to this subsystem. The additional work required for developing the algorithms, writing the needed software, analyzing the data, etc., is a TMT project responsibility.

5.3.2 APT Requirements

The APT shall have a FOV of 1 arcmin diameter
The APT plate scale shall be <0.25 arcsec/pixel
The APT full field plate scale distortion shall be <1 arcsec over 1 arcmin full FOV = 1.66%
The APT central field plate scale distortion shall be <100 milliarcsec over 10 arcsec FOV = 1.00%
The APT image FWHM shall be better than 0.5 arcsec over full FOV
The full APT CCD shall be be able to be read out in 5 seconds.
A 2 arcsecond (ROI)of the APT CCD shall be able to be read out in 0.1 seconds.
APT shall publish camera frames on request
APT shall achieve SNR>5 (TBR) for a 20sec exposure on a 14th magnitude star
APT shall achieve SNR>5 (TBR) for a 0.1sec exposure on a 0th magnitude star
APT shall be capable of providing frames at 100Hz(TBR) for at least 500x500 pixel ROI
APT shall provide a method to split the optical path and provide an optical interface for the LOWFS
APT shall operate with coolant temperatures listed in REQ-2-APS-0080
APT shall operate with coolant supplies, as listed in REQ-2-APS-80 with a pressure of 5 bar.
APT shall have a maximum pressure drop through any single equipment heat exchanger of less than 1 bar.
APT shall use chilled glycol coolant at the Nasmyth areas for removal of its heat.
APT shall have a peak load inside the Enclosure of less than 160 W
APT shall have a Nighttime power dissipation to water/glycol inside the Enclosure of up to 160 W
APT shall have Nighttime power dissipation to the air inside the Enclosure of less than 8 W
The mass of the APT shall be less than TBD.
APT shall be able to withstand complete loss of electrical power without sustaining damage or causing damage to personnel and other equipment.
APT shall be able to sustain repeated exposures to the conditions listed in REQ-2-APS-0132 without incurring any damage, with or without Observatory power
APT shall be able to withstand multiple E-stop occurrences without damage.
APT shall be designed for maintainability, including the use of standard components where possible.
APT shall use metric hardware where possible.
APT shall be able to transition from Standby Mode to Operational Mode in less than 1 minute (TBC), including initialize itself with a default configuration and without further human intervention.
APT shall be able to transition from OFF to Standby Mode in less than 24 hours (TBR).

5.3.3 APT Optical Design

5.4 Collimator Assembly

5.4.1 Collimator Overview

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. Optical Research Associates (ORA) was contracted to investigate and design the collimator assembly. 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 percent 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. In their last report, ORA performed a final design with these specifications. The remainder of this section will describe this final design (see the ORA report for full details). The figure below shows the collimating lens, fold flat, and field lens included in this assembly.

5.4.2 Collimator Optical Design

The collimator is evaluated in finite-conjugate and infinite-conjugate modes. In finite-conjugate evaluation the lens relays object points on the curved primary mirror to the flat lenslet mask plane at 1/400 demagnification. Cones of light emerge from the primary mirror, reflect off the secondary and tertiary, pass through the TMT focus plane, and focus onto the lenslet array, as shown conceptually in Figure 5-15 below. In the case of a SH camera, we are interested in how object points on the primary map onto the lenslet array and, thus, use the finite-conjugate evaluation for the majority of the analysis.

5.5.1 SH Overview

The SH assembly shown in the figure below 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 for SH measurements, masks for phasing, a relay lens to image subimages onto the detector, and a CCD detector.

5.5.2 SH Requirements

5.5.2.1 SH Pupil and Filter Wheel

• The pupil wheel shall hold six pupil chuck assemblies.
• The diameter of the pupil chuck assemblies will be 125 mm in diameter (TBR)
• It should be possible to remove and reinsert a pupil chuck assembly with a repeatability of <10 microns.
• Each of the six pupil wheel positions needs to reposition with a repeatability of <10 microns. This results from the need to have a precision of 0.5 mm at the M1 pupil, which is 12.5 microns at the reimaged pupil.
• The mechanism should be able to move between any two positions within 10 seconds.
• The pupil and filter wheel should share a common axle.

5.5.2.2 SH Measurements

All SH measurements require enough pixels across each subimage for accurate centroiding. Subapertures must be internal to the segments (subimages that span segments edges are not useful for SH measurements).

• Coarse segment tilt: This is the segment-capture mode. The most important aspect to 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.

• Fine tilt: 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).

• Segment figure: To measure individual segment figures accurately, there must be sufficient samples across each segment to measure the first 15 Zernikes. Note that only 2nd and 3rd order Zernikes till be correctable by the warping harnesses.

5.5.2.3 SH Relay Lens

The purpose of the SH relay lens is to relay the 75-mm diameter subimage array to the detector. In addition to the appropriate demagnification, the lens must meet the following requirements:

- FOV: 25 arcseconds
- Image quality: uniform subimage shapes across the array over the full wavelength range
- Wavelength range: 600-900 nm
- Lateral color effect: Centroid shift between 600 and 900 nm of less than 0.15 arcsec at the edge of the FOV, where 0.15 arcsec = 1/10 of the fringe separation (λ/subaperture size)
- Platescale distortion: less than 1% at the edge of the FOV (goal).

5.5.2.4 Phasing Measurements

Phasing modes measure the relative piston between two segments, so they require a subaperture that spans two segment edges. Phasing also requires that the light 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 ($\lambda/10$) and well-sampled subimages on the CCD (a minimum of 10 pixels across the subimage diameter of 2.44lambda/d, where d is the subaperture diameter at the primary mirror).

Each phasing mode 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.

5.5.3 SH Design

SH design goals include:
• Minimize the number of different lenslet arrays.
• Have one lenslet/mask combination fulfill all requirements
• Maximize the number of pixels per subimage while retaining the necessary sensitivity
• Provide enough separation between subapertures to separate diffraction patterns clearly during phasing
• Match the subaperture pattern to the telescope segment pattern.
• CCD parameters: The need for several samples across each segment and for well-sampled subimages constrains the choice of detectors to those with a large number of pixels (4k to 8k on a side).

5.5.3.1 Lenslet Arrays

5.5.3.2 SH Pupil and Filter Wheel Design

The pupil and filter wheel assembly was designed as an adaptation of the assembly used in the Keck PCS because the design has been proven to meet the requirements for repeatability and reliability. The APS assembly is larger due to the required 125-mm diameter pupil chuck assemblies. The wheels are positioned using the same technique as PCS. That is, a plunger, controlled by a magnetic solenoid, drops into the female detents and allows for repeatable positioning of the mechanism. The wheel is driven by a stepper motor via an O-ring friction drive. The pupil chuck assemblies and the mounting holes on the pupil wheel are match drilled and pinned to ensure repeatability when removed and reinserted. The filter wheel is located on the same axis as the pupil wheel and uses similar mechanisms for control.

5.5.3.3 SH Mask Design

For the selected lenslet pattern, the individual subapertures represent 17.6 cm on the sky. Masks will be applied to the lenslets to reduce the apertures of the lenslets to the 12 cm needed for phasing. Masks were also used in the Keck PCS. The Keck masks were separate pieces, aligned by hand to the optics. The alignment of the phasing masks for Keck was trivial because prisms not lenslets were used. In the case of APS the masks must be aligned to the lenslet arrays to better than 3 microns. Due to improvements in technology, the masks for APS will be black chrome deposited directly onto the flat side of the lenslets and will be aligned using the photo-lithographic equipment that is used to create both the lenslets and the masks. This will provide more accurate alignment and a significant cost savings.
With the use of masks, the requirements for all the SH modes as well as the phasing modes can be satisfied using a single lenslet design.
The masks listed below and shown in Figure 6 21 cover the full range of requirements for the SH subsystem. The individual aperture size used is 300 microns to meet the 12-cm on-sky requirement. For subapertures that are not used for phasing, the aperture size can be as large as a full lenslet, but all lenslets will have circular apertures to mask the lenslet edges.
a. Ultimate mask: 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.
b. Coarse tilt: one center subaperture per segment, no edge subapertures. This mask eliminates all but the center subaperture to minimize confusion for coarse tilt mode.
c. One-subaperture phasing: one center subaperture per segment, plus one subaperture per edge. This mask provides the maximum separation between subimages for phasing.
d. Three-subaperture phasing: one center subaperture per segment, with three subapertures per edge. This separates out the phasing subimages, but gives more samples per segment edge to improve the phasing measurement.
e. “FS” type mask: ~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 in the image plane. In the case of an incomplete mirror this mask will use the PIT loop to measure and adjust the primary mirror pupil position.
f. “FS” type mask: ~13 sparse subapertures per segment, with one edge subaperture on the outer ring of segments. By increasing the spacing between subapertures internal to a segment, this mask will be able to accommodate larger segment figure errors, associated with unwarped segments, without confusion. As with the “FS” type mask in the case of an incomplete mirror the PIT loop will be used to measure and adjust the primary mirror pupil position.

5.5.3.4 SH Relay Lens Design

A double telecentric lens relays the SH lenslet focus to the SH CCD (see Figure 5-22). The unrelayed SH focus plane is 75-mm wide and the target CCD is 60-mm wide.
The SH lenslet clear aperture is 300 microns and the focal length is 45 mm, so the F/# is 150. However, the relay lens design is shown using an input F/# of 17 for ease of visibility.
The approximate image distance is 250 mm and the approximate object distance is 190 mm. The total length of this design is 504.7 mm.

5.5.3.5 Lenslet Array Design

The CCD that best fits our needs has 4k x 4k 15-micron pixels. Matching the area of the subimage pattern to the size of the detector sets the demagnification of the relay lens to 0.8 (allowing for a small margin on the detector).

By matching the pattern of the subapertures to the segment pattern, it is possible to create an array that can satisfy the requirements for both segment figure and phasing. Allowing for three samples per edge for phasing and seven samples across the segment (large diameter) for figure measurement, there are 168 samples across the full TMT pupil.

With these constraints, the only remaining free parameter is the focal length of the lenslets. Figure 5-20 shows the optimum parameters for the system.

5.5.3.6 SH Filter Design

There are a total of six filters in the APS SH camera. Table 5-11 lists the wavelength and full width at half maximum for each of the filters along with the modes in which the filters will be used. Table 5-12 contains the optical specifications for the Shack-Hartmann filters that were developed and used when obtaining quotes.

5.6 Pupil Image and Tracking Assembly

5.6.1 PIT Overview

The APS PIT assembly provides several top-level functions including measurement and control of:
1. Telescope pupil position (x, y, and theta) within the APS at a rate of once every ~10 seconds.
2. Star location (telescope pointing) within the APS at a rate of once every ~10 seconds.

The initial versions of the APS design did not have a PIT assembly, because it was believed that the telescope could meet the APS pupil stability requirement of 0.03% of a pupil diameter over 180 seconds of time. However, when the ORD was written it was decided that the telescope could not, in fact, meet this requirement. This resulted in the addition of the PIT assembly within APS. The PIT provides for measurement and control of the pupil position, as well as a measurement of the image pointing. Given the addition of the PIT assembly, it was possible to relax some of the specifications on the K-mirror. In particular, the tolerance on pupil and image stability over 180 seconds of time can be relaxed as the PIT assembly will provide faster updates and thus correct errors introduced by both the K-mirror and telescope tracking errors.

The figure below shows a Logical layout of the PIT subsystem. The tilt plate enables translation of the telescope pupil. The beam splitter redirects 50% (TBR) 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. And finally, there is also a shutter and a CCD.

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. Note that since APS must handle almost arbitrary combinations of incomplete mirrors, the edge subapertures on interior segments will not, in general, be used unless there are missing segments in TMT.

5.6.1.1 PIT Requirements

5.6.2 PIT Requirements

We list the top-level PIT requirements followed by those of each element.
The phasing subapertures are 120 mm when mapped to the primary mirror, and they must be centered to better than 10 mm or 0.03% of the 30-m pupil. As a result, APS needs the pupil to be stable to 0.03% of the pupil diameter during an exposure, which can last from 20 to 300 seconds. The telescope requirements only hold the pupil stable to 0.3% of the pupil diameter [REQ-1-ORD-2875]. In addition, the telescope OAD states that:
[REQ-1-OAD-2215] The APS shall incorporate any pupil-steering systems necessary to achieve its pupil stability requirements relative to what the telescope system delivers.
The requirements on the PIT are as follows:

1. Measure and control the telescope pupil location in x and y to 0.03% (10 mm)
2. Measure and control the telescope pupil rotation to 0.019 degrees
3. Measure and control the image position to 0.25 arcseconds
4. The PIT assembly shall run at an update rate of once every 10 seconds
5. The PIT assembly shall pass the entire APS field of view
6. The PIT assembly shall operate in the visible wavelengths (600–900 nm)
7. The PIT assembly shall work in all operational modes of APS.

5.6.3 PIT Design

5.6.3.1 PIT SH Camera

The PIT SH camera provides the pupil translation and rotation measurements for the tilt plate and K-mirror, respectively. It also provides the tip/tilt measurement for adjustments in telescope pointing. An initial design was to use a 1k x 1k CCD with 24-micron pixels. This would require a relay lens demagnification of 0.295 and lenslet focal lengths of 10 mm, with a 300-micron pitch. This lenslet array is difficult to build. Even if the lenslet array is replaced by a single lens (as is done in PCS) the required effective focal length of 30 mm corresponds to an F/0.3 lens. Thus we settled on the concept of using the same lenslet, relay lens, and CCD as in the SH camera. We will bin the CCD 2x2 to achieve the necessary frame rates.

The functions of the PIT SH camera can all be accomplished using the SH lenslet design with the one-subaperture phasing mask. This provides one subaperture on each segment edge for pupil measurement and one subaperture per segment center to measure overall image motion. By using the same design as the SH assembly, the PIT SH camera also fulfills the FOV and wavelength requirements. Using the same design as the SH assembly also reduces labor costs and system complexity.

5.6.3.2 PIT Beamsplitter

The beamsplitter picks off part of the light from the SH path to send to the PIT camera. With the filters, this fulfills the requirement that the PIT subsystem work in all APS operation modes. The APS system is not limited by available star flux, so a broadband 50/50 beamsplitter will provide the pick-off for the PIT assembly.

5.6.3.3 PIT Tilt Plate

The tilt plate is simply a transmissive optical flat in the collimated beam that when tilted translates the position of the M1 pupil. This mechanism is used to maintain the alignment of the M1 pupil to the PIT and SH lenslet arrays. Table 5-14 lists the optical parameters of the tilt plate. The tilt plate is mounted in an Aerotech AOM130-6 stage. The range of the optical mount is ±4 deg. which will move the pupil ±375 mm (referenced to 30 m). This range of motion is more than sufficient as the telescope has a requirement [REQ-1-ORD-2875] to maintain the pupil alignment to 0.3% or 90 mm. The phasing modes in APS require that the pupil be aligned to 10 mm, which is equivalent to 0.11 deg. of tilt plate motion. The optical mount has a resolution of better than 2x10-4 deg., which is more than sufficient to maintain the pupil alignment.

5.6.3.4 PIT Filters

The filter wheel will be populated with broadband neutral density filters. With the beamsplitter, this fulfills the requirement that the PIT subsystem work in all APS operation modes. The operational mode of the SH assembly determines the amount of starlight required for a particular measurement. The PIT must be able to adapt to the amount of incoming light. While the dynamic range of the CCD will cover most of this range, the filters will be useful in keeping the incident flux in the linear range of the CCD.

The filter wheel mechanism will be a copy of the one used in the SH Assembly in order to minimize cost and risk and maximize reliability.

5.7 Optical Enclosure

The optics and mechanisms on the APS optical bench need to be enclosed in order to keep them clean and to protect against stray light when in operation. The majority of problems with mechanisms on the Keck PCS cameras have been directly related to volcanic dust getting through the enclosure and into the mechanisms. An enclosure should protect the optics from contamination, be light tight and allow easy access to work on the optics when needed.

Several companies manufacture and sell optical bench enclosures which have removable top and side panels. A Logical design of one is shown in Figure The location where the telescope light enters APS will be sealed with an automated shutter when APS is not in use. The enclosure will likely have several high efficiency particulate air (HEPA) filters installed and the current plan is to maintain a slight positive air pressure when APS is not in use.

6 ICS Software Architecture

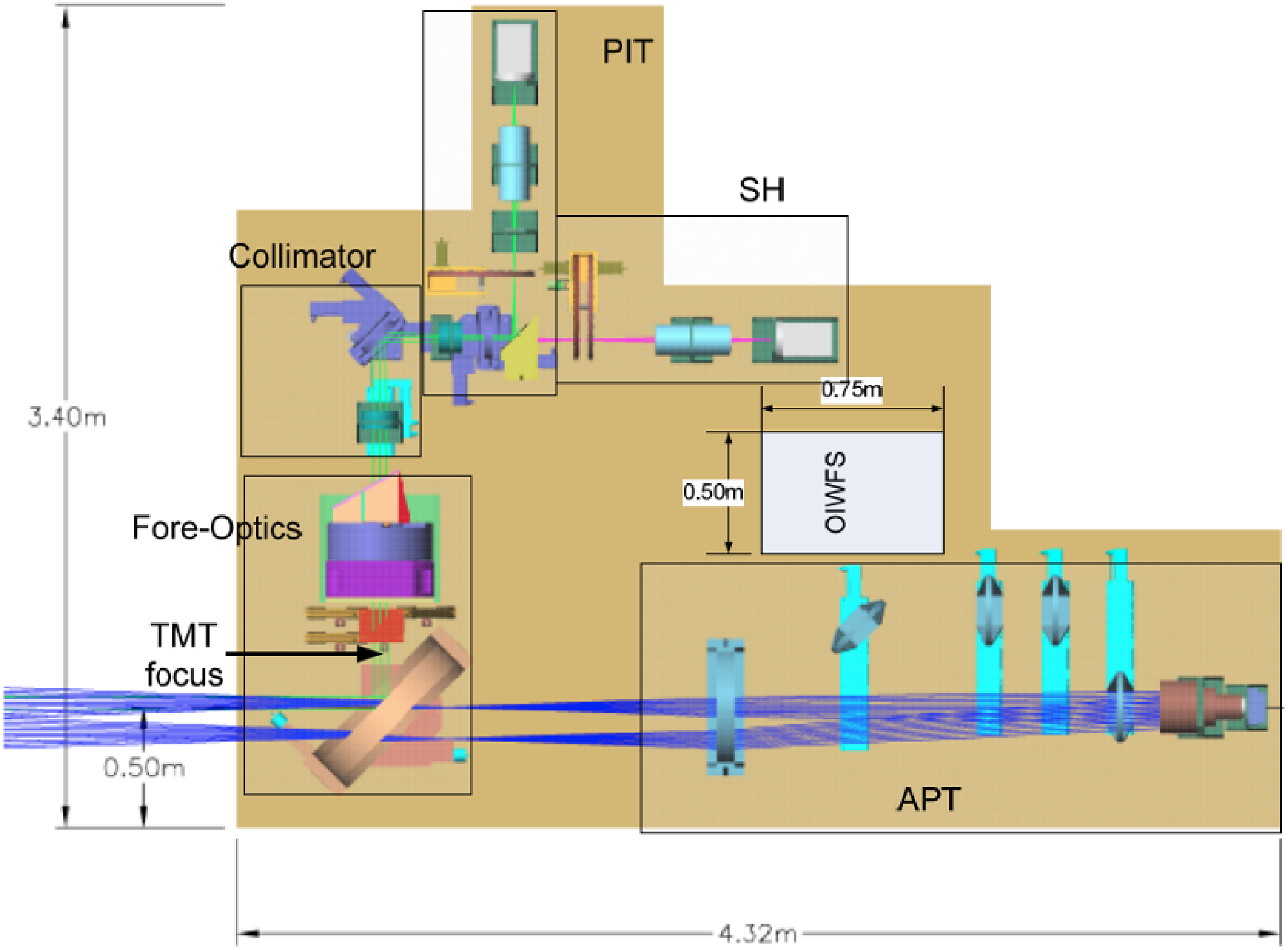
This documents the Alignment and Phasing System (APS) Instrument Control System (ICS) software architecture. Although it mostly deals with the ICS it includes the Procedure Execution and Analysis Software (PEAS), which is the APS executive layer equivalent and in fact is at the TMT executive layer of software. The ICS architecture is at the Logical stage and will evolve as TMT further defines its software architecture and selects specific implementations technologies. We first describe the Executive to Assembly software layer, followed by the Assembly to HCD layers.

The governing documents for the TMT software architecture are the following:

- https://docushare.tmt.org/docushare/dsweb/Services/Document-24356
- https://docushare.tmt.org/docushare/dsweb/Services/Document-24358

The following figure shows the APS CAD drawing from the APS Logical Design Report (2006) for reference. Although the layout may change, the essential sub-assemblies will remain the same. The software architecture is set up to match this hardware configuration. Note that each of these sections also has specific functionality that it provides to the overall APS system.

APS CAD drawing



6.1 ICS Overview

The APS Instrument Control System (APS-ICS) is the single point of control for all components on the APS optical bench. The ICS includes the computers, electronics, software and cables needed to interface and control the optical-mechanical components on the APS bench. Components controlled by the ICS include motors, CCDs, shutters, photo-diodes, light sources, and temperature controllers.

6.1.1 ICS Hardware Controllers

6.1.1.1 ICS CCDs

The APS optical bench has three CCDs: one for the APT camera, one for the PIT camera, and one for the SH camera. [cf:Table 6-1.name] lists the specifications for each Camera and mode supported.

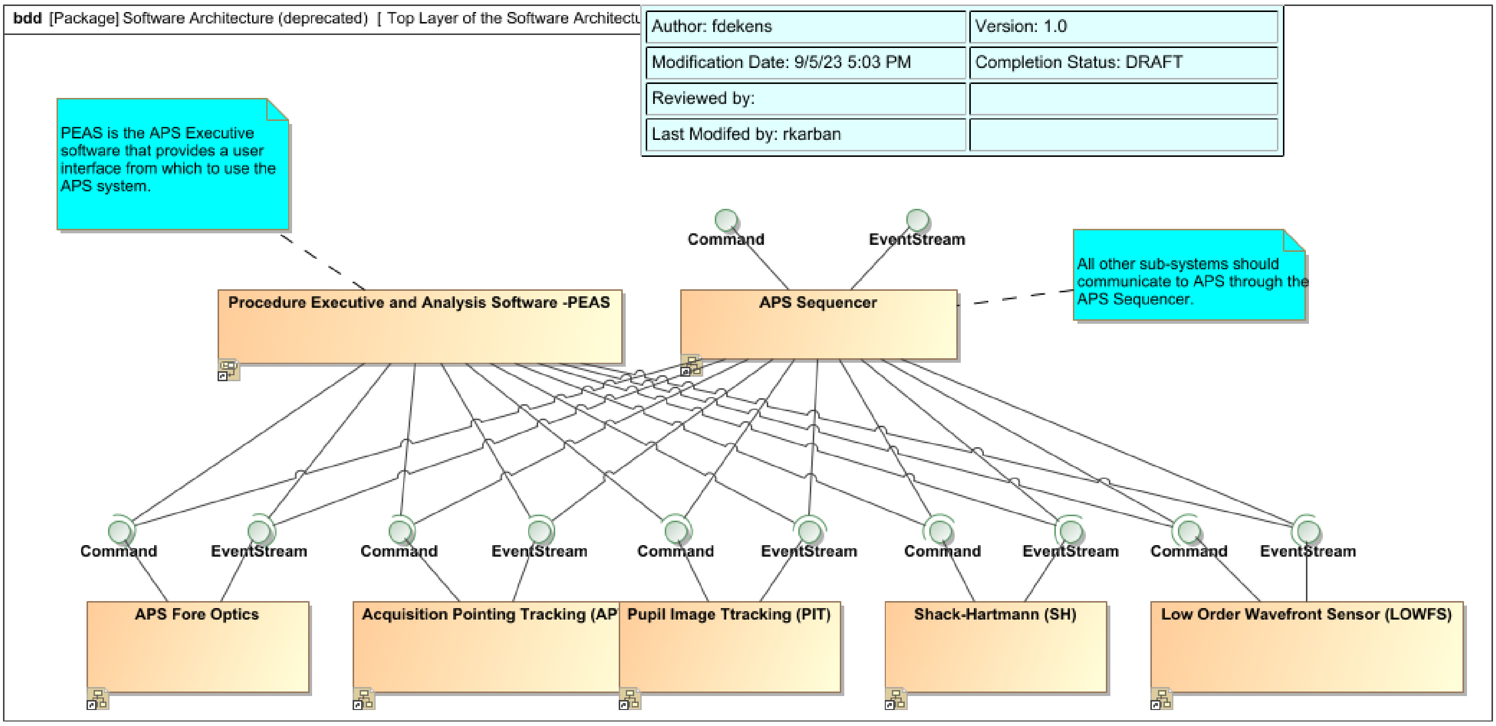
6.1.1.2 ICS Controlled Mechanisms

[cf:Table 6-2.name] shows the motion control motor axes needed in APS (there are a total of 17). In addition, there are a total of 30 single-bit digital inputs and outputs needed for sensing filter, pupil, and shutter positions. There are also seven analog outputs to control light sources and 15 analog inputs for temperature sensors and to monitor the status of light sources. The telescope simulator is still being designed so the device count will likely increase during the preliminary design phase.

6.2 PEAS and APS Top Layer

The figure below shows the top level software architecture. The Procedure Executive and Analysis Software (PEAS) is the APS equivalent of the executive software and controls the instrument. All other TMT sub-systems will communicate to APS through the APS Sequencer. PEAS communicates directly with the assemblies, all other telescope systems communicate to the ICS via the APS sequencer, as shown in the figure below. Each of the assemblies has a set of Hardware Control Demons (HCD) that it communicates with, which are described and shown in later figures.

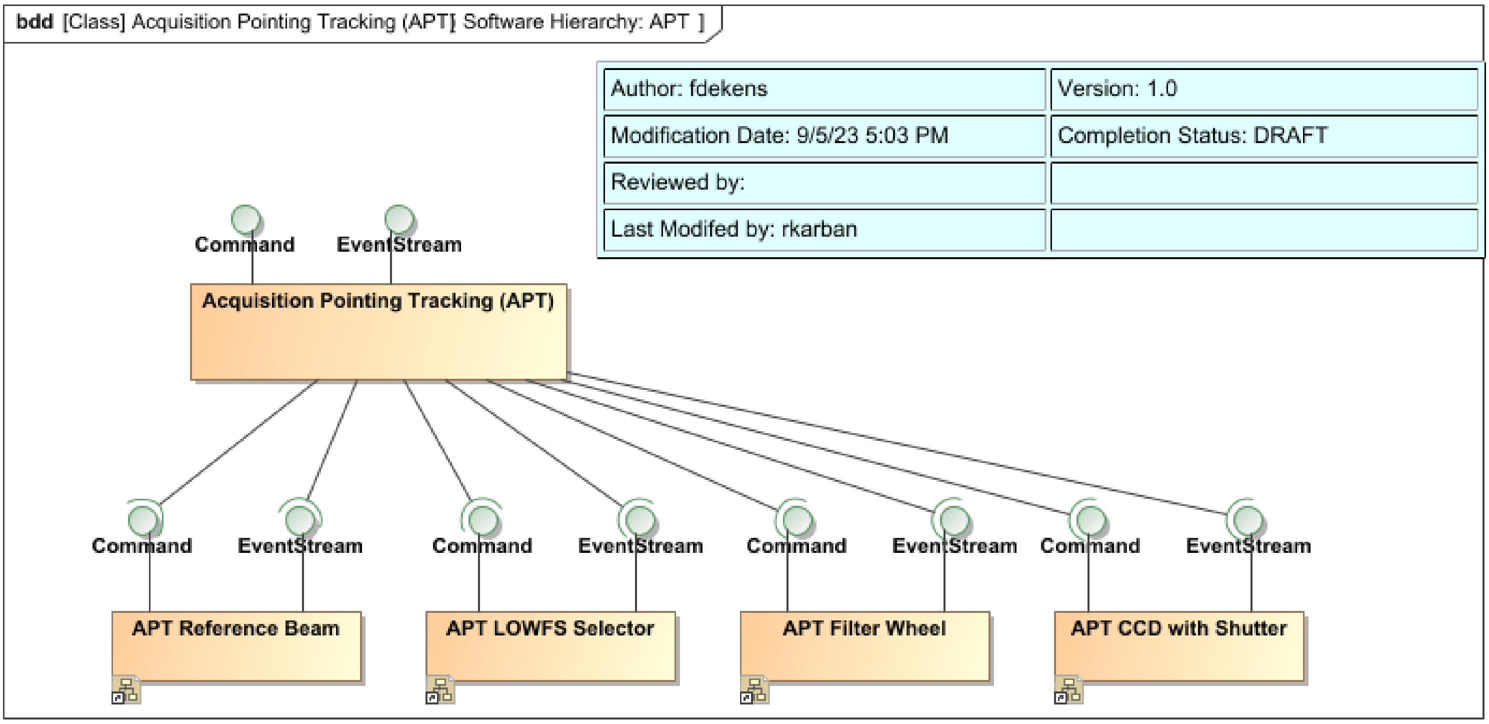
Top Layer of the Software Architecture



6.3 Assembly Layer

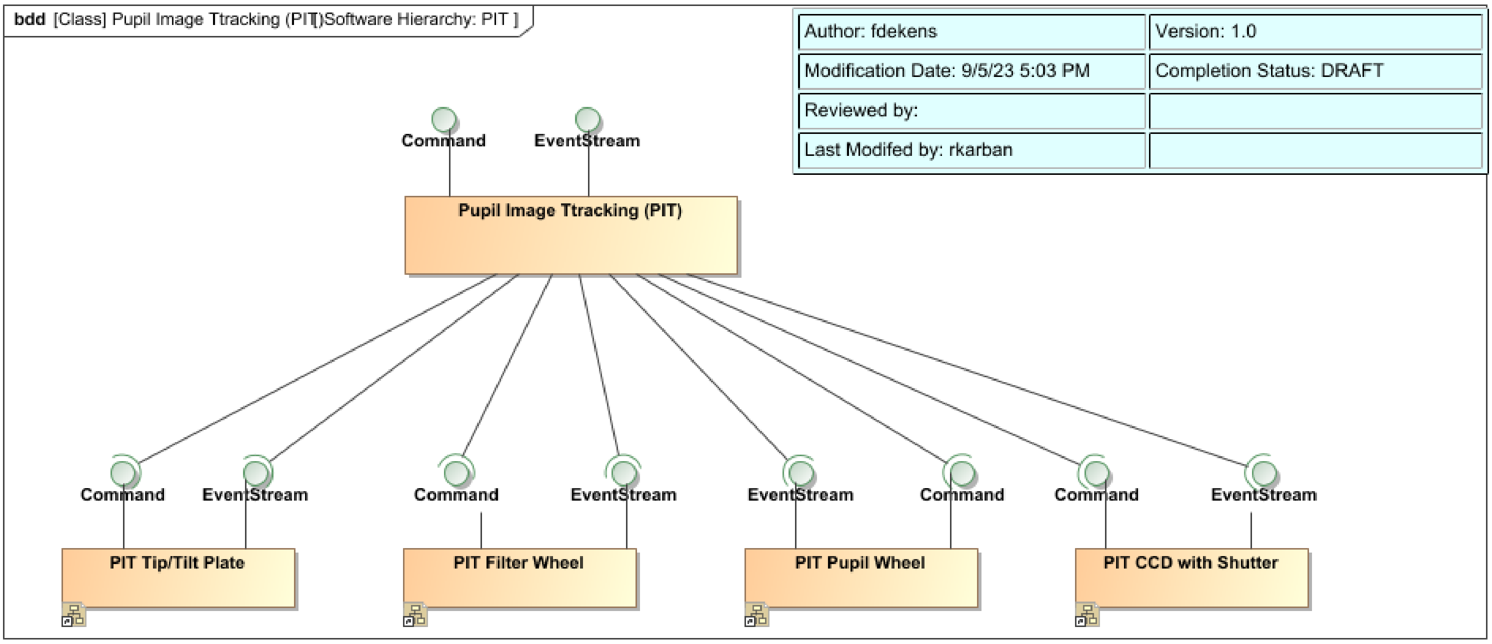
The following diagrams show how each <<Assembly>> is responsible for the <<HCD>>s below it. APS does not allow directly commanding any of the HCDs from any other assemblies or executive software.

Software Hierarchy: APT



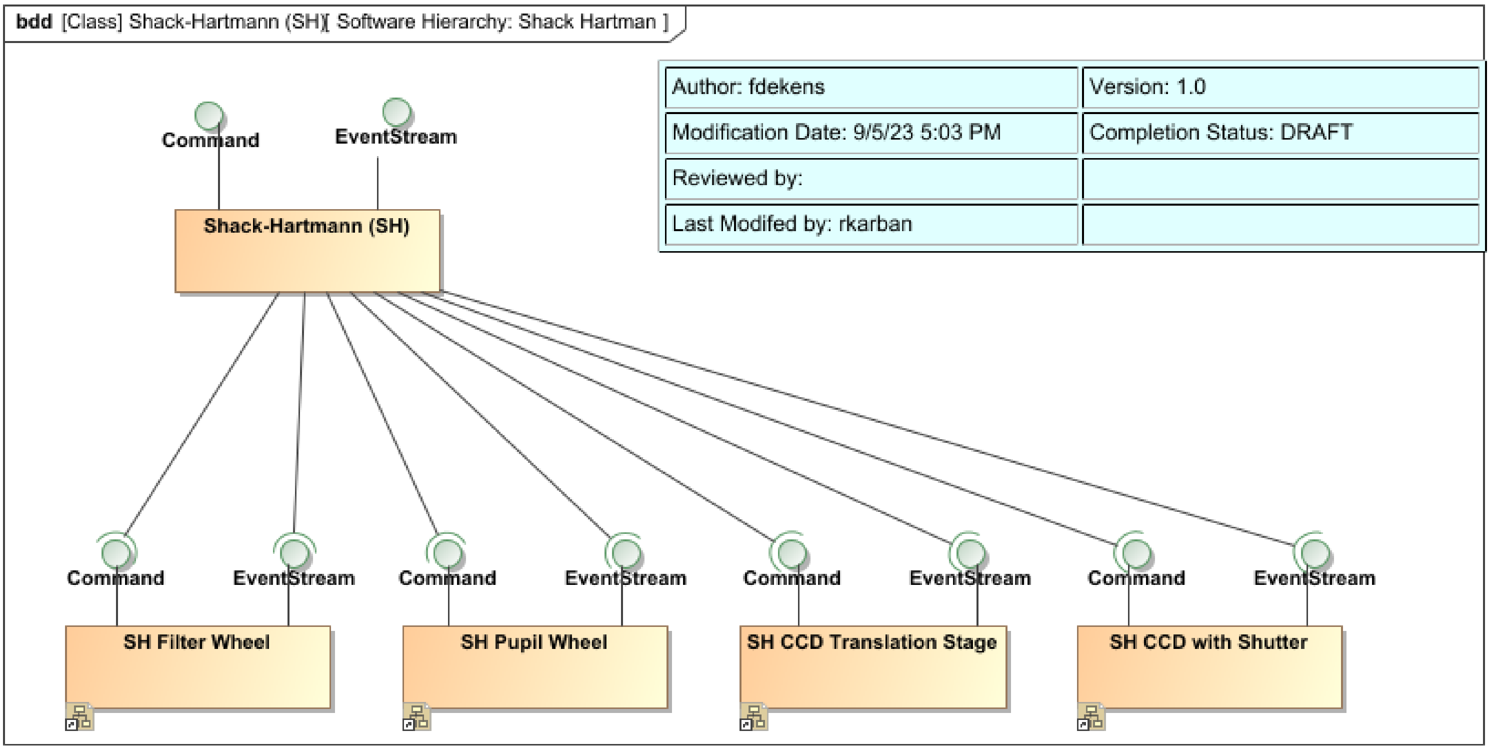
The figure above shows the Acquisition Pointing Tracking <<Assembly>>, which handles the APT arm of APS. It will prevent collisions, such as taking a CCD image while the wheel or LOWFS selectors are moving. We have not yet decided what the appropriate action is; however, if such a collision occurs the <<Assembly>> will either delay taking the CCD image until the LOWFS selectors have finished moving or return an error.

Software Hierarchy: PIT



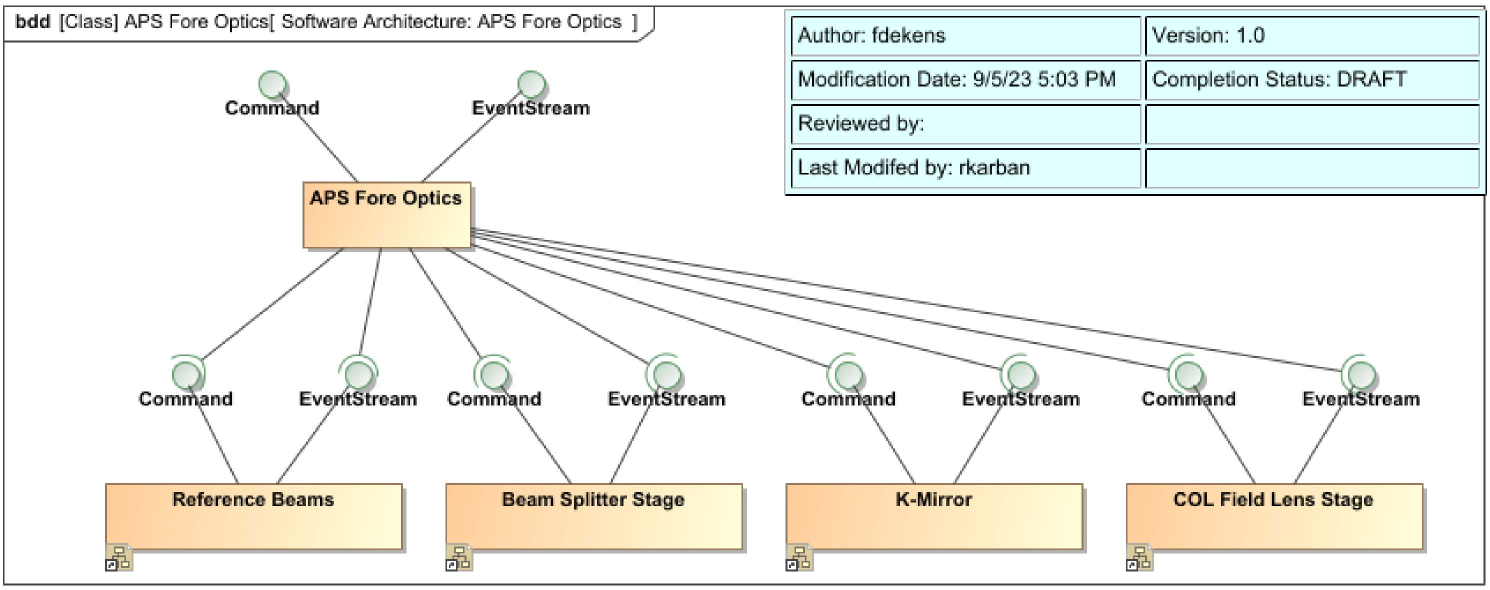
The figure above shows the Pupil Image Tracking (PIT) <<Assembly>>, which is possibly the most complicated <<Assembly>>. It needs to handle the fact that the PIT loop may be running, and should stop that loop when for example the filter or pupil wheels are moved. Our current baseline design is to have the actual loop controller and associated algorithms inside of PEAS.

Software Hierarchy: Shack Hartman



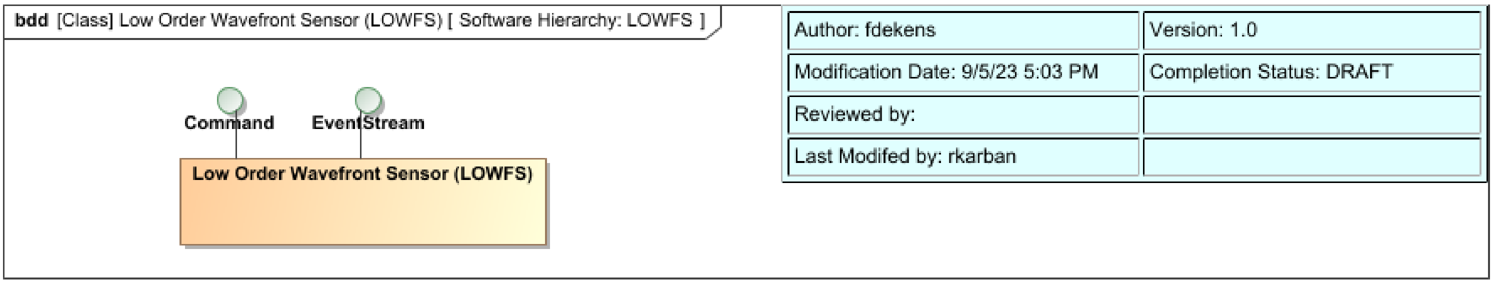
The figure above shows the Shack-Hartman (SH) <<Assembly>>, which handles the SH arm of the APS bench. It's a fairly straightforward implementation, just watching for collisions between taking images and anything moving.

Software Architecture: APS Fore Optics



The APS Fore Optics Assembly, shown in the figure above, is the only <<Assembly>> that was originally for convenience, so that there is a layer between PEAS and the APS sequencer and the <<HCD>>s. However, this will change as during the preliminary design we will be adding a telescope simulator to the Fore Optics Assembly.

Software Hierarchy: LOWFS



The next figure shows the LOWFS <<Assembly>> layer without any views of what <<HCD>>s might exist below it. Assuming the LOWFS is delivered as part of APS then, whoever delivers the LOWFS hardware will also be responsible for providing the LOWFS <<Assembly>> and associated <<HCD>>s. APS will not have visibility into the HCD layer, and will only communicate with the LOWFS Assembly. It is also possible that the LOWFS software will be entirely external to APS in which case there would be no LOWFS <<Assembly>>.

6.4 Adherence to TMT Common Services

The ICS will conform to the TMT standard software interface definition; as a result, the APS bench can be commanded by any TMT system. APS-ICS will also conform to the OMOA component based architecture and utilize the common services integration framework. APS-ICS will use the CSW services shown in [cf:Table 6-3.name].

6.4.1 Command Locking

Command locking an OMOA Assembly is essential to APS-ICS to prevent unwanted command sources to accidentally command an assembly and its subordinate HCDs.

The agreed upon design will be that each OMOA component will have an internal client UUID (computer generated unique identifier) that is passed with each command service ‘submit’ that component sends. APS-PEAS and APS sequencer will have the ability to lock an assembly using a lock message that acts as a lease on the lock with a timeout. While the lease is active, if a different component (application or sequencer) with a different UUID tries to send a command to the locked assembly, the CSW CCS service will reject the command. If the client that originally locked the assembly does not renew the lease before the timeout, the lock is released.

This feature is still in the design stage and is not available in the prototype CSW implementation.

7 Procedure Executive and Analysis Software

The APS Procedure Executive and Analysis Software (APS_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 APS_PEAS interacts with the APS subsystem interfaces and with telescope software interfaces — primarily M1CS, M2CS, M3CS, and TCS — to analyze and correct misalignments through a set of defined procedures.

APS_PEAS provides the software framework within which the analysis computations and alignment procedures will run. APS_PEAS relationship to the other APS components and external components is shown in Figure 8-1. The design and development of the analysis computations and alignment procedures is not within the scope of the APS_PEAS. The implementation of procedures and analysis computations, once developed, is within the scope of APS_PEAS. The specific alignment operational scenarios that will be implemented as APS_PEAS procedures are described in Section 5.

7.1 Functional Concept

7.1.1 Functional Requirements in Brief

The Alignment and Phasing System 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.

The following sections briefly discuss the functional requirements for APS_PEAS. For more detailed information refer to RF2.

7.1.1.1 Procedure Execution Functional Requirements in Brief

APS_PEAS will support procedure execution and provide user interfaces supporting the configuration and execution of each procedure. Procedure in-progress and completion status will be included. Expert users will have the ability to decide if alignment commands will be sent.

APS_PEAS will derive appropriate visualization displays to present important diagnostic and results information for alignment. APS_PEAS will provide user interfaces to display this information.

During the execution most of the ‘on-sky’ related procedures, APS will implement a pupil- and image-tracking loop that maintains correct pupil and image tracking through image analysis and commands to TCS, M3CS, and APS_ICS.

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

Once a procedure has been completed, the following will be made available by APS_PEAS to non-expert users through a reporting user interface:

- Nightly summary reports
- Procedure summary reports
- Procedure detailed information including:
    - Real-time visualization displays
    - Initial procedure configuration, and procedure branch decisions taken
    - Captured images
    - Detailed archived data

The reporting user interface will include search, and browse capabilities.

7.1.1.2 Monitoring and Diagnostics

APS_PEAS will provide diagnostic expert interfaces and tools to diagnose and pinpoint the source of problems with the system as a whole. These will include interface diagnostics for each external subsystem interface that APS_PEAS commands/queries, interface diagnostics for each APS subsystem interface that APS_PEAS commands/queries, and a CCD image (frame) analysis tool.

APS_PEAS will provide a user interface that monitors status, state, and availability of APS subsystems and associated devices.

APS_PEAS will provide a user interface that will display procedure commands sent and resultant states in real time and at any time after procedure execution.

7.1.2 Relevance of Legacy Systems

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

7.1.2.1 PCS Successes

- The PCS user interface was easy to use and understand. Many of the user interface concepts first developed in PCS will be built upon and expanded in APS_PEAS.
- PCS supported the ability to rerun old procedures from archived CCD frames, allowing reproducibility of results and the ability to compare results where procedures and computations have been improved/altered, supporting new algorithm development and debugging telescope anomalies.
- In PCS, the path from R&D usage to automated usage was made gradual through UI configuration elements. The system also supported reverting to R&D usage modes as well. These concepts will be brought forward and expanded upon in APS_PEAS.
- Data archiving capability. The original PCS did not have much data archiving, and much was added in an incremental release. APS_PEAS will build on the successes here and expand the archiving to cover areas missing in PCS.
- PCS contained a problem/solution database.
- PCS contained an email notification system that alerted support team when various monitored values exceeded thresholds.

7.1.2.2 PCS Weaknesses

- The PCS software became brittle after many procedure and algorithm changes.
- The system architecture did not support a remote user interface client.
- Configuration management grew in complexity and became unwieldy.
- Code was tied to particular machine and OS.
- Services code was scattered through code base, procedure code, etc.
- PCS did not archive data using a relational database, and many features that could have taken advantage of the relational nature of the PCS data could not be developed.

7.1.3 PEAS_PCS Project

The PEAS_PCS project was undertaken as a joint project between TMT and Keck to rewrite the outdated PCS code and prototype design concepts applicable to APS_PEAS.

7.1.3.1 PEAS-PCS Project Contributions to APS_PEAS

- Computations have been isolated, reorganized and refactored to not contain any state and run without side effects.
- The system will be used in production at Keck, and will continue to be a valuable research tool for APS.
- Enabled the discovery of end-user requirements, such as providing a more directive UI rather than a dashboard with popups.
- Enhanced understanding of technical issues that inform technology requirements for APS.
- Validates the workflow concept for PEAS with all PCS use cases.
- Reduced the scope of reporting requirements for PEAS.
- Exposed overlooked processes and design, e.g. the external I/F and ICS simulation and connection control.
- Exposed unanticipated design requirements and constraints. For example:
    - Sub-procedure come in two flavors: stand-alone and only called within a procedure. Procedure reporting design need to take this into account.
    - Computations (and thus new computations) can have configurations. Unanticipated design requirement.

7.1.3.2 PEAS PCS Exposed design challenges relevant to APS-PEAS

7.1.4 APS_PEAS User Roles

7.1.5 Alignment Procedure Functionality

7.1.5.1 Alignment Procedure Execution Scenarios

7.1.6 Alignment Procedure Common Features

7.1.6.1 Procedure Execution Use Cases

7.1.6.1.1 Generic Alignment Procedure Use Cases – Development through Early Operations

During an APS observing session, several procedures may be executed. For each procedure, the high-level use cases are defined as shown in Figure 7-2. Typically, a user (Observing Assistant or System Developer user) will select a procedure to be run, complete any procedure-specific configuration that is required, and submit the procedure for execution.

7.1.6.1.2 Generic Alignment Procedure Use Case – Late Operations

Once a procedure has gained a high degree of reliability and can be considered ‘production-ready’, its default configuration will be used and the procedure will not typically require configuring prior to execution.

As sets of procedures normally run during an APS observing run become standardized, super-procedures will be developed that call each procedure in the set in turn (see Figure 7-3). A ‘super-procedure’ can be implemented in the same way a procedure is: procedures can call other procedures. One example would be a super-procedure that automatically aligns all segments after a segment exchange.

The ultimate automation goal is for the super-procedure execution to be automatically called through a programmatic API. Although this will not occur for several years after operations begin, the system design will support it.

7.1.6.1.3 Generic Alignment Procedure Use Cases – Research and Diagnosis

The System Developer user can run procedures just as an Observing Assistant can, but can also retrieve previous procedure configurations and use CCD simulators that provide frames from a selected previous procedure execution (see Figure 7-4).

The System Developer user can also substitute new procedure elements (such as altered analysis computations) and run that procedure, or rerun a previous procedure, with alterations using a previous configuration and CCD simulators.

Results from procedure execution can be analyzed by viewing reports and running ad-hoc queries against the procedure data store using 3rd party tools such as MATLAB.

7.1.6.2 Procedure Execution User Interface Elements

An Observing Assistant will use APS_PEAS to execute APS procedures through a graphical user interface. The following list describes GUI elements that would typically be used during development through early operations, and for ongoing image quality research.

- **Procedure Configuration** – displays the configuration data for a given procedure, during and post-execution
- **Procedure Execution Control and Status** – procedure start/abort and procedure overall progress
- **Analysis Data Visualization Displays** – each display renders a particular data visualization used within the procedure.
- **Procedure Execution Flow History** – displays the procedure data in a workflow context.
- **User Prompt** – enables user to specify flow direction at pre-defined decision points.
- **CCD Frame Display Tool** – displays frames as they are taken during a procedure execution. Supports sub-image marking and analysis.
- **Command Log** – display of all commands and responses to APS_ICS and external subsystems.
- **Instrument State Display** – displays the current state of components within the instrument in real-time.
- **I/F communication display** – Enables user to run in simulation or connected mode for any of the external I/Fs, including the ICS.

The following sections describe the purpose and behavior of each element.

7.1.6.3 Procedure Configuration Concepts

7.1.6.3.1 Procedure Element Configuration Options

7.1.6.3.2 External Subsystem Simulators

Developer Users can change the behavior of APS_PEAS to execute procedures using one or more simulated external subsystems.

APS_PEAS is run with external subsystems simulators set on or off globally for the application. The APS_PEAS user interface will include a display of external subsystem connection information on all screens that will include simulation state on/off.

7.1.6.3.3 CCD Frame Simulator

Through a user-interface configuration screen, Developer Users can change the behavior of APS_PEAS to execute procedures using an artificial or archived frame source.

Simulated frames can be specified during procedure configuration, and will support multiple simulated or archived frames for procedure steps that execute within the context of a loop.

7.1.6.4 Analysis Data Visualization Displays

7.1.6.5 Procedure Alignment Command Go/No-Go Prompts

7.1.6.6 Procedure Execution Control and Status Display

7.1.6.7 CCD Frame Display

7.1.6.8 Data Archiving within Procedures

During the execution of any procedure, APS_PEAS will archive the following data as soon as it is available:

- CCD frame data.
- Reference beam map data.
- Internal and external subsystem commands and return values.
- Analysis-computations results.
- All data required to reconstruct an analysis visualization display.
- All configuration data used within the procedure
- All user input from decision-point prompts.
- APS-subsystem-monitored data.

Figure 7-6 shows a typical data-archiving scenario during a procedure execution.

7.1.7 Concurrent Image/Pupil Tracking Process

An Image/Pupil tracking process will run more or less continuously during an APS observing session and concurrently with each procedure executed. APS_PEAS procedures will send messages to the Pupil tracking process (running concurrently) and to the TCS to acquire a star/object, to command driving to field points, or to pause and restart Image/Pupil tracking.

7.1.8 APS_PEAS Procedure Reporting Functions

7.1.8.1 APS_PEAS Reporting High-Level Use Cases

Figure 7-8 illustrates the high-level APS_PEAS reporting use cases.

7.1.8.2 Procedure Reporting User Interface Elements

7.1.8.3 APS Sessions List

7.1.8.4 APS Session Summary Report

A list of all sessions run with APS will be available for viewing in real-time while APS is running and at any other time that APS_PEAS is running. The sessions list will provide links for the user to view a particular session in the Session Summary Report.

7.1.8.5 Procedure Summary Report

7.1.8.6 Frame Summary Report

The Frame Summary Report will summarize the frames taken during a procedure and provide a programmatic handle to display a selected frame in the CCD Frame Display Tool.

Frame Summary Report fields will include a APS ICS state snapshot, and other relevant information about the frame and the context in which it was generated.

The Frame Summary Report will be downloadable to the user in .csv or other suitable format.

7.1.8.7 Diagnosing Procedure Anomalies

At any time after the execution of a procedure, a user can view that procedure's set of analysis data visualization displays, the procedure's configuration values used, the actual execution flow of the procedure using the Procedure Execution History Display, and relevant summary data in the Procedure Summary. These can be used to determine the source of alignment-procedure anomalies or for R&D analysis purposes.

More in-depth analysis of the complete set of archived procedure data is possible with ad-hoc queries of the procedure database, using 3rd party tools such as MATLAB.

The user can view the Frame Summary Display and view the frames taken during the procedure using the CCD Frame Display Tool. These can be used to check frame data as the source of anomalies.

7.1.8.8 Loading Archived Data for Reporting

All data archived in the execution of a procedure will be used to populate the data required for the procedure-related reporting UI elements. This includes:

- CCD Frame data.
- Reference beam map data.
- Commands sent to other subsystems and returned
- Commands sent to ICS and returned data
- Analysis computations results.
- All data required to reconstruct each analysis visualization display for the procedure.
- Configuration data used in the procedure
- User input from decision-point prompts.

Data archived from each procedure executed during an APS observing session will be used to construct the APS Session Summary.

7.1.8.9 APS Problem/Solution Database

During normal operations when problems occur and/or are solved, all information will be cataloged for future reference.

Assumption: It is currently assumed that this will be achieved through a TMT-wide solution.

7.1.9 Diagnostic Functions

7.1.9.1 Diagnostic Use Cases

The System Developer will use the diagnostic functions frequently during development and integration (see Figure 7-10). The APS Support Engineer will use these functions in rare operational cases where no other method can uncover a problem.

7.1.9.2 Diagnostic User Interface Elements

7.1.9.3 APS – ICS Communication Diagnostics

The APS Internal Subsystem Diagnostics enable the user to submit ad-hoc commands manually to the APS Instrument Control System (APS_ICS). Commands and return values are displayed on the Interface Communication Status Display (see Section 7.1.10.14).

7.1.9.4 External Subsystem Diagnostics

Enables the user to submit ad-hoc commands manually to each of the external subsystem with which APS_PEAS normally communicates. The available commands will be restricted to those command APS_PEAS can submit in a procedure execution.

Commands and return values are displayed on the Interface Communication Status Display (see Section 7.1.10.14)

7.1.9.5 Frame Display and Analysis Tool

The Frame Display and Analysis Tool is a diagnostic tool for CCD, instrument optics, and telescope optics. This tool will support manual reading of CCD image frames, loading archived frames, displaying frames, manually storing frames into persistent store, manual analysis of centroids, and displaying various frame statistics.

The tool will support searching and browsing persistent store for image frames by date range, by night session, and by procedure type.

7.1.9.6 Data Archiving During Diagnostics

Data archiving of commands and responses is handled through the monitoring functions (Section 7.1.10).

CCD Frames taken with the Frame Display and Analysis Tool are persisted to a data store much as CCD Frames are within procedures, except that there is no procedure context with which to retrieve the Frames. Such frames will be stored in such a way so that they may be retrieved by date, by pupil mask, and by filter.

7.1.10 Monitoring Functions

7.1.10.1 Monitoring Use Cases

7.1.10.1.1 Continuous Updating Display Mode

APS_PEAS monitoring use cases (see Figure 7-12) allow the user to view a continuously updated display of the APS instrument (APS_ICS) states, and a log of all interface commands (external and internal subsystems) and the command responses received.

7.1.10.1.2 Viewing Archived Monitoring Data

Monitored data is archived and can be reloaded for display in the context of viewing a previously executed procedure. Monitored data can also be retrieved for display by date range.

7.1.10.2 Monitoring User Interface Elements

Monitoring user-interface displays can be viewed in the context of a running procedure and historically for a procedure once the procedure has completed. Both displays support loading of historical data in the context of a procedure and a simple date/time range.

- **Command Log** – display of all commands and responses to APS_ICS and external subsystems that occurred during a procedure.
- **Instrument State Display** – displays the current state of components within the instrument in real-time or for the currently selected frame.

7.1.10.3 Instrument Monitoring

APS ICS monitored data will be retrieved at a rate of TBD. Monitored data shall include current-position information for all instrument devices, CCD temperatures, shutter open/close status, reference beam on/off status, etc. All failures, warnings, and alerts will be recorded.

A continuously updating display of the monitoring data will be available to the APS_PEAS user through the APS Subsystem Monitoring Display. Subsystem warnings and alerts, including any failure of the monitoring system itself, will be prominently displayed. The display will show near-real-time states for all devices, and will support display of historical data.

7.1.10.4 Interface Communication Log

All commands/requests between APS_PEAS and APS subsystems and all external interfaces — and the response — will be logged. All failures, warnings, and alerts will be recorded.

The Interface Communication Log Display will display all logged communication data, with failures, warnings, and alerts more prominently displayed. The display will display near-real-time commands and responses, and will support display of historical data.

7.1.10.5 Archiving of Monitoring Data

All monitored subsystem data will be immediately archived once it is available. Archiving of monitored data in the context of a procedure will be related to the procedure execution archive.

The responsibility for archiving monitored APS subsystem telemetry data has not been defined.

7.1.11 Configuration Functions

7.1.11.1 Configuration Use Cases

Global configuration use cases (see [cf:Figure 7-14.name]) encompass any configuration of the system that is used across all procedures and occurs often enough to merit a user interface to view and/or set values. These may include missing-subimages configurations, mask/image-related configuration, default motor positions of all APS devices, and calculation parameters that might change often during initial operations.

7.1.11.2 Global Configuration User Interface Elements

7.1.11.3 Archiving of Global Configuration Data

7.1.12 Security Features

Assumption: The Observatory as a whole will provide a common mechanism for application security. APS_PEAS will require role-based authorization to its features, plus a handle to the logged on user for audit trail archiving.

7.1.12.1 Authentication Features

APS_PEAS will require that users log into the system prior to having access to it.

7.1.12.2 Authorization Features

7.1.12.3 Audit Trail

All procedure execution data will include the logged-in user as related data.

All diagnostic execution archived data will include the logged-in user as related data.

All procedure definition and analysis-computation archives will include the logged on user as related data for all created procedures/functions and versions thereof. All changes to configuration defaults will include an audit trail including logged in user.

7.1.13 Other Features

7.1.13.1 Notification Feature

7.1.13.2 Problem/Solution Database

Assumption: it is assumed that a problem/solution database will be achieved through an observatory-wide solution.

APS_PEAS will support access to a problem/solution database that contains information on operational problems and operational process fixes, software bugs found and fixed, image quality problems found and fixed, etc.

7.2 Technical Concept

7.2.1 Technical Requirements Overview

7.2.1.1 Extensibility

7.2.1.2 Remote User Access

7.2.1.3 Performance/Scalability

7.2.1.4 Resiliency

The code should be resilient to changes in implementation choices made by the project now and in the future. This affects the data store, subsystem, and common services communications, and the user-interface implementation.

7.2.1.5 Heterogeneity

The best programming language to implement the framework and services may not be the best programming language to implement analysis computations. The system will, therefore, support multiple implementation languages.

7.2.1.6 Assumptions

7.2.1.6.1 Communications

All APS_PEAS to external communication (ESW, TCS, M1CS, APS_ICS, etc) will be implemented though the TMT common services.

7.2.1.6.2 Data Store

Data management services will be provided by the CSW database service, which will support standard JDBC database access to an APS_PEAS specific database. Database models will be implemented and tested by the APS group and ported to the telescope data-archiving environment prior to integration.

7.2.2 General Design Approach

7.2.2.1 Layered Architecture

A system utilizing a layered architecture is a system where components are isolated in layers so that changes can be made in one layer without affecting the others.

Benefits of a layered architectural approach include:

- Many upper layers can share the services of a lower layer. Thus, layering enables and enforces code reuse.
- Similar responsibilities are grouped, which aids understandability and maintainability.
- Segmentation of high-level and low-level issues; therefore, complex problems can be broken into smaller, more manageable pieces.
- Development by teams is aided because of the logical segmentation.

A layered architectural approach helps to fulfill the technical requirement of resiliency by isolating impacts of changes. A layered architectural approach fulfills the UI vs automatic API usage requirements for PEAS, as the UI features can be cleanly separated from the base API.

7.2.2.2 Distributed Architecture

7.2.3 General Design

7.2.3.1 Services and Layers

7.2.3.2 Distributed Deployment Architecture

7.2.3.3 Programming Languages

Java is the leading programming language choice for the APS_PEAS framework and, possibly, most other APS_PEAS implementation (with the exception of certain analysis computation functions).

Java is the leading selection because:

- Java's extensible class-loading mechanism, along with late binding, allows multiple versions of the same component to coexist in the same environment, which will support procedure-execution-results comparison between different versions of a procedure or analysis computation.
- Java has a wider user base. This is an important factor in choosing a language because it will influence the ability to find talent to program in it.

There are many other reasons for using Java as the framework implementation language (simple thread programming model, exception handling programming model, garbage collection, portability, etc.).

Scala is a second choice and will be evaluated further in the PD phase.

C may be employed when implementing analysis computations because:

- It may be faster than Java.
- Off-the-shelf numerical computation libraries are written in C/C++ and Fortran only.

Fortran may be used for analysis computations because many of the APS analysis computations have been already written in Fortran as part of the PEAS_PCS project.

7.2.3.3.1 PEAS_PCS J2F Package

Prior to the PEAS_PCS project, a Java to Fortran interface was developed by the APS team. J2F (Java to Fortran) generates C and Java code given Fortran source files annotated with descriptive XML-based information in a comment section at the start of the Fortran source file.

The J2F program also generates a makefile and scripts that produce Java source classes to interface with the Fortran code, and a libpeas.so library that can be dynamically linked to a running Java program.

J2F has been tested extensively at Keck as it is part of PEAS_PCS.

There are existing packages that perform similar functions, but since J2F is already written, simple to use and well understood by the team, an upgrade to an existing package like SWIG or JNI 2.0 is currently considered low priority.

7.2.4 APS_PEAS Communication Design

APS_PEAS is responsible for communicating with the APS_ICS: sending commands for diagnostic purposes and receiving status information and events/alerts.

APS_PEAS is responsible for communicating with external telescope subsystems: commanding and receiving status from M1CS, M2CS, M3CS, TCS, and Telescope Common Services.

All communication between APS_PEAS and external subsystems (M1CS, TCS) will be via CSW (see Figure 7-17).

7.2.4.1 External Subsystem Communication

7.2.4.1.1 Protocol/Implementation

7.2.4.1.2 APS_PEAS to External Subsystem Data Flow

Figure 7-18 illustrates the general data flow between APS_PEAS and external subsystems.

The specific details of the data flow between the subsystems is given in their respective ICDs.

Simulators for each of the external subsystems will be developed. Procedure execution code will be agnostic to whether a simulator is being used or the actual subsystem. A simulator can be substituted for each subsystem independently and will be controlled by configuration and user interface components.

7.2.4.2 APS_PEAS to APS_ICS Data Flow

7.2.4.2.1 Protocol/Implementation

APS_PEAS will communicate with APS_ICS using the common services integration framework.

CSW will provide a locking mechanism to prevent simultaneous access by any other observatory system to APS_ICS assemblies when APS_PEAS or APS_ICS engineering I/F has locked access.

7.2.4.2.2 APS_PEAS to APS_ICS Data Flow

Figure 7-19 illustrates the general data flow between APS_PEAS and APS subsystems.

During the preliminary design phase, an internal ICD will be developed that will specify the commands and events flowing between APS_PEAS and APS_ICS in greater detail.

A simulator for APS_ICS will be developed for APS_PEAS. Procedure execution code will be agnostic as to whether a simulator is being used or APS_ICS. The simulator being substituted for APS_ICS will be controlled by configuration and user interface components.

7.2.4.3 APS_PEAS Inter-Component Communication

7.2.4.3.1 Protocol/Implementation

7.2.4.3.2 Inter-Component Data Flow

The APS_PEAS inter-component data flow will be refined during the preliminary design phase.

A simulator for APS_ICS will be developed for APS_PEAS. Procedure execution code will be agnostic as to whether a simulator is being used or APS_ICS. The simulator being substituted for APS_ICS will be controlled by configuration and user interface components.

7.2.5 Procedure Design and Execution Architecture

7.2.5.1 Requirements

Procedure definition and execution requirements are as follows

- Implementation must be separate from the rest of the system; that is, easily loadable without recompiling and verifying any other part of the system.
- A procedure definition should be easily readable by developers and scientists.
- New versions of procedures and analysis-computation functions should be easily loaded and executed.
- Reverting to old versions of procedures and analysis-computation functions should be a matter of configuration.
- Parallel thread execution should be supported to meet procedure-execution-performance requirements.
- Exception handling should abort a procedure if necessary and log applicable messages/values and produce user interface alerts. Exception handling should be handled consistently for all procedures.
- The APS_PEAS user/operator should be able to request to abort a procedure at any time during its execution. A procedure abort will return APS_ICS to a known state and any external subsystems affected will be returned to known states. Reports and logging for aborted procedures should function with all data collected up to the time of the abort.
- A procedure that has been run in production should be able to be rerun at any time with the same procedure version and the same version of analysis computation functions used. The system will support substituting different analysis computation functions and/or with different procedure control and execution sequences into a defined procedure to support research/analysis.
- Use all or part of archived procedure data for re-execution of a procedure for research and/or diagnostics.

7.2.5.2 Design Goals

7.2.5.3 Design Approach

7.2.5.3.1 Benefits of a Procedural Language or Script Approach

7.2.5.3.2 Benefits of a Process Engine Approach

- The approach imposes a clean separation between procedure element (step) implementation (I/F commands, Analysis Computation function calls, UI events, etc.) and the processing flow wherein they will be executed.
- The approach does not permit computations coding or other general-purpose coding within the process flow; instead, forces the developer to write code only within process step implementations as reusable, versioned elements that expose their interfaces (inputs/outputs) in a standard fashion.
- When implemented using a form-based design tool, the system can be self-documenting, self-validating and easy to understand by the non-programmer.
- Parallel processing is handled by the framework; therefore, the user need only declare which elements will be processed simultaneously.
- Because of the clean separation between process-flow execution and process-step implementation, creating a process flow with any supported versions of the process steps is easily accomplished.
- Comparison of procedure versions can be automated using a process definition language, whereas a scritpting language would have to be hand read to determine the exact nature of the differences.
- Data archiving of declared step-element outputs is automatically performed by the framework each time a step is completed.

7.2.5.4 Procedure Execution Design

The current design choice is a process engine using a DSL process definitions. This section describes that design.

The process execution design (see Figure 7-20) outlines how a Procedure Execution Kernel controls the execution of procedures.

The principal components of the design are:

- The Procedure Definition Document.
- The APS_PEAS Procedure Execution Kernel.
- The Procedure Step Component Pool.

A Procedure Definition is read in the Procedure Definition Archive where each step in the procedure is defined. Procedure Steps implement interfaces that follow a common pattern, so that the Procedure Execution Kernel can identify and command execution of the appropriate step when needed.

The Procedure Step Component Pool is a set of Akka Actors, each of which implements a procedure step instance (e.g., a computation function, an interface command, etc.). Each procedure step component follows a standard pattern in exposing its inputs, outputs, and execution-call interface.

The Procedure Execution Kernel is the controller component for procedure execution and is capable of reading and executing multiple procedures simultaneously and handling thread splits and joins.

The Procedure Definition Document is the DSL that the Kernel reads to execute the flow. Commercial workflow engines also operate in this manner. Many workflow engines use XML Process Definition Language (XPDL) documents as the workflow definition. XPDL is a format standardized by the Workflow Management Coalition (WfMC).

Prototype work during the preliminary design phase uses a JSON based subset of the XPDL scheme, adapting only those elements of XPDL that are useful to the system.

7.2.5.5 Procedure Definition Management Tool

7.2.5.5.1 Procedure Definition Document

The Procedure Definition Document is the output artifact of the Procedure Definition Management Tool and the input to the Procedure Execution Kernel. The language and format of this document have not been defined yet. The current thinking is that a subset of XPDL is the best candidate because it already exists, fits the problem space well, and is the standard process definition language used in many workflow engines.

7.2.6 Other Application Services Layer Components

7.2.6.1 Monitoring Services

7.2.6.1.1 APS Instrument Monitoring

7.2.6.1.2 APS_PEAS Command and Response Monitoring

7.2.6.2 Pupil and Image Tracking Service

The Pupil and Image Tracking service encapsulates the Pupil and Image Tracking Loop process. The service will support monitoring, starting, stopping, pausing, and restarting the loop, as well as receiving correction offsets (x, y, θ pupil errors and x, y image errors) calculated from pupil registration of Shack-Hartmann Camera images.

Detailed flow and sequence diagrams for the Pupil and Image Tracking Loop are detailed in Section 4.

7.2.6.3 CCD Frame Analysis Services

The CCD Frame Analysis services support the CCD Frame Analysis Tool. The service:

- Accepts user commands for ad-hoc reading of CCD frames.
- Computes frame statistics (such as average counts/subaperture, mean/median/standard deviation of frame, centroid of frame, rotation).
- Accepts user commands to find and identify sub-images, analyze sub-images, and perform other analysis functions TBD.

7.2.6.4 Diagnostic Functions Services

Diagnostic functions services manages requests from the diagnostic user interface, commands external and internal subsystems, logs requests and responses; maintains a list of available diagnostic commands, queries and requests; and reports errors and timeouts.

7.2.6.5 Reporting Services

Reporting services manages requests from the reporting user interface screens and queries the PEAS database for procedures, session summaries, procedure summaries, procedure frame summaries and procedure archives.

7.2.7 Shared Services Layer Components

7.2.7.1 Subsystem Communication Service

The subsystem communication service is the single point of interface between APS_PEAS and all telescope subsystems, including APS_ICS. This service will also be the single point of interface between APS_PEAS and any telescope common services that are developed.

General APS_PEAS communication design concepts are described in Section 7.2.4.

7.2.7.2 Analysis Computation Service

The analysis computation service contains the repository of analysis computation functions, including all current and previous versions.

The analysis computation service is responsible for managing computation function loading and registration and handling multiple versions of computation functions.

APS performance requirements dictate strict performance requirements on analysis computations. The analysis computation service components will be deployable across a scalable execution environment for any computations that are intensive enough to require it. The most computationally intensive functions currently identified are listed in [cf:Table 7-4.name] and will be updated during the preliminary design phase.

The analysis computation service will support computations written in Java, C and Fortran 95.

7.2.7.3 Data Store Service

The data store service is the single point of interface between APS_PEAS and the OSW data management system and between APS_PEAS and the PEAS database.

The interface between APS_PEAS application functions and the APS_PEAS data store service will pass object structures based on concepts outlined in Section 7.2.8.3.

General APS_PEAS data concepts are outlined in Section 7.2.8.

7.2.7.4 Metadata Service

As an aid supporting rapid procedure development and a flexible nimble system, all fields used in any interface, computation, report or display will be ‘unit-aware’ and ‘coordinate system aware”, and a standard service for transforming units and coordinate systems will be developed, keeping such code contained as a service, rather than having this kind of information and functions spread out in the codebase ad-hoc, which would require data field specific coding when new procedures and/or computations are added.

The metadata service design will include a metadata database that will contain entries for all data fields, their descriptions, short display labels, output formats, units, coordinate systems and data type descriptions (integer, float, array dimensions).

Reports, user interfaces and all interfaces will make use of the service to display data fields and/or transform them.

7.2.7.5 UI Layer

The UI layer is the single layer through which all user interaction will occur. All UI inputs and outputs will pass through this layer. This layer will be responsible for user input validation, configuration form layout, and option-data population. This layer will also be responsible for rendering analysis visualization displays.

General user interface design concepts are outlined in Section 7.2.9.

7.2.8 APS_PEAS Data Concept

7.2.8.1 Data Management Plan

An APS_PEAS database will be managed by the observatory software group. The observatory software will enable JDBC access to APS_PEAS.

APS_PEAS data is engineering data, not observing data. APS is an independent system (i.e., no other telescope system requires APS to be running in order for it to run). APS data is, therefore, more isolated than other engineering data, being only of interest to APS users. The data is highly relational in nature.

It makes sense that the majority of APS_PEAS data should be stored in a database instance solely for APS_PEAS use (see Figure 7-22), but managed by the telescope. The logical data model will be the responsibility of the APS_PEAS team.

7.2.8.2 APS_PEAS Data Storage

APS_PEAS data persistence structures fall under seven broad categories:

- Procedure definition data
    - This is stored in the Procedure Definition Archive, where versioned procedure definitions can be stored and retrieved.
- Procedure execution data
    - All procedure step output data
- CCD frame data
    - All information related to the context of a CCD frame, including instrument state and telescope state data.
    - All CCD frame data, potentially stored in a filesystem maintained by OSW (TBD)
- Reference map data.
    - Reference map centroid data along with all context data sufficient to retrieve a current reference map and to determine if a new reference map needs to be taken.
- Configuration data
    - Procedure configuration
    - Instrument configuration
    - Computation configuration
    - Relational configuration (configuration of the interaction of two or more components, e.g. missing spots is telescope and mask)
- Field metadata
    - Descriptions of all data (configuration and procedure output) including units, coordinate systems, data type and desired view formatting
- Constants
    - Telescope constants, segment constants
    - Conversion and transformation constants

The following sections describe how these logical data sets are partitioned into physical data stores.

7.2.8.2.1 APS_PEAS Read and Update Oriented Database

APS_PEAS read and update oriented data ([cf:Table 7-7.name]) has relatively low write rates, but highly relational data. The database will contain a mixture of mutable and immutable objects, with rich foreign-key relationships.

7.2.8.2.2 Read-Oriented Engineering Database

APS_PEAS telemetry data is stored with other telemetry engineering data in a read-oriented database (see [cf:Table 7-7.name]). APS subsystem telemetry data collection mechanism is still being refined:

7.2.8.2.3 Bulk (Large Image) Data

APS bulk data is large, write-once, slower-read CCD pixel data (see [cf:Table 7-8.name]).

7.2.8.2.4 CSW Configuration Service Database

The configuration service will be used for Instrument configuration and procedure definition archiving/versioning (see [cf:Table 7-9.name]).

7.2.8.3 APS_PEAS Relational Data Structures

In this section, the broad data categories are described in greater detail.

In the UML aggregation diagrams that follow:

- All relationships are shown as aggregations, but further refinement will change many of these to associations.
- When multiplicities are not given they are assumed to be 1 to 1.

7.2.8.3.1 Procedure Execution Data

Procedure-execution-related data is stored in a single logical archive that includes:

- Procedure data such as procedure number, user, start and end times
- Procedure configuration data
- Procedure CCD frame handle and frame context info including integration time, and ICS state
- Reference map data used in the procedure
- Procedure output data: command return values, computation output data, user prompt decisions

Assumption: Component controller telemetry data archiving responsibility is assumed to be handled by CSW, however this needs to be related to a procedure when appropriate.

APS_PEAS will write the archive to the APS_PEAS database in an incremental fashion during the execution of a procedure (see Figure 7-25). APS_PEAS will write procedure context and configuration data to the archive when a procedure has started execution. As each step in a procedure is completed, APS_PEAS will write step output values to the archive.

Once the procedure is completed, the entire archive should be retrievable in 5 seconds from the APS_PEAS database.

Procedure output data will be stored in a common format for all fields of all procedures. Functions will be developed to transform stored data formats to in-memory classes.

7.2.8.3.2 Reference Beam Map Data

The reference beam map archive contains:

- Date/timestamp, procedure taken with
- CCD Frame used (which includes ICS state when frame was taken)
- Centroid data
- All procedures that used this reference beam map data

APS_PEAS will support storage and retrieval of reference beam archives. For any procedure that uses reference beam maps, the system will use a previously and most recently generated map that matches criteria based on a correct match of pupil mask and filter used, age of the map and other ICS state changes exceeding limits.

These maps are referred to as the Current Maps. For a given pupil mask and filter, the system will maintain an in-memory and stored list of current maps and corresponding archives (see Figure 7-27).

7.2.8.3.3 Procedure Definition Data Structure

Procedures definitions are a functional unit of the system that governs procedure execution. Procedure definitions are archived to meet requirements of retrieving and running any procedure or version of a procedure. Procedure definition archives, once used to execute procedures in production, cannot be removed from the data store.

A procedure definition archive (see Figure 7-29) contains procedure name and version information; a set of step definitions: each containing information that tells the system how to execute a step; configuration data definition, which tells the system how to provide for default and custom initialization values; and a procedure summary report definition, which specifies which output values will be displayed in the procedure summary:

7.2.8.3.4 CCD Frame Archive Structure

Every CCD frame taken within the context of a procedure will be archived. Each CCD frame that is archived through APS_PEAS will be part of a CCD archive (see Figure 7-31) that contains related device-state snapshot and procedure-related context in addition to the pixel data itself. The most likely database implementation of this would be an archive header table in the fast-read database whose rows would contain the references to the CCD pixel data in fits frames in bulk storage and references to the snapshot data and procedure in the fast-read database.

7.2.8.3.5 Procedure Configuration

7.2.8.4 APS_PEAS Configuration Data and Constants

APS_PEAS metadata and constants reflect data that is written seldom and read often. Some of the data is written/updated using APS_PEAS user interfaces, while the rest of this data is maintained by manual data insertion into the database.

7.2.8.4.1 Global Configuration

Global configuration is updated using the Global Configuration user interface. The data includes missing sub-images configurations, mask/image related configuration, and calculation parameters that might change often during initial operations.

7.2.8.4.2 APS_PEAS Initialization Template Option Data

APS_PEAS will support the dynamic addition of option data (such as integration times, number of iterations, etc.). All option data will be maintained in the database and will support dynamic changing and extending of option data values.

7.2.8.4.3 APS_PEAS Instrument Configuration Data

Instrument configuration data includes data that relates procedure and diagnostic device constants to actual device positions, such as filter wheel positions and mask positions. These change very seldom; historically, however, these have changed on PCS on occasion for various reasons.

Instrument configuration data includes all possible values for a device (including masks and filters not currently being used) with an identifier and human-readable name and description.

APS will use the CSW configuration service to maintain this kind of data.

7.2.8.4.4 APS_PEAS Constants

APS_PEAS constants are data used in APS-specific calculations. These may be image-quality computation specific constants, mirror-segment-mapping constants, phasing templates, or anything deemed computationally useful for APS computations to function. Constants can be scalar or multidimensional.

Constants are not expected to change; in the event that mistakes need to be uncovered or fixed, however, all previous versions of constants used in an operational context will be maintained. A constants snapshot — a list of all constants versions being used — will be maintained along with all previous distinct constants snapshots. The constants snapshot reflecting the constants used in a particular procedure execution is referenced in the procedure execution archive.

7.2.9 User Interfaces

7.2.9.1 Requirements

7.2.9.2 Architecture

APS_PEAS user interfaces will support web client user interfaces (see Figure 7-35).

The web interface runs on a HTTP Server Environment that will be deployed to one of the physical APS_PEAS servers.

The UI Layer manages requests, validation, and locking of resources during critical operations. The UI Layer also is responsible for a common mechanism for rendering analysis visualization displays and handling asynchronous event rendering.

7.2.9.3 Web Interface Technology

The implementation technology choice for the web interface will be specified by OSW. Specific APS_PEAS UI technology requirements will be determined during the preliminary design phase.

7.3 System and Facilities Design

Figure 7-36 illustrates the physical design of the hardware in the system.

7.3.1 Computer Hardware

The current design of APS_PEAS is that it will consist of three servers, but be scalable to more computation servers, if required. The specifications for each physical server are described in [cf:Table 7-10.name]. This will be re-evaluated during the preliminary design phase.

7.3.2 Networking

7.3.2.1 LAN

All APS_PEAS computers will be connected to the same LAN and communicate with one another using TCP/IP. All APS_PEAS computers will use a set of communication ports (TBD) for inter-computer communication.

7.3.2.2 Common Services Communication Bus

The APS_PEAS core server will be connected to the telescope common services communication bus using the CSW integration framework.

7.4 APS_PEAS Development Environment

7.4.1 Development Platform

The majority of APS_PEAS development will be on the Java platform and programming language. An IDE is typically used for Java development. The APS_PEAS development team is familiar with the Eclipse IDE, which supports extensibility through plug-ins, including source-code-control system integration with systems such as git or Subversion.

7.4.2 Source Code Control System

It is assumed that APS_PEAS will share the same source code control system with all other telescope software development. APS_PEAS software would be its own project within the source tree.

7.4.3 Procedure Development

7.4.3.1 Procedure Definition

Procedure definitions will be developed by APS research and development engineers and scientists, not necessarily APS_PEAS programmers.

A procedure definition is the step-by-step instructions to APS_PEAS to execute a procedure. Procedure definitions specify the steps, the execution flow of the steps, and the data inputs of each step.

Procedure definitions include a procedure configuration definition, which tells the system how a user is allowed to configure or customize the procedure. Procedure definitions include a procedure summary definition, which defines the data that will appear in the procedure summary report.

7.4.3.2 Procedure Definition Management

The procedure definition management tool described in Section 7.2.5.5 will be used by APS research and development scientists to create and update procedure definitions (see Figure 7-37).

7.4.3.3 Archiving of Procedure Design Data

7.4.4 Analysis Computation Development

The analysis computation development work is part of the APS System Engineering WBS, but the APS_PEAS team will provide the process and tools for analysis computation function management and migration.

7.4.4.1 Analysis Computation Migration

The APS team will be responsible for the development of analysis computations. The APS_PEAS team will be responsible for the migration/integration of those computations to the APS_PEAS execution environment. The APS_PEAS team will be responsible for making sure that the integrity of the computations is not compromised during the migration process.

Much of this work for many of the analysis computations has been performed during the PEAS_PCS project.

7.4.4.2 Analysis Computation Function Management

Analysis computation functions are code that cannot be lost once procedure execution data has been archived against them. Every version of every analysis function will be available for execution by APS_PEAS at any time.

When the APS developer creates an analysis computation or a new version of an analysis computation, the executable code will be persisted in a way that it will not be lost and it will be registered with the procedure creation function as an available procedure step.

At procedure execution time, the analysis computation is located, loaded, and executed as a step within the executing procedure.

Strategies and tools to be used for analysis computation persistence, versioning, and loading by APS_PEAS are TBD.

7.5 Risks

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8 Assembly, Integration and Commissioning

8.1 Assembly, Integration, and Commissioning Procedures

At the start of Assembly, Integration and Verification (AIV), APS will have arrived at the observatory site, and must be unpacked, assembled, and checked out. Initially the APS bench and electronics rack will be installed on the telescope elevation axis, but it can be moved off at a later point if necessary to accommodated instruments that need to utilize that location. During AIV with the telescope, we plan to use APS initially for 14 nights after approximately 100 M1 segments have been installed; but APS is capable of working with any number of segments.

We will start with pointing, acquisition, and tracking tests, and then proceed to align the telescope on-axis. On-axis alignment includes M1 segment tip, tilt, and piston; M2 piston, tip/tilt (or x/y-decenter); M3 tilt and rotation and M1 segment shape control. After the initial commissioning APS will be used after every additional 100 segments are installed to continue to align the telescope optics. When all 492 segments are installed, we will complete the commissioning of the APS on-axis alignment functionality. The next and last step will be to test and commission off-axis wavefront measurements.

8.1.1 APS Needs before AIV

Before APS is shipped to TMT it will have been completely assembled and tested with end-to-end testing using the APS software and a stimulus. In addition, we will have interfaced to TMT telescope software simulators to test our commands and communications. The optics will likely be removed before APS is shipped. All of APS will be shipped directly to the telescope summit.

8.1.2 APS Needs during AIV

After receipt at the summit, we will unpack APS, reinstall and align the optics, and reproduce the tests executed for the pre-ship review. This work should be performed at the summit either in a clean room on the Nasmyth deck or at another summit location. We envision that a crane will pick up the entire APS instrument bench and move it to its operational location with all optics installed, but an alternative is to reassemble APS in its operational location on the Nasmyth platform.

If built up before installation on the Nasmyth platform, APS will need a Class 100,000 clean room of sufficient size to hold the instrument and its associated computers and electronics. A rough order of magnitude for this size is 6 by 8 m. The APS AIV team will need support to install and set up the APS optical bench, computers, and electronics in the room. The APS AIV team will bring all the necessary tools to reassemble and test the APS system, assuming things go without significant problems. If problems are encountered, the APS AIV team will need support in the way of troubleshooting tools (oscilloscopes, standard machine shop tools and equipment, etc.) and time from experts (electrical engineer, machinist). There will also likely be a need to perform further testing of the APS software interface with the TMT software.

Moving APS from the assembly room to its location on the Nasmyth platform will, of course, require significant support from TMT in order to move the instrument physically and to cable up the necessary cooling and electronics.

8.1.3 APS Needs after AIV

8.2 Verification

As the “bottom line” wavefront sensor for the TMT optics, APS provides a variety of useful diagnostics and verification for M1, M2, and M3, but it is not easy for APS to test itself. Nevertheless there are several things that can be done in the way of self-verification. These will be documented prior to arriving at TMT as part of the verification plan that will sign off the DOORS requirements and require in-situ testing on starlight. Below is an overview of what these test comprise of.

Testing of the coarse tilt and coarse phasing alignment is straightforward since the purpose of these functions is to align the segments within the capture range of the fine-tilt and fine-phasing algorithms. Therefore, verification of these coarse functions is a simple matter of checking whether they regularly bring all segments within the required fine capture ranges.

For the fine-tilt and fine-phasing alignment, as well as warping harness adjustment, the testing is more indirect. Clearly, these alignments must converge. This means that when they are run twice in succession, the difference between successive solutions should be within of the measurement accuracies predicted by extrapolating the Keck results.[1] In addition, the edge residuals measured in phasing should be consistent with the values of the residuals predicted from the segment figure measurements.

Verification of the M1/M2 alignment and tomographic alignment functions is complicated because of the difficulty in distinguishing a pathology of APS from a pathology of the telescope. In general, the lookup tables generated from APS data are expected to be appropriately smooth functions of temperature and elevation, but even this weak property can be compromised by intermittent telescope problems. An example of such a problem at Keck is the introduction of focus mode associated with sensor gain changes; without a careful regression analysis these focus mode changes would appear random.

[1] G. A. Chanan, M. Troy, and I. Crossfield, “Predicted Measurement Accuracy of the TMT Alignment and Phasing System,” TMT Docushare: TMT.CTR.PRE.07.007.REL01, February 2007.

9 Issues and Risks

9.1 Key Issues and Challenges

Because of the delays that TMT has had over the last several years, APS has been able to make good progress on several issues that were addressed during the 2007 study. There is now less risk in fabrication of the lenslets, since a lot of progress has been made by industry in this area. Software related issues are also less risky because of the testing that has been done with PEAS-PCS. Their are two remaining challenges though, which are: tomographic alignment and concerns related to early operations. These are now both discussed.

Tomographic Alignment

No simulations have yet 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. This analysis is a high-priority item for the post-CoDR phase. Note that this risk can be mitigated by determining the extent to which disentangling the respective mirror aberrations is actually necessary. The preliminary investigation done to date suggests that there may be a large potential payoff associated with this issue.

First-Light Issues

APS will effectively be the first-light instrument for the telescope. This makes it particularly vulnerable to schedule delays. For example, the integration of PCS on Keck-1 was delayed significantly because the telescope secondary mirror was not delivered on schedule. This in turn had an impact on other instruments down the line that were dependent on the high-quality wavefronts delivered by PCS. Similarly, considerable software had to be written on-site for PCS because the corresponding observatory software was not ready in time; examples of this included data archiving routines and a routine to move the telescope to compensate the pointing after making a tip/tilt correction to the secondary mirror. In general, the APS schedule drives the telescope software schedule in a number of areas: adoption of software and communications standards, provision of common services, etc. Since the APS software is a long-lead item, many of the decision points come surprisingly early in the overall schedule, and the Keck experiences suggest that this may be problematic for the TMT project as well.

As a result of the open-loop philosophy inherent in the TMT design, there is a great premium on the efficiency of APS operations, which take time away from scientific operations. (By contrast, closed-loop alignment would take place in parallel with science.) The timing estimates for APS operations necessarily assume smooth functioning of other telescope systems. If other systems do not function smoothly, the time required to execute various APS procedures can increase greatly. For example, a major inefficiency in broadband phasing at Keck results from the unanticipated (and unexplained) change of primary mirror focus mode whenever the sensor gain is changed.

9.2 Risks

The table below contains the APS Risks, along with their probability, severity, overall rating and mitigation plans. The formal spreadsheet of these is kept here: APS Risk Register (doc#: TMT.CTR.TEC.16.017.DRF01)

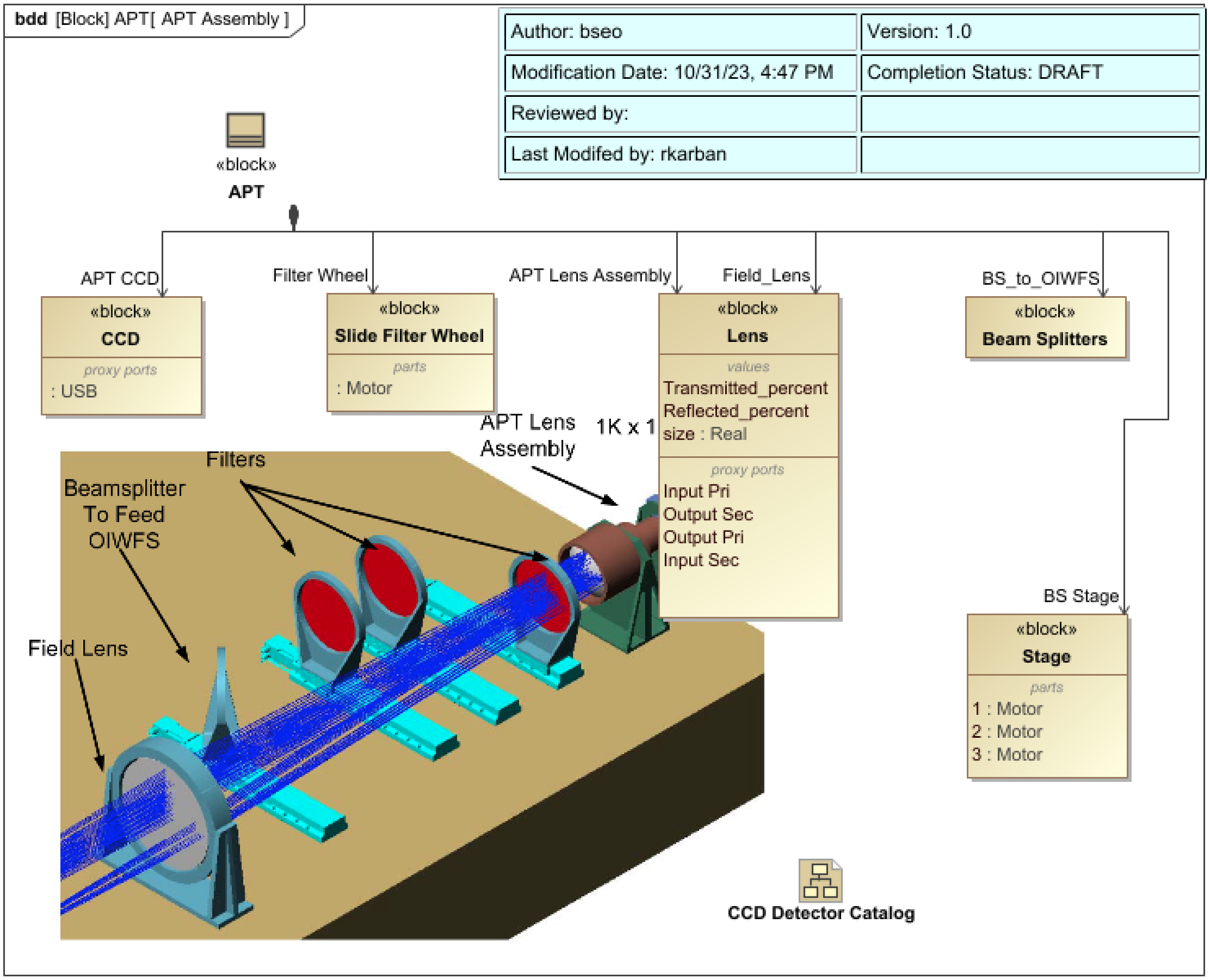
ID	Risk Description	Prob.	Severity	Overall Rating	Mitigation Plans
1	If the TMT/APS schedule continues to slip, then this may result in the loss of key APS staff.	1	1	1	A. Mentor potential replacements (requires additional funding). B. Continue good documentation of current work.
2	If the current mitigation strategy for dealing with Gary Chanan's retirement is insufficient, then there will be an increase impact on schedule and budget.	2	2	2	The current mitigation is for Gary to develop and document the key algorithms as well as for Mitchell to learn as much as possible about them.
3	If the required APS main Shack-Hartmann CCD does not meet specifications or delivery schedule, then there will be an increase in schedule and budget.	3	2	2	Purchase CCD early and test performance and interfaces.
4	If the required APS main Shack-Hartmann CCD does not meet specifications, then APS will have degraded performance	3	1	2	A. Use a smaller CCD and deal with image crowding and/or sample fewer subimages per segment. B. Use the large CCD as is, but develop mitigation strategies as needed.
5	If APS development remains significantly behind other systems, then this may necessitate interface rework	3	2	3	Concentrate efforts on development and documentation of interfaces.
6	If the current problems with narrowband phasing take more resources to understand than budgeted, then there will be an increase in budget.	1	2	2	Continue to work on the problem as a high-priority.

7	If the requirements on M1CS sensor calibration require more observing time, then APS post segment exchange observing time will increase.	1	3	2	Work with the M1CS team to determine requirements on M1CS sensor calibration and estimate needed observing time.
8	If the incomplete mirror algorithm combined with the automation of handing > 30,000 subimages proves to be more difficult than estimated, then there will be an increase in schedule and budget.	3	2	2	A. Test algorithms at Keck. B. Test algorithms on simulated images. C. Test algorithms on phasing testbed.
9	If the LOWFS implementation is different from our current assumptions, then there will be an increase in schedule and budget.	2	1	2	Work to get a baseline design and agreement with TMT and ITCC.
10	If at APS first light other sub-systems fail to meet their performance and/or functional requirements, then there will be a significant increase in required APS engineering support.	1	3	3	A. Design PEAS to be flexible. B. Insure adequate APS engineering support.
11	If the CSW large image transfer and store service fails to met performance requirements, then the time to perform APS alignment will exceed requirements.	3	2	3	A. Insure protype implementation meets requirements. B. Implement transfer and storage outside of CSW.

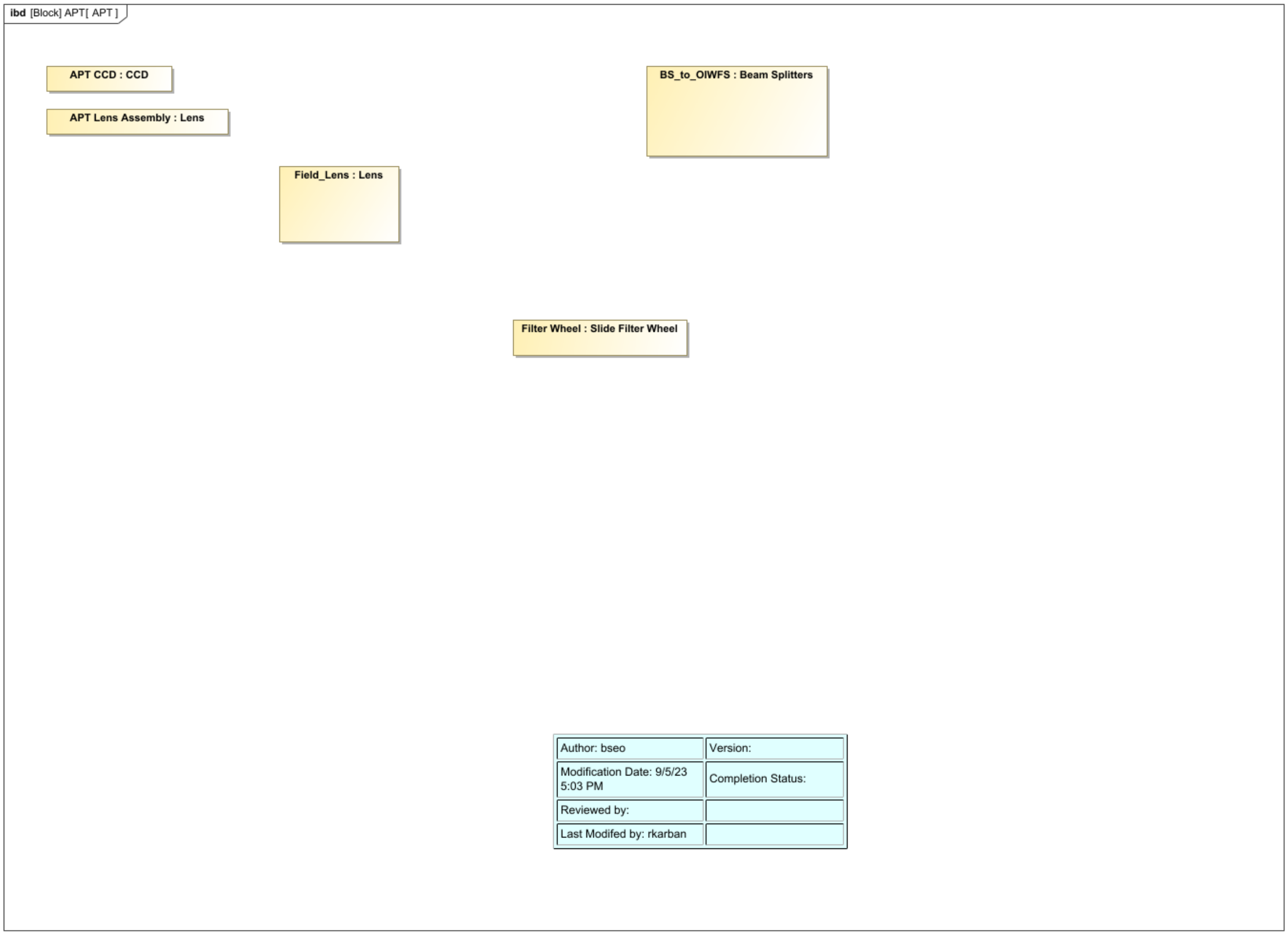
10 Hardware Decomposition and Interfaces

- Analog Outbox
- APT

APT Assembly

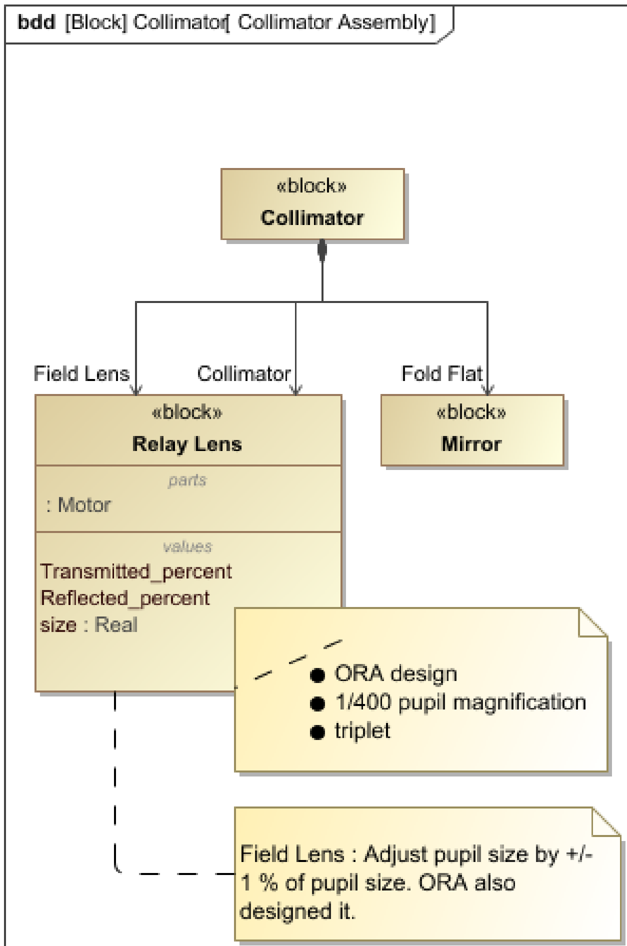


APT



- APT Control S/W
- Beam Splitters
- BN sensor
- BS
- Camera Ctrl
- CCD
- CCD Detector
- Collimator

Collimator Assembly



Author: bseo	Version:
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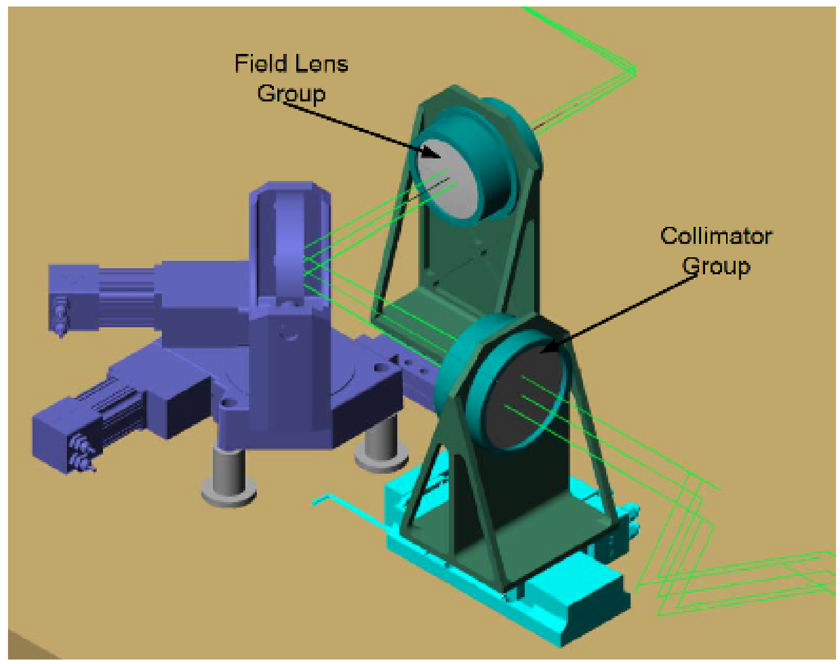
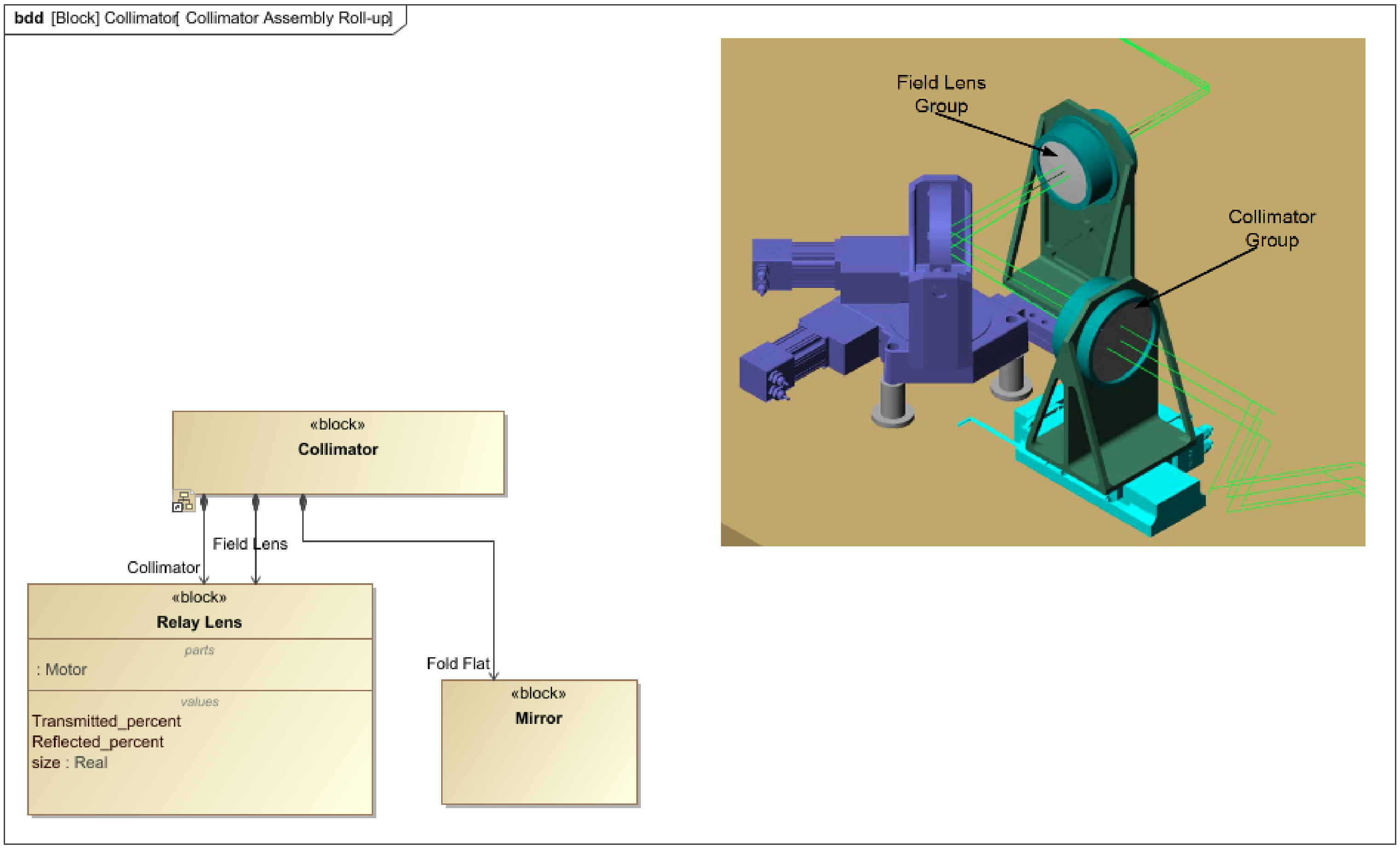
Last Modifed by: rkarban	

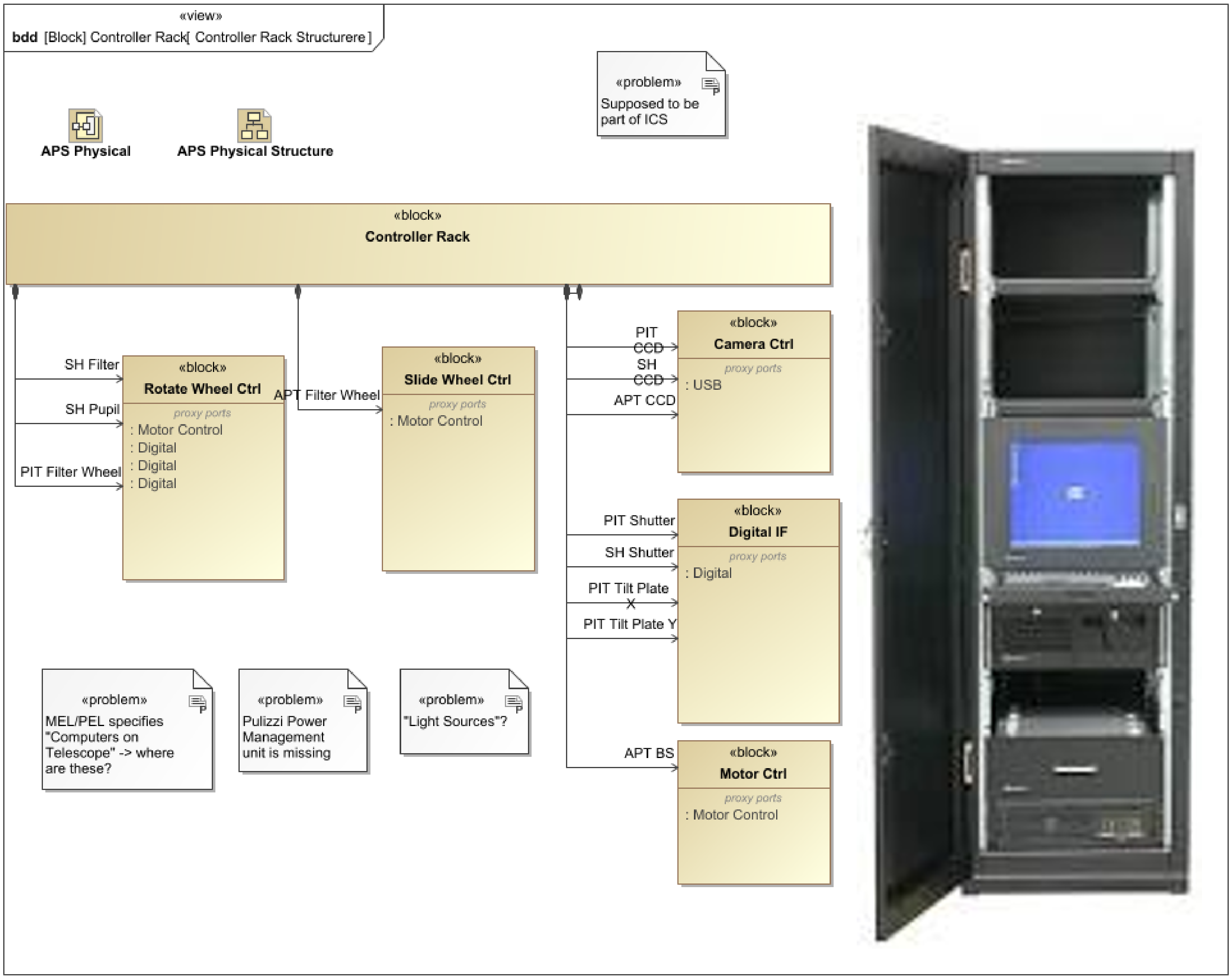


Collimator Assembly Roll-up



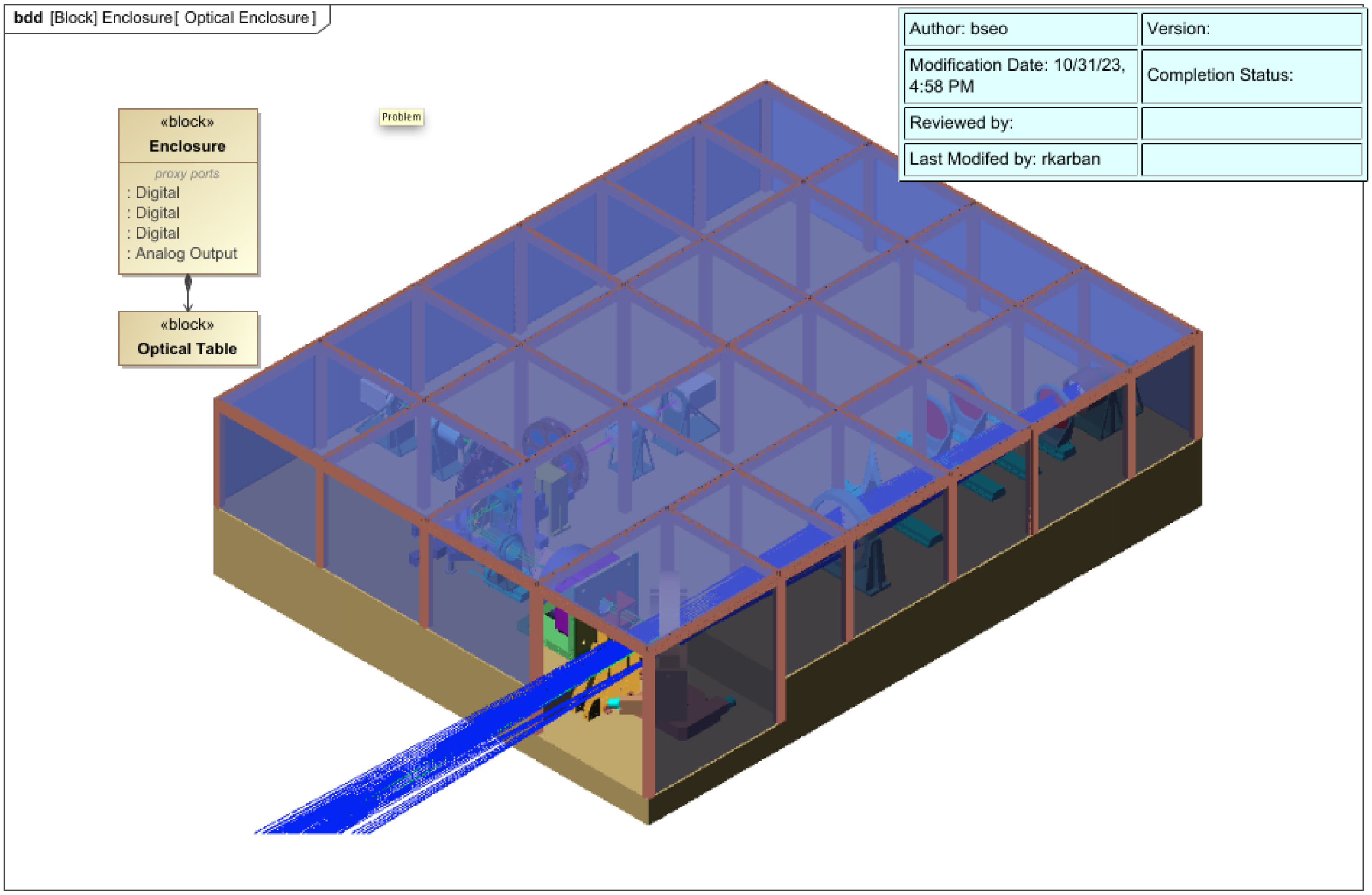
- Collimator Lens
- Controller Rack

Controller Rack Structurere



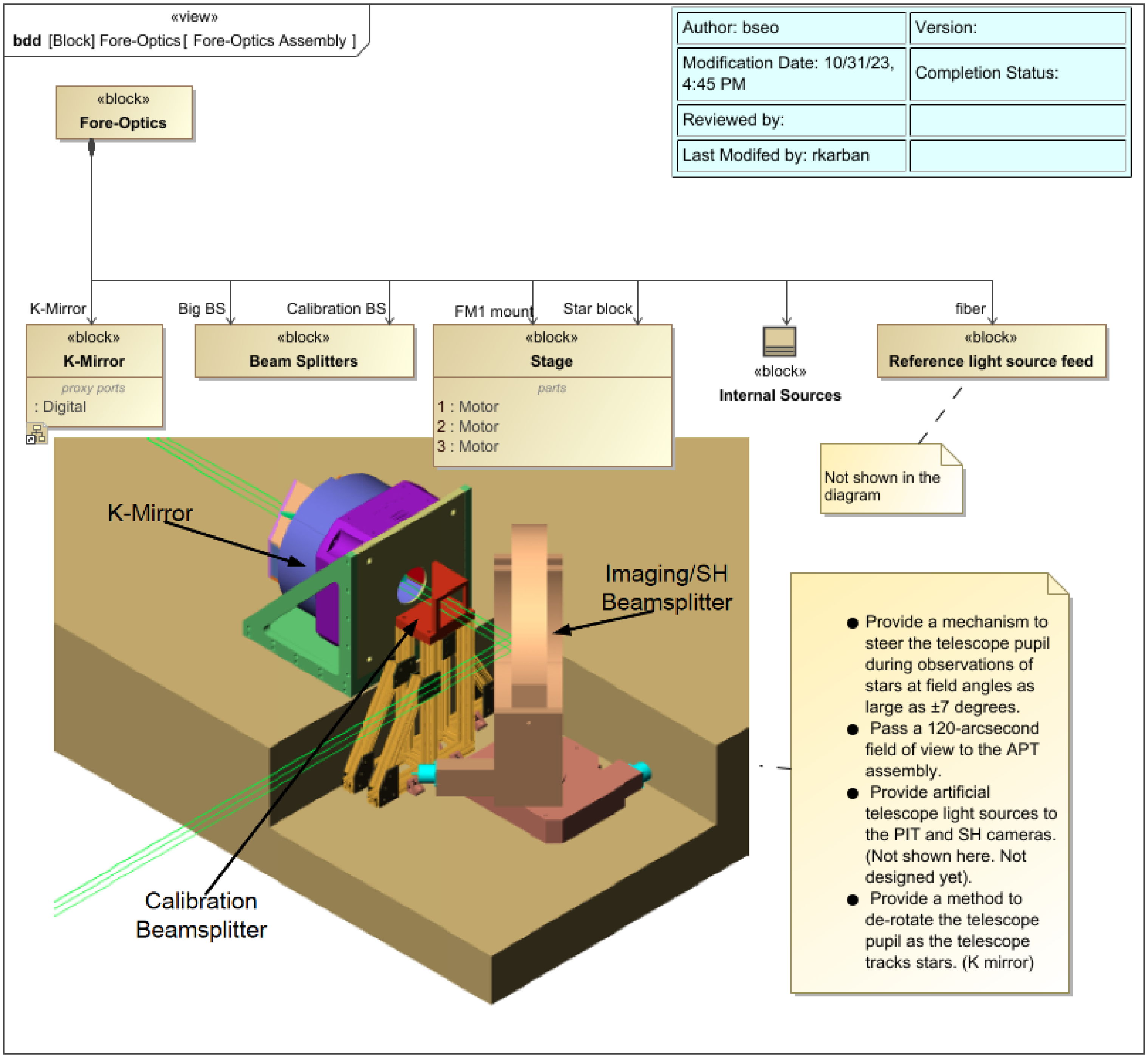
- Deformable Mirror
- Deformable Mirror Segments
- Detent
- Digital IF
- Enclosure

Optical Enclosure



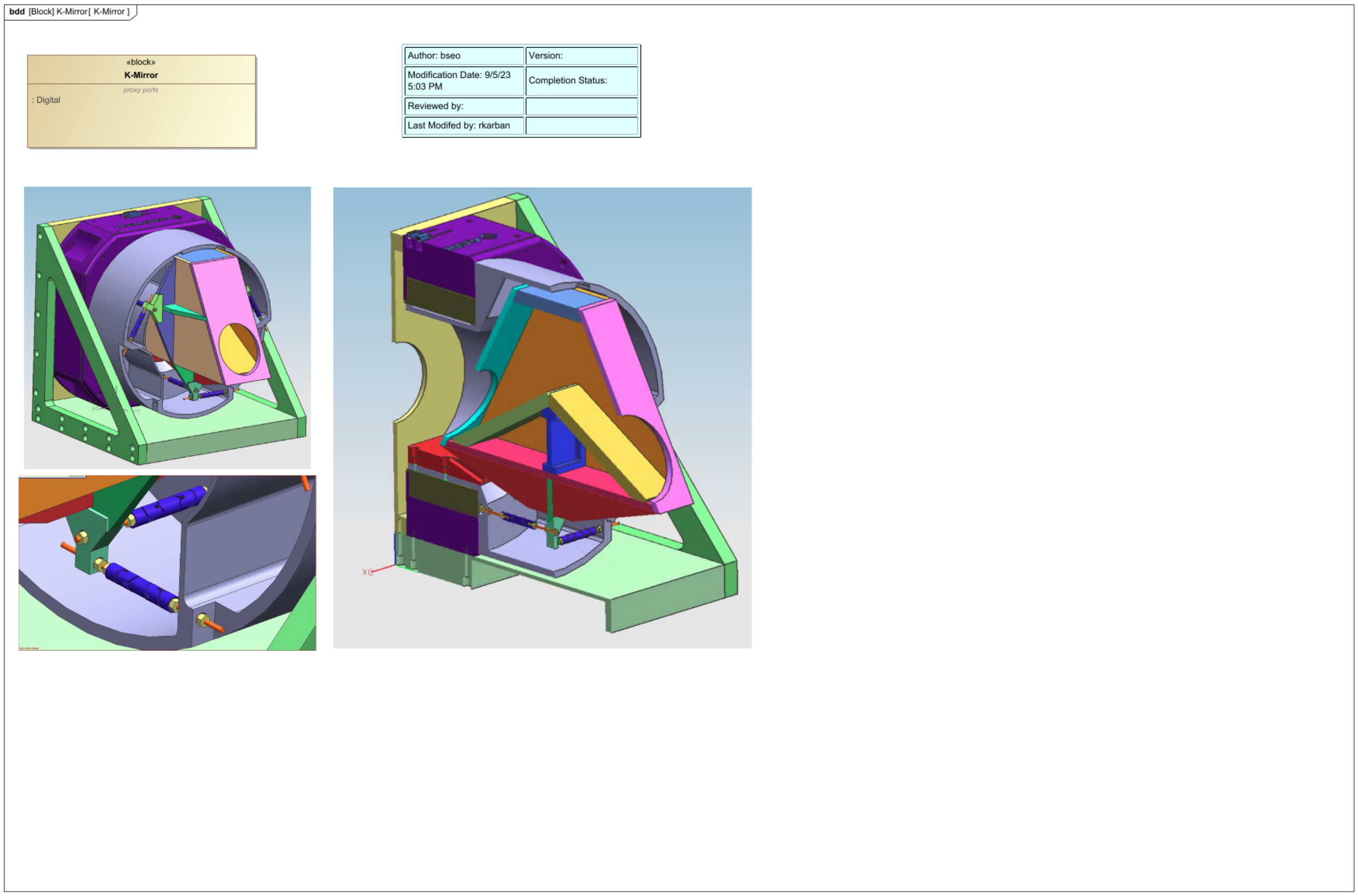
- Field_Lens
- Filter Control S/W
- Filter Grating HCL
- Flat Mirror
- Fold Flat
- Fore-Optics

Fore-Optics Assembly



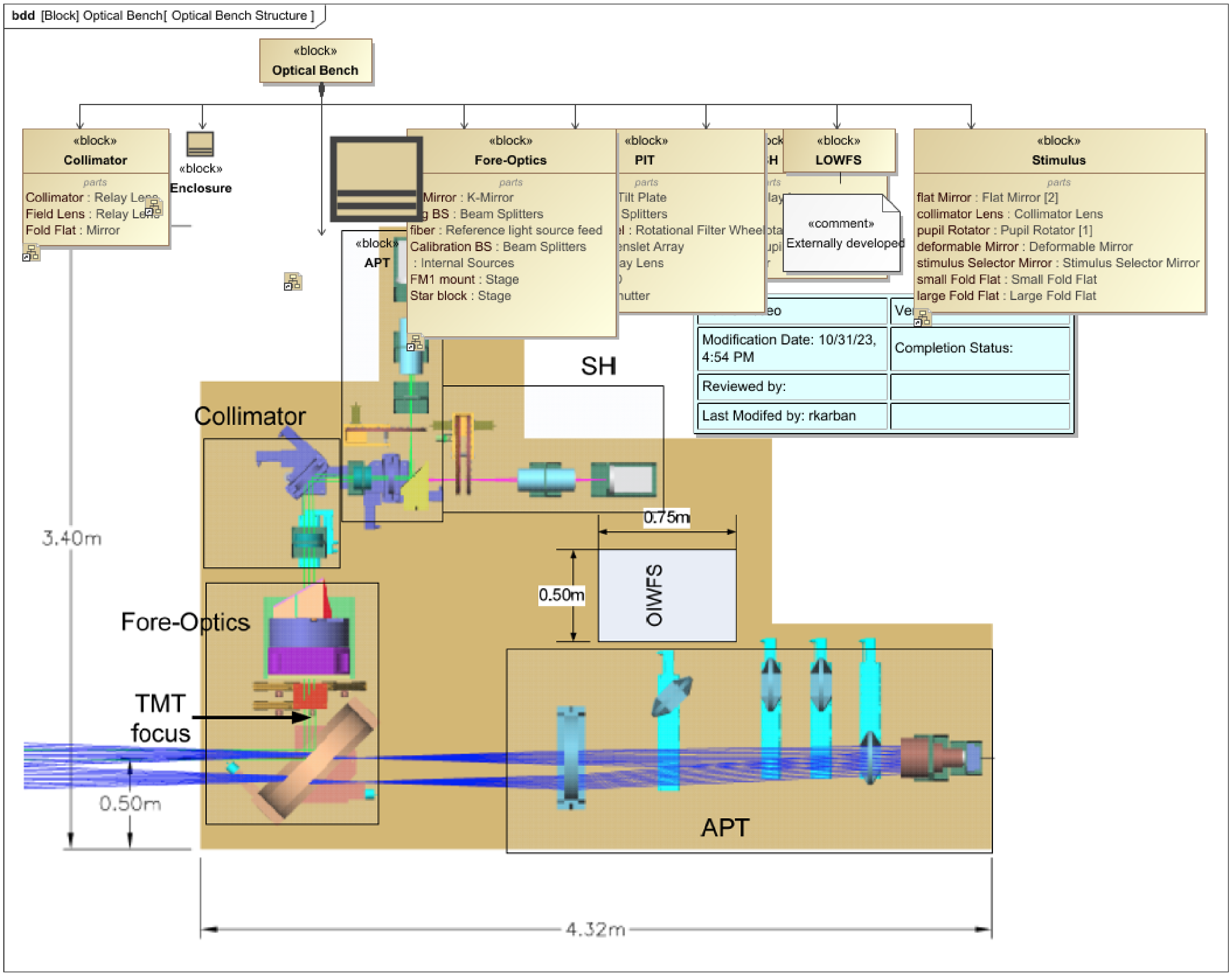
- FoV
- Internal Sources
- K-Mirror

K-Mirror

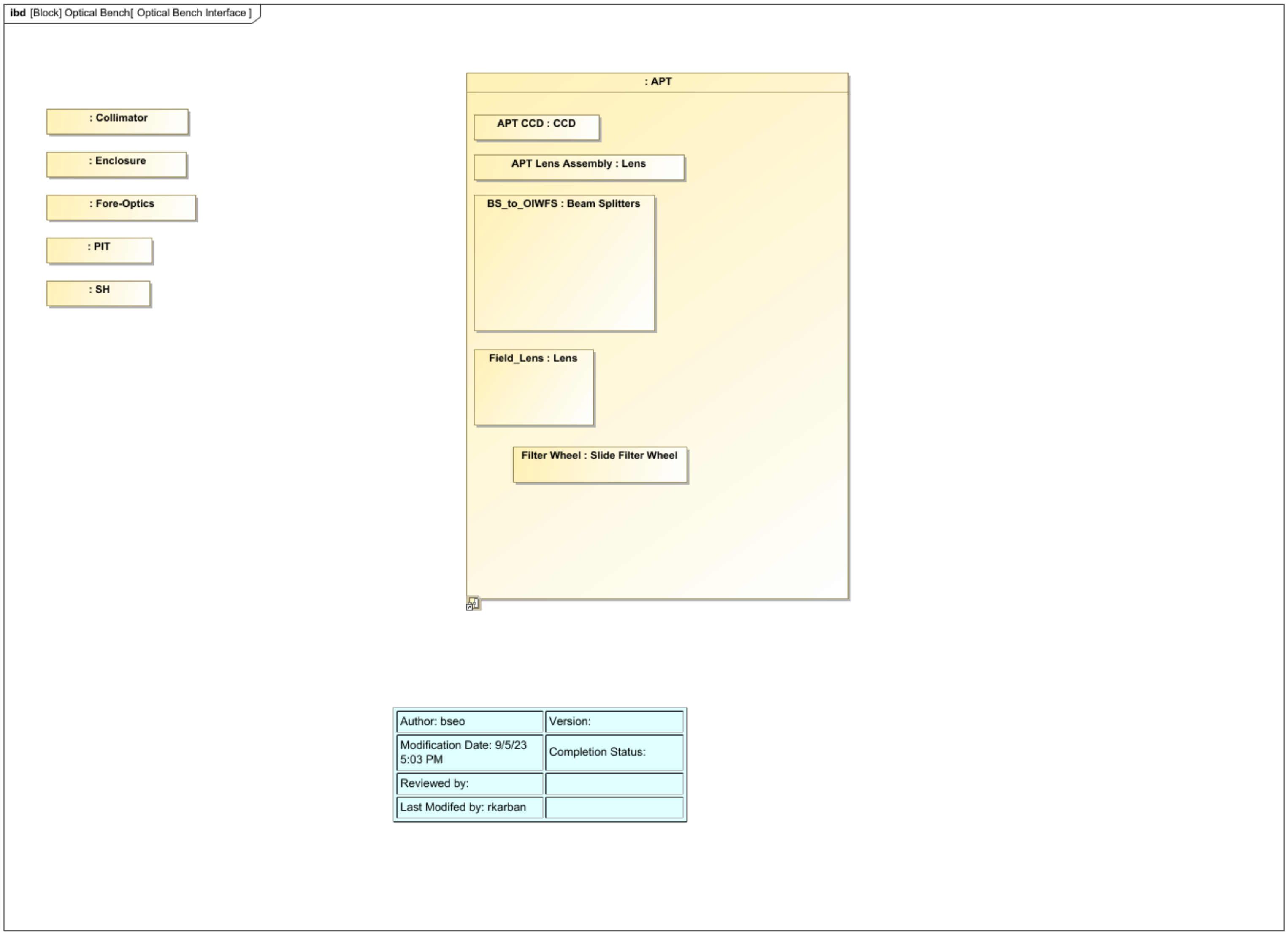


- Large Fold Flat
- Lens
- Lens
- Lenslet Array
- Light Source
- LOWFS
- Mirror
- Motor
- Motor Ctrl
- Optical Bench

Optical Bench Structure



Optical Bench Interface



- Optical Table
- PIT

PIT Assembly

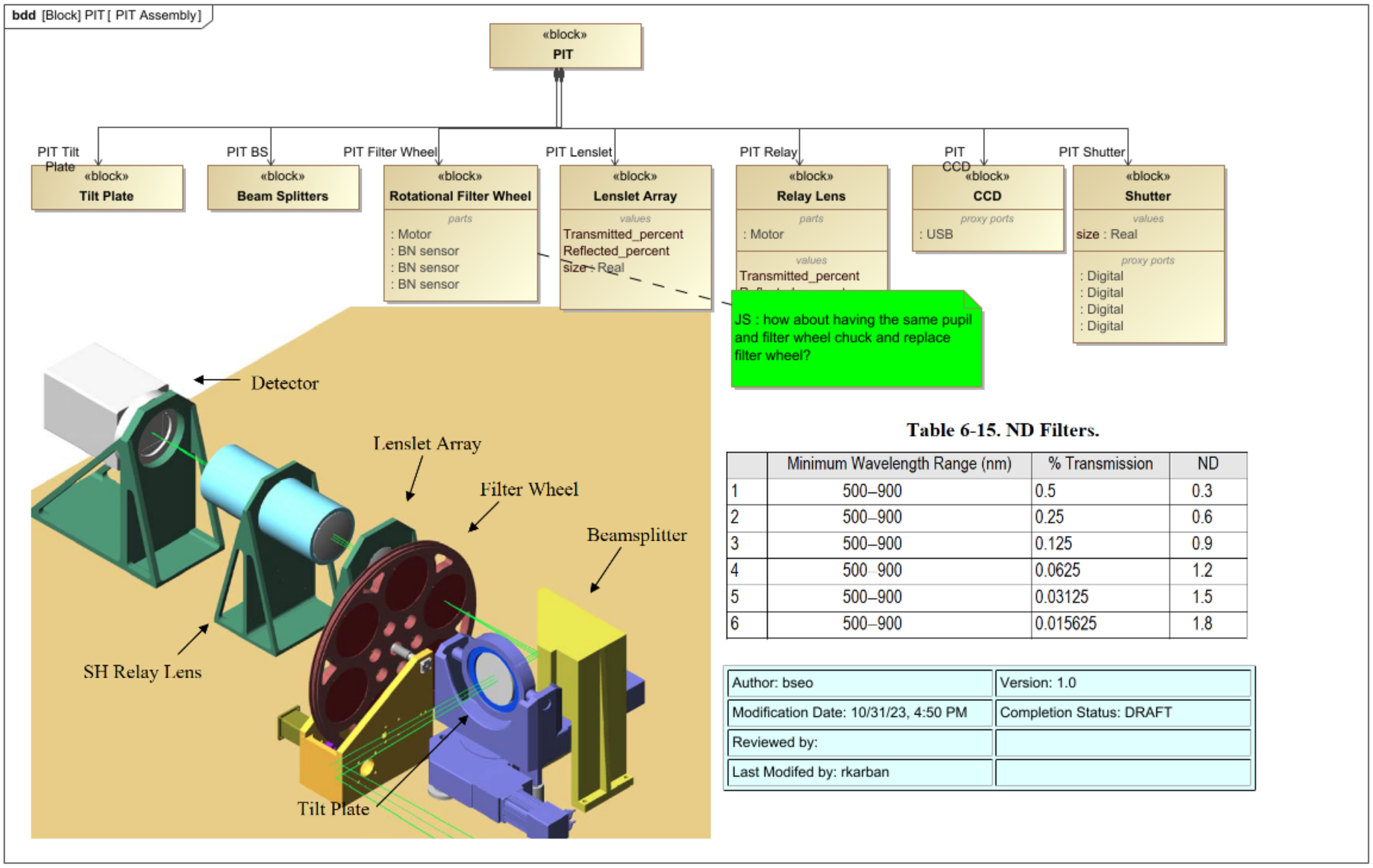


Table 6-15. ND Filters.

	Minimum Wavelength Range (nm)	% Transmission	ND
1	500–900	0.5	0.3
2	500–900	0.25	0.6
3	500–900	0.125	0.9
4	500–900	0.0625	1.2
5	500–900	0.03125	1.5
6	500–900	0.015625	1.8

Author: bseo	Version: 1.0
Modification Date: 10/31/23, 4:50 PM	Completion Status: DRAFT
Reviewed by:	
Last Modifed by: rkarban	

- PIT CCD Detector
- PIT Control S/W
- Pupil
- Pupil Rotator
- Pupil Wheel
- Reference Beam
- Reference light source feed
- Relay Lens
- Rotate Wheel Ctrl
- Rotational Filter Wheel
- SH

SH Assembly

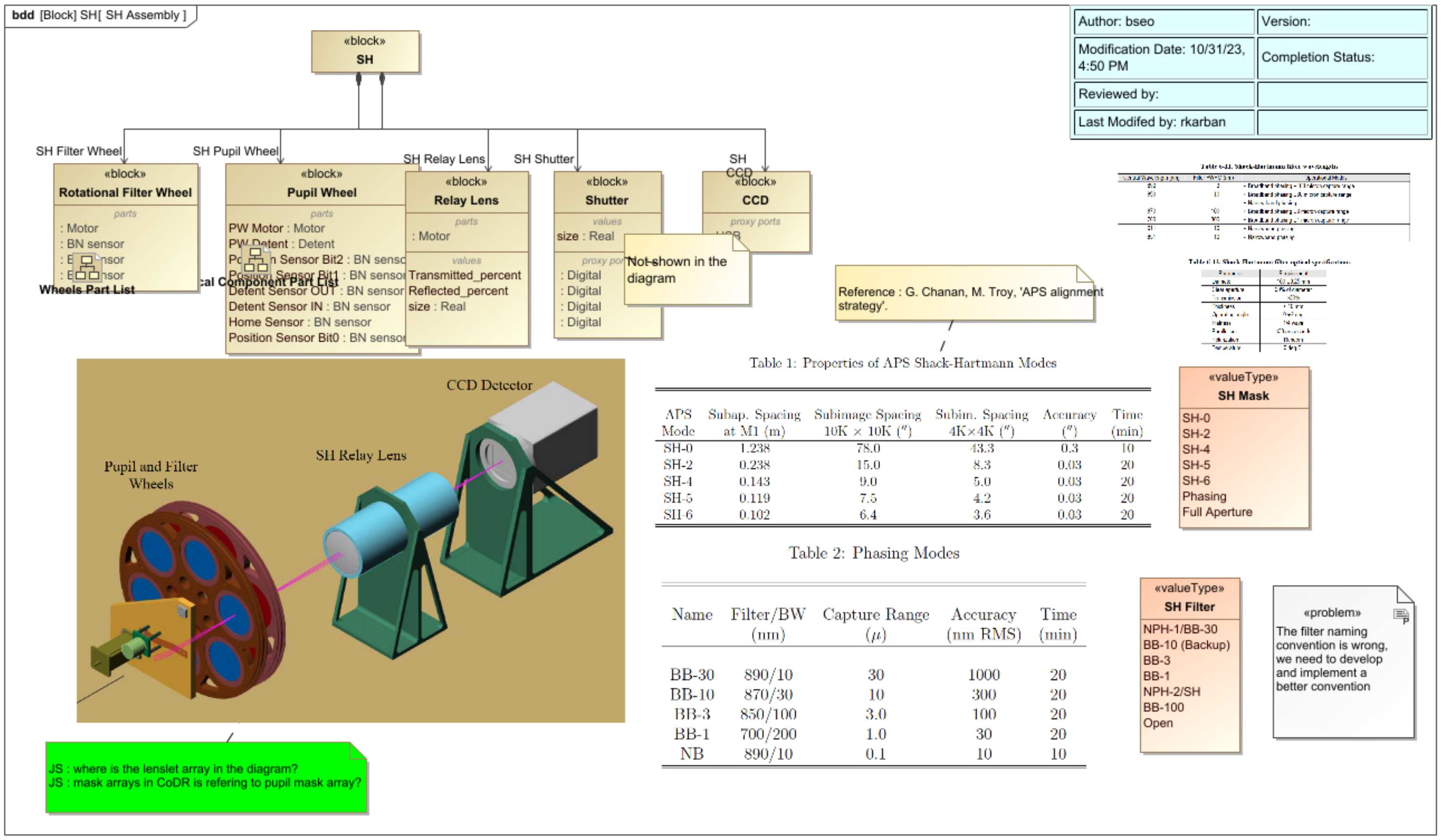


Table 1: Properties of APS Shack-Hartmann Modes

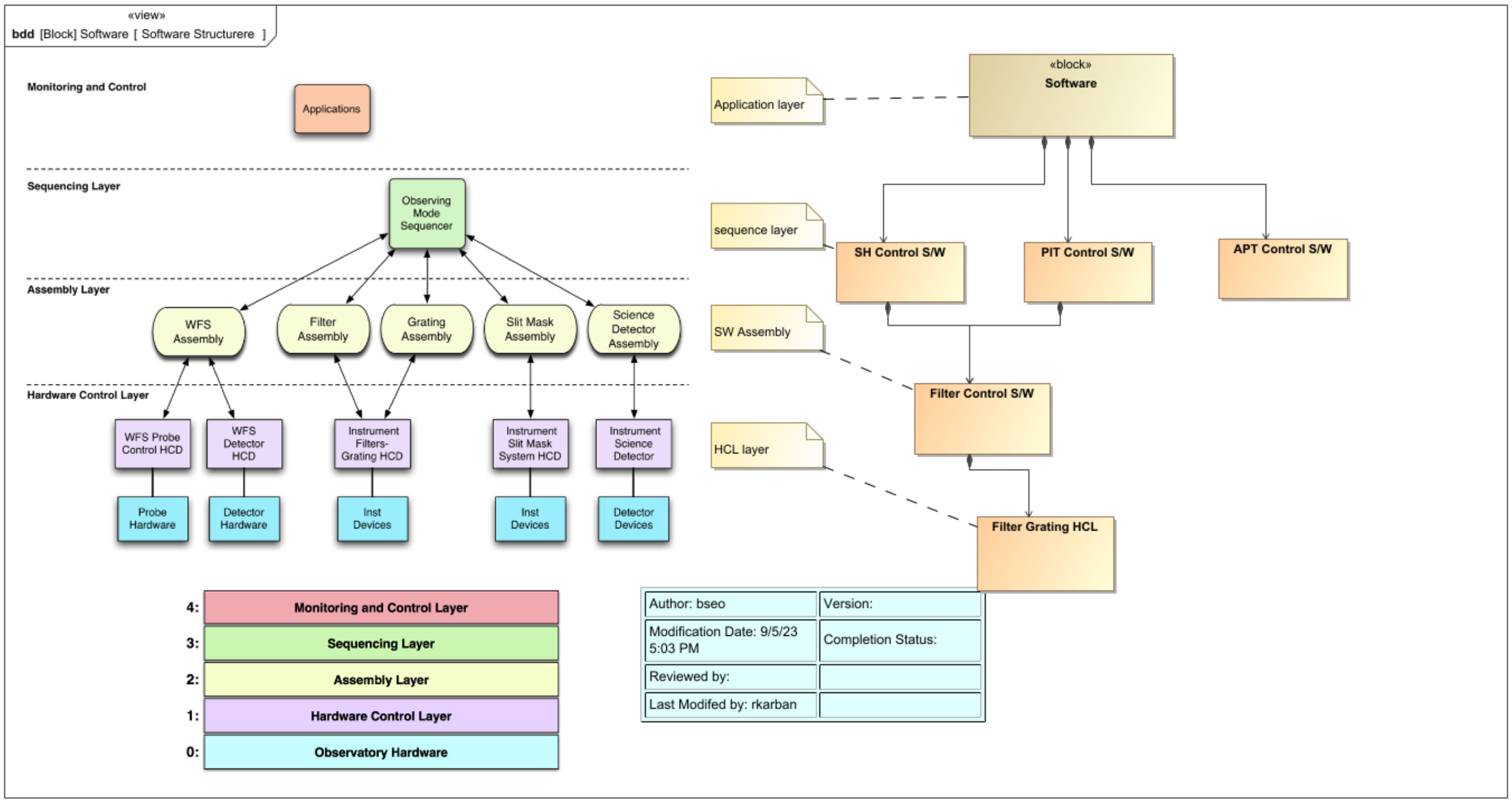
APS Mode	Subap. Spacing at M1 (m)	Subimage Spacing 10K × 10K (″)	Subim. Spacing 4K×4K (″)	Accuracy (″)	Time (min)
SH-0	1.238	78.0	43.3	0.3	10
SH-2	0.238	15.0	8.3	0.03	20
SH-4	0.143	9.0	5.0	0.03	20
SH-5	0.119	7.5	4.2	0.03	20
SH-6	0.102	6.4	3.6	0.03	20

Table 2: Phasing Modes

Name	Filter/BW (nm)	Capture Range (μ)	Accuracy (nm RMS)	Time (min)
BB-30	890/10	30	1000	20
BB-10	870/30	10	300	20
BB-3	850/100	3.0	100	20
BB-1	700/200	1.0	30	20
NB	890/10	0.1	10	10

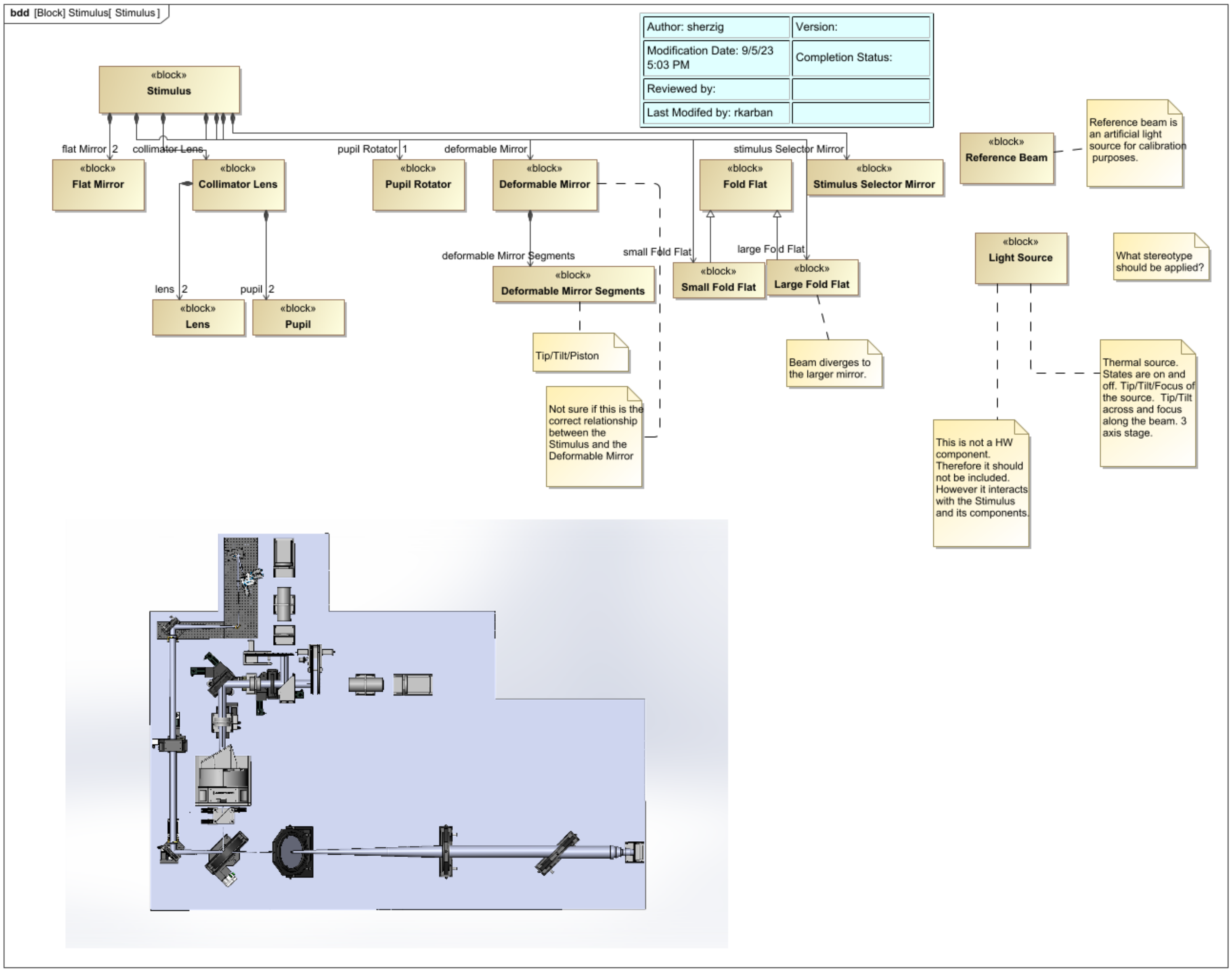
- SH Control S/W
- SH Mask Array
- Shutter
- Slide Filter Wheel
- Slide Wheel Ctrl
- Small Fold Flat
- Software

Software Structurere



- Stage
- Stimulus

Stimulus



- Stimulus Selector Mirror
- Tilt Plate

10.1 interface table

- Collimator

Interfaces Table

#	Name	Description	Interfaces
1	Relay Lens		Motor Control
2	Mirror		

- Fore-Optics

Interfaces Table

#	Name	Description	Interfaces
1	K-Mirror		
2	Beam Splitters		
3	Reference light source feed		
4	Internal Sources		
5	Stage		Motor Control

- APT

Interfaces Table

#	Name	Description	Interfaces
1	Lens		
2	Beam Splitters		
3	Slide Filter Whe el		Motor Control
4	CCD		
5	Stage		Motor Control

- SH

Interfaces Table

#	Name	Description	Interfaces
1	Relay Lens		Motor Control
2	CCD		
3	Rotational Filter Wheel		Motor Control BN Sensor Rea ding
4	Pupil Wheel		Motor Control Detent Reading BN Sensor Rea ding
5	Shutter		

- PIT

Interfaces Table

#	Name	Description	Interfaces
1	Tilt Plate		
2	Beam Splitters		
3	Rotational Filter Wheel		Motor Control BN Sensor Reading
4	Lenslet Array		
5	Relay Lens		Motor Control
6	CCD		
7	Shutter		

- Enclosure

Interfaces Table

#	Name	Description	Interfaces
1	Optical Table		
2	Digital		
3	Analog Output		

- LOWFS
- Stimulus

Interfaces Table

#	Name	Description	Interfaces
1	Flat Mirror		
2	Collimator Lens		
3	Pupil Rotator		
4	Deformable Mirror		
5	Stimulus Selector Mirror		
6	Small Fold Flat		
7	Large Fold Flat		

10.2 connection table

10.3 Interface Counts

Interface Totals

#	Interface Type	Number of Interfaces
1	Analog Data	3
2	Analog Input	8
3	Analog Output	9
4	BN Sensor Reading	1
5	Detent Reading	1
6	Digital	17
7	Digital Data	2
8	Ethernet	6
9	FilterWheelCable	0
10	Motor Control	9
11	P_in	3
12	P_inout	5
13	P_out	3
14	USB	4

11 References