TMT-APS OCDD

Author: Robert Karban (rkarban)
Date: Oct 31, 2023
Type: Document report

Document Information:

Last published at 2:55 PM on Oct 24, 2023
by Robert Karban (rkarban)

Project Information:

TMT

Last modified at 4:20 PM on Oct 27, 2023
by Robert Karban (rkarban)

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TMT-APS OCDD

1 Introduction

This document describes the use cases and activities for the Alignment and Phasing System (APS). Use cases are high level procedures which describe the various telescope alignments and calibrations to be performed using APS. In general, use cases are made up of one or more *activities*. Examples of use cases are "Post Segment-Exchange Alignment" and "APS Pre-observing Internal Calibrations". Example activities include "Coarse Tilt Alignment", "Broadband Phasing", and "Narrowband Phasing".

This document does not cover use cases that are specific to Assembly, Integration and Verification (AIV) or commissioning. Those cases will be detailed in the APS integration and test plan. In addition, this document does not cover off-nominal use cases. Off-nominal uses cases will be addressed in the final design phase.

1.1 Introduction

The goal of this document is to define how APS will operate to align and phase the telescope. These use cases and activities will also be used to help develop and verify interfaces to external sub-systems, APS requirements, APS software requirements and requirements on other telescope sub-systems.

1.2 Organization of the OCDD

This document is organized as follows. System Description provides an overview of APS and the modeling approach for the use cases and activities. Use Cases provides a detailed look at the high level APS use cases. The purpose, entrance, exit and execution time requirements as well as the use case itself are all described. High Level Activities provides a description of the high level activities which make up the APS higher level use cases. Lower Level Activities provides a description of lower level activities and these will be further developed in the next phase of APS development.
PFC Use Cases provides a list of the use cases that relate to the Prime Focus Camera (PFC) and will be used at TMT before M2 and M3 are installed.

1.3 Applicable Documents

N/A

1.4 Reference Documents

RD1 – APS Design Description Document (TMT.CTR.TEC.16.016)

RD2 – Observatory Architecture Document, (TMT.SEN.DRD.05.002)

RD3 - Alignment of TMT Using Only On-Axis Wavefront Measurements (TMT.SEN.PRE.13.039)

RD4 - Optical Modeling Error Manual (TMT.SEN.TEC.13.003)

RD5 - APS Algorithms Book (TMT.CTR.TEC.15.022)

RD6 - WH Influence Function Uncertainty Impact: Use of on-Sky APS Measurements (TMT.CTR.PRE.15.073)

RD7 - APS Photometry Budget (TMT.CTR.TEC.15.161)

RD8 - WH Influence Function Uncertainty Impact: Use of on-Sky APS Measurements (TMT.CTR.PRE.15.073)

RD9 - APS Acquisition and Guiding Workflow (TMT.CTR.TEC.21.113)

RD10 - ICD TCS-APS SDB ---- Detailed Software Interface Control Document Telescope Control System to Alignment and Phasing System (TMT.CTR.ICD.19.003)

RD11 - M1CS Test Cases using the Prime Focus Camera (TMT.CTR.COR.20.026)

RD12 - APS PEAS Architecture Document (TMT.CTR.TEC.21.001)

RD13 - The OpenSE Cookbook: A practical, recipe based collection of patterns, procedures, and best practices for executable systems engineering for the Thirty Meter Telescope (TMT.CTR.JOU.18.005)

RD14 - Verifying Interfaces and Generating Interface Control Documents for the Alignment and Phasing Subsystem of the Thirty Meter Telescope from a System Model in SysML (TMT.CTR.JOU.18.004)

RD15 - Creating systems engineering products with executable models in a model-based engineering environment (TMT.CTR.JOU.16.001)

1.5 Abbreviations

AIV	Assembly, Integration, and Verification
APS	Alignment and Phasing System

APT	Acquisition Pointing and Tracking
BDD	Block Definition Diagram
CAGS	Commissioning Acquisition and Guiding System
CoDR	Conceptual Design Review
CSW	Common Software
DDD	Design Description Document
DM	Deformable Mirror
DMS	Data Management System
ESW	Executive Software
FMEA	Failure Mode and Effects Analysis
FOV	Field of View
ICD	Interface Control Document
ICS	Instrument Control System
LOWFS	Low Order Wavefront Sensor
M1	Primary Mirror

M1CS	Primary Mirror Control System
M2	Secondary Mirror
M3	Tertiary Mirror
OOSEM	Object-Oriented System Engineering Method
ORA	Optical Research Associates
PCS	Phasing Camera System
PDPP	Product Data Package Definition
PDR	Preliminary Design Review
PEAS	Procedure and Executive Software
PFC	Prime Focus Camera
PIT	Pupil and Image Tracking
PSH	Primary/Main Shack-Hartmann
SH	Shack-Hartmann
SMR	Spherically Mounted Retroreflector
SysML	Systems Modeling Language

TCS	Telescope Control System
TMT	Thirty Meter Telescope
TOFS	Telescope Optical Feedback System

2 System Description

2.1 Overview

The Alignment and Phasing System (APS) is a Shack-Hartmann wavefront sensor responsible for the sensing and commanding of the pre-adaptive-optics wavefront quality of the Thirty Meter Telescope (TMT). To produce wavefronts of acceptable quality, APS will adjust the following parameters as required: segment pistons and tip/tilts, segment surface figure (via warping harness adjustments), rigid body degrees of freedom M3, and three of the rigid body degrees of freedom of M2 (piston, tip, and tilt or alternatively piston, *x* translation, and *y* translation).

The APS design and concept is based upon that of the Phasing Camera System (PCS), which plays a similar role for the Keck Observatory telescopes. APS will use algorithms similar, but more generalized and improved, 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 the appropriate calibrations can be constructed for nominal elevation and temperature corrections. (Note, however, that the construction of these calibrations from the APS data is not itself an APS responsibility.) A more detailed description of APS is available in RD1.

2.2 Responsibilities

2.2.1 APS Development Team

Responsibility for implementation and technical support of the APS will reside with a team led by the Principal Investigator with a team of engineering specialists, primarily at JPL. This team will work 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 level of support will gradually decrease 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, 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.

2.2.2 TMT Operations Staff

Observatory engineering staff are planned to be available to assist in installation of the APS, e.g., for the movement and positioning of heavy components, 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 telescope operator. The telescope operator directly controls the APS during its operation. The optical scientist is the 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.

2.3 Modeling Approach and Context

The information about APS operational scenarios in this document was captured by following the Object-Oriented System Engineering Method (OOSEM) in the Systems Modeling Language (SysML) and leveraging executable models. This approach allows simulation of a system model in terms of temporal constraints and mass and power consumption to verify that it meets requirements. More information about the modelling of APS with SysML can be found in RD13, RD14 and RD15.

The operation of APS is driven by the APS Procedure Executive and Analysis Software (APS-PEAS), which coordinates activity of the instrument through the APS Instrument Control System (APS-ICS) software as well as the Telescope Control System (TCS) and M1 Control System (M1CS) interfaces. The diagrams in this document describe instrument operation in detail through the use of diagrams, which are directly referenced from the SysML system model. The diagrams are of two types, representing a hierarchy of detail in the behavioral description:

- State Machine Diagrams, which show the high level-behavior of the APS system when executing one of a number of use cases. These use cases are described in Use Cases.
- Activity Diagrams, which show detailed behavior of APS-PEAS when executing the steps of each use case. These are separated in to High Level and Lower Level Activities, and described in High Level Activities and Lower Level Activities respectively.

As described in RD14 SysML can be used to verify the interfaces against existing ICDs (or to generate new ones if desired). This SysML model already contains the majority of the APS related ICD details, but future work remains to verify and correctly map names of events.

The model can also be used to calculate the time for execution of any sequence of events, as it includes time estimates for external commands as well as computations. In this way we can verify that APS meets it's various time execution requirements results are presented in Use Cases.

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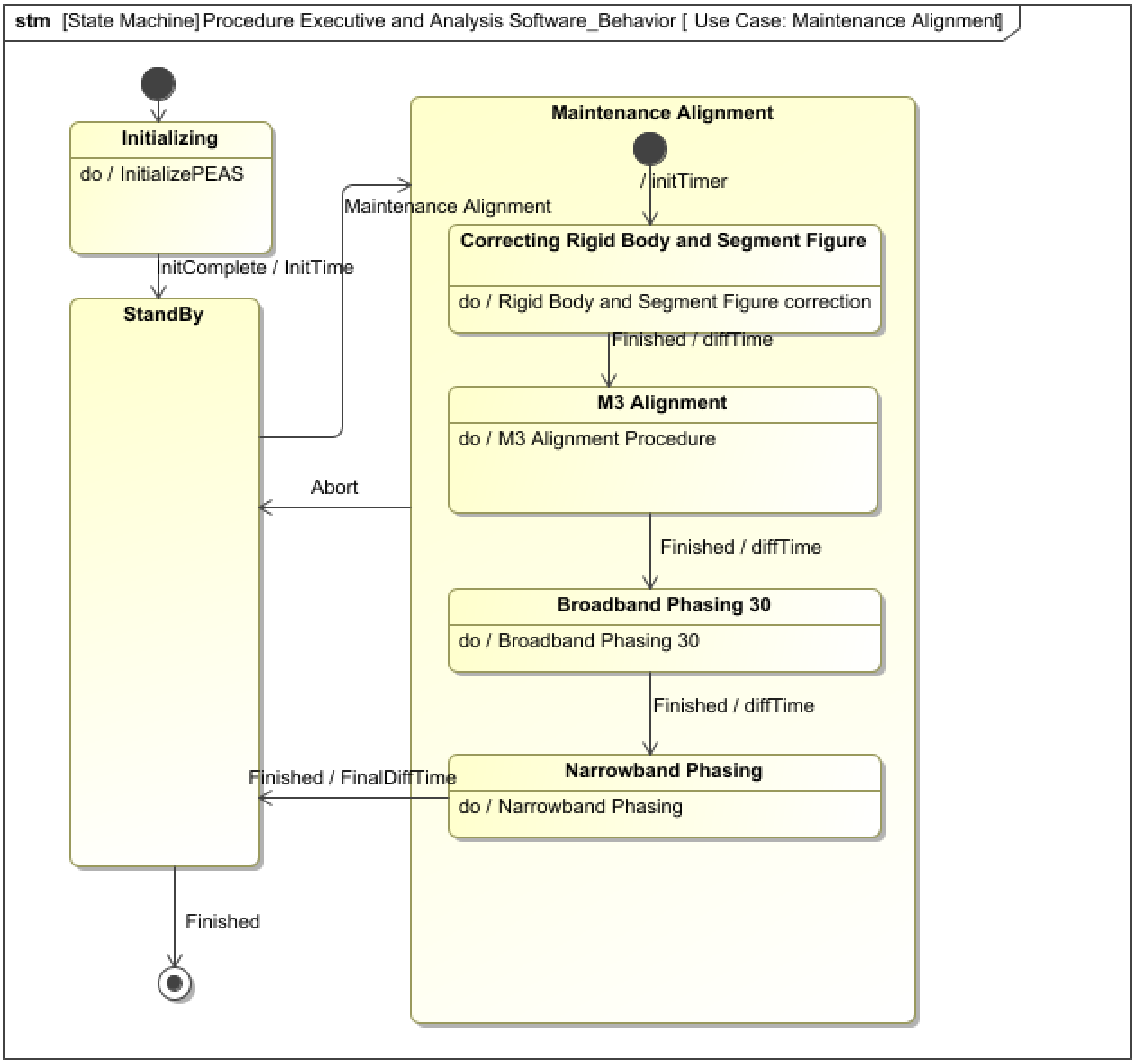
2.3.1 State Machine Diagrams

The high-level behavior of APS-PEAS is captured in the form of state machines. Each major operational scenario (use case) is described by a PEAS state. Every major step in such a scenario corresponds to a sub-state.

Figure 1 shows an example of a state machine diagram illustrating the Maintenance Alignment use case. Each state or substate is labelled in bold, and arrows representing transitions between states are labelled with the name of the signals that trigger those transitions. Each substate references a *do* activity, which is a detailed sequence of behaviors described by an associated activity diagram.

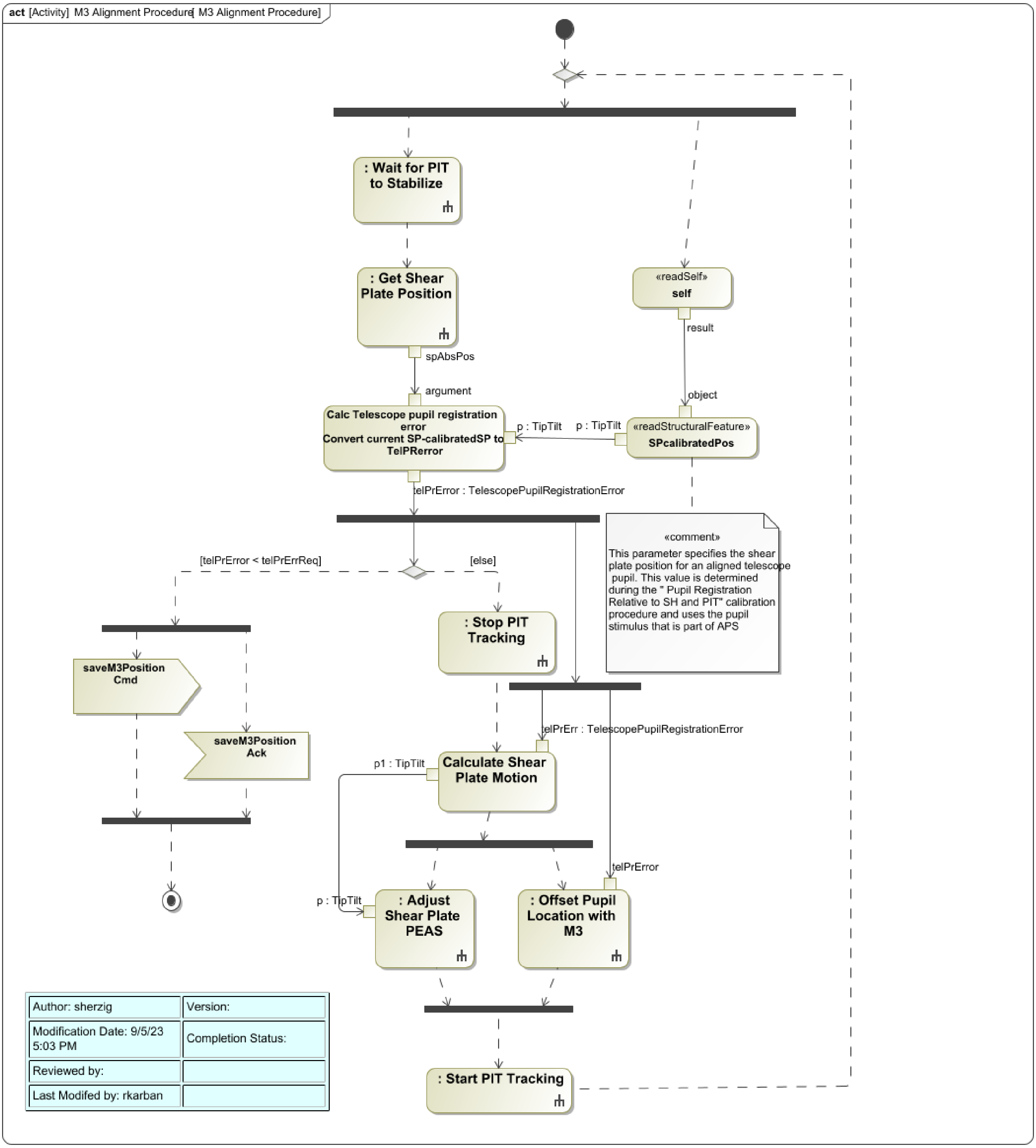
Use Case: Maintenance Alignment



2.3.2 Activity Diagrams

Detailed descriptions of APS activities are represented as SysML Activity Diagrams. An example activity is shown in Figure 2. The solid black circle represents the starting node of control flow, and dotted lines indicate the sequence of flow. Solid lines represent control flow that also includes a transfer of data. Each rounded rectangle represents a sub-activity, which in some cases has its own activity diagram. Horizontal black bars indicate a split of control flow into parallel activities, or subsequent merge of parallel paths. Arrow-shaped boxes indicate a signal is sent from APS-PEAS to APS-ICS, TCS or M1CS, while banner-shaped boxes indicate that APS-PEAS will wait for a signal before proceeding. Diamond shapes represent logic gates that control activity flow based on the evaluation of logical expressions, shown in the labels of the arrows that branch from them. The white circle with a black dot indicates the end of the activity.

M3 Alignment Procedure



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.

3.1 Post Segment-Exchange Alignment

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.

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.

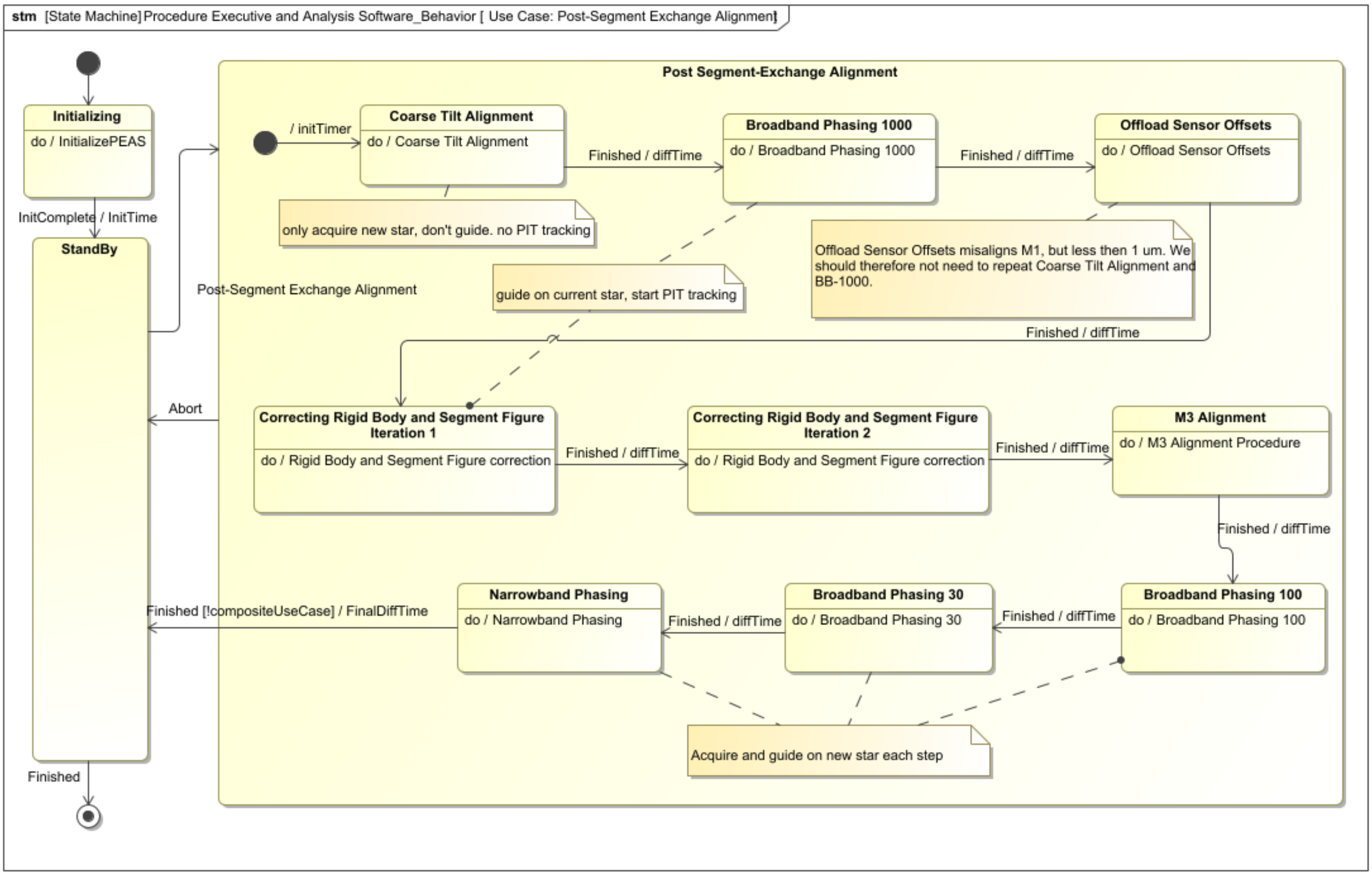
3.1.3 Typical Observing Parameters and Operating Conditions

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.

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.

Use Case: Post-Segment Exchange Alignment



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	

3.2 Calibrate M1CS Edge Sensors

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.

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.

3.2.3 Typical Observing Parameters and Operating Conditions

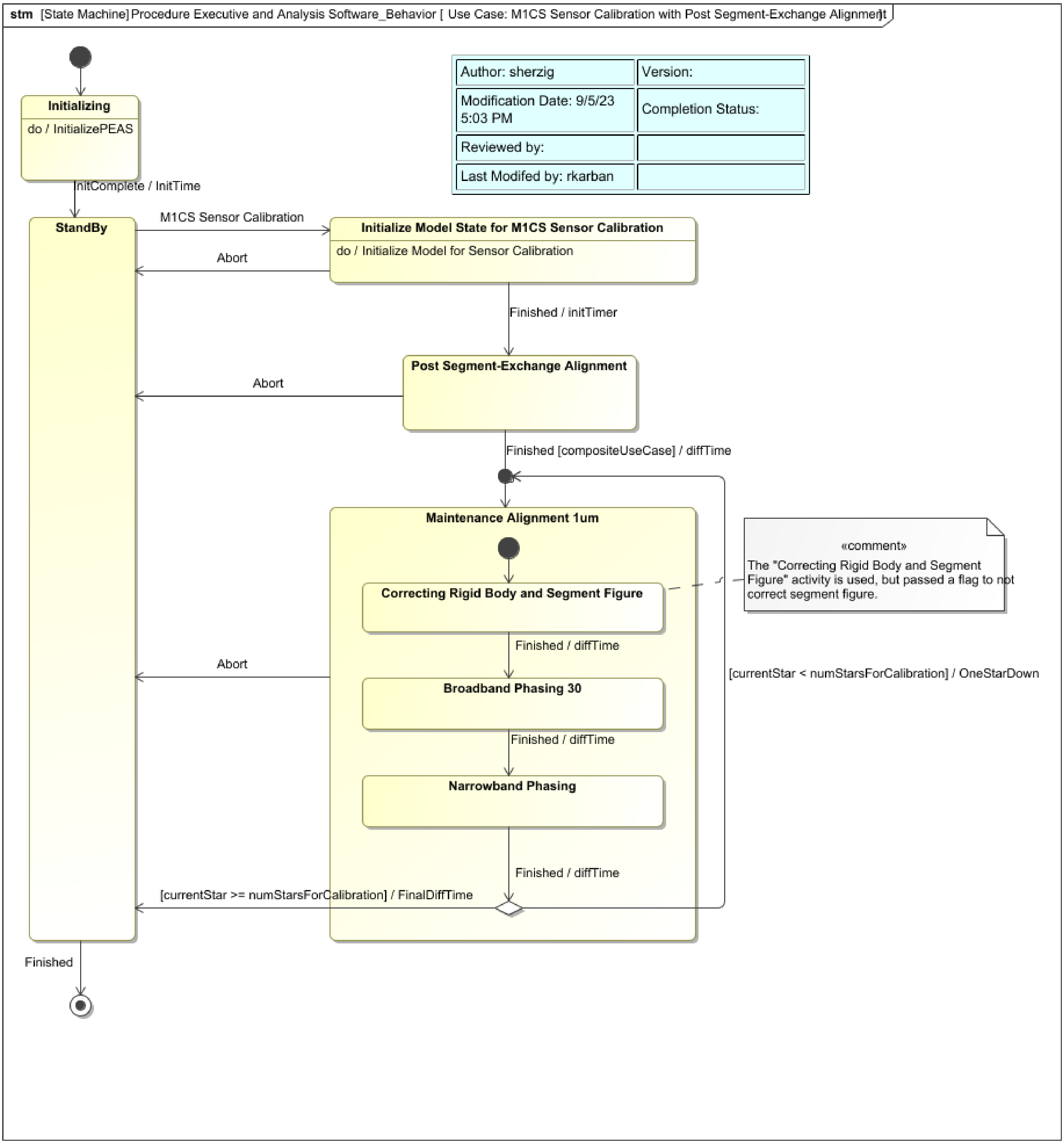
This use case will typically be executed as soon as possible after the segment exchange recovery process has completed, but no sooner then 20 minutes after sunset. The first activity coarse alignment uses a 10 nm bandwidth filter and is not very sensitive to sky background compared to the required accuracy 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.

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



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	

3.3 Maintenance Alignment

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.

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.

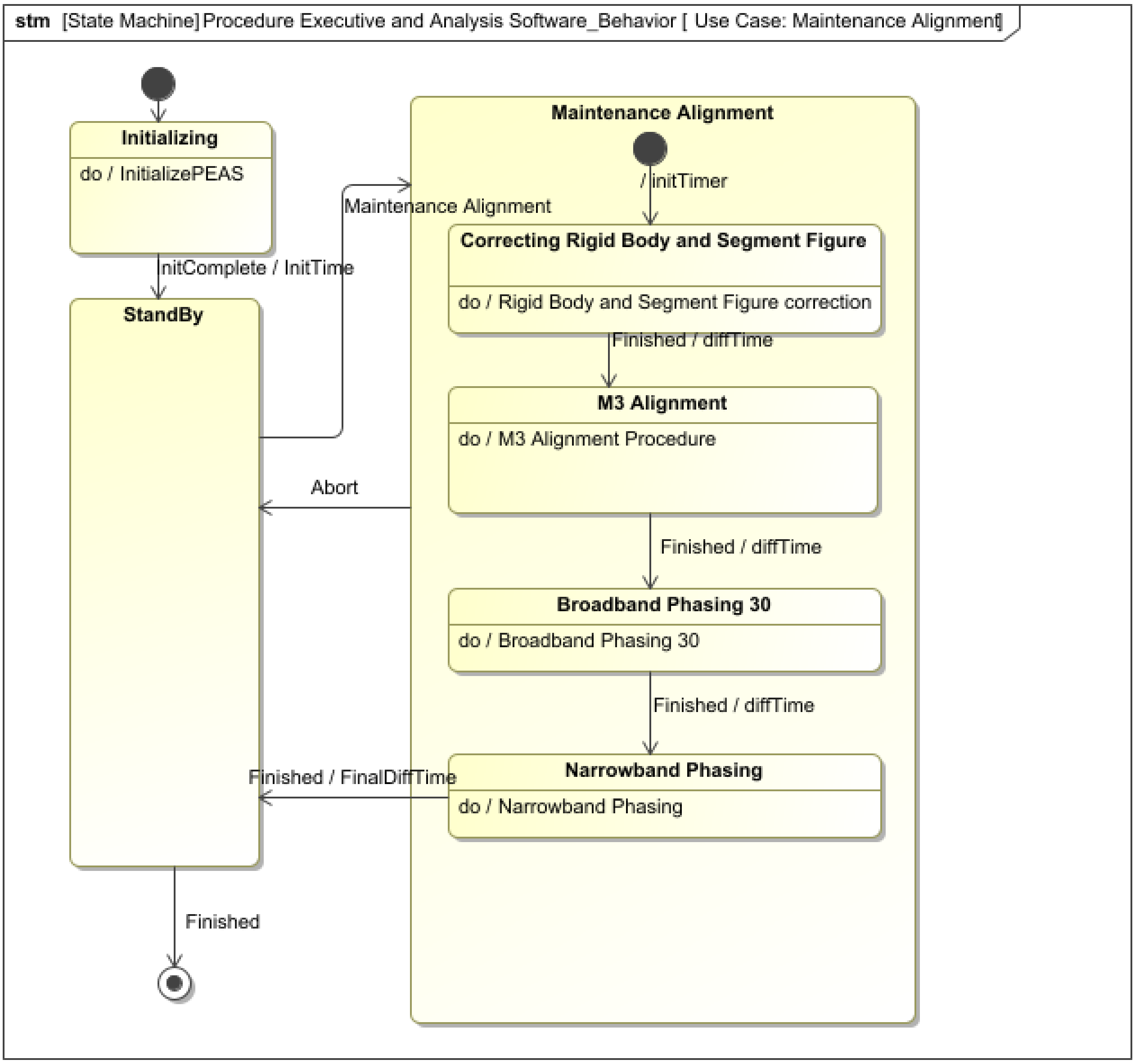
3.3.3 Typical Observing Parameters and Operating Conditions

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.

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



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

3.4 Off-Axis Measurements of WFE

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.

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.

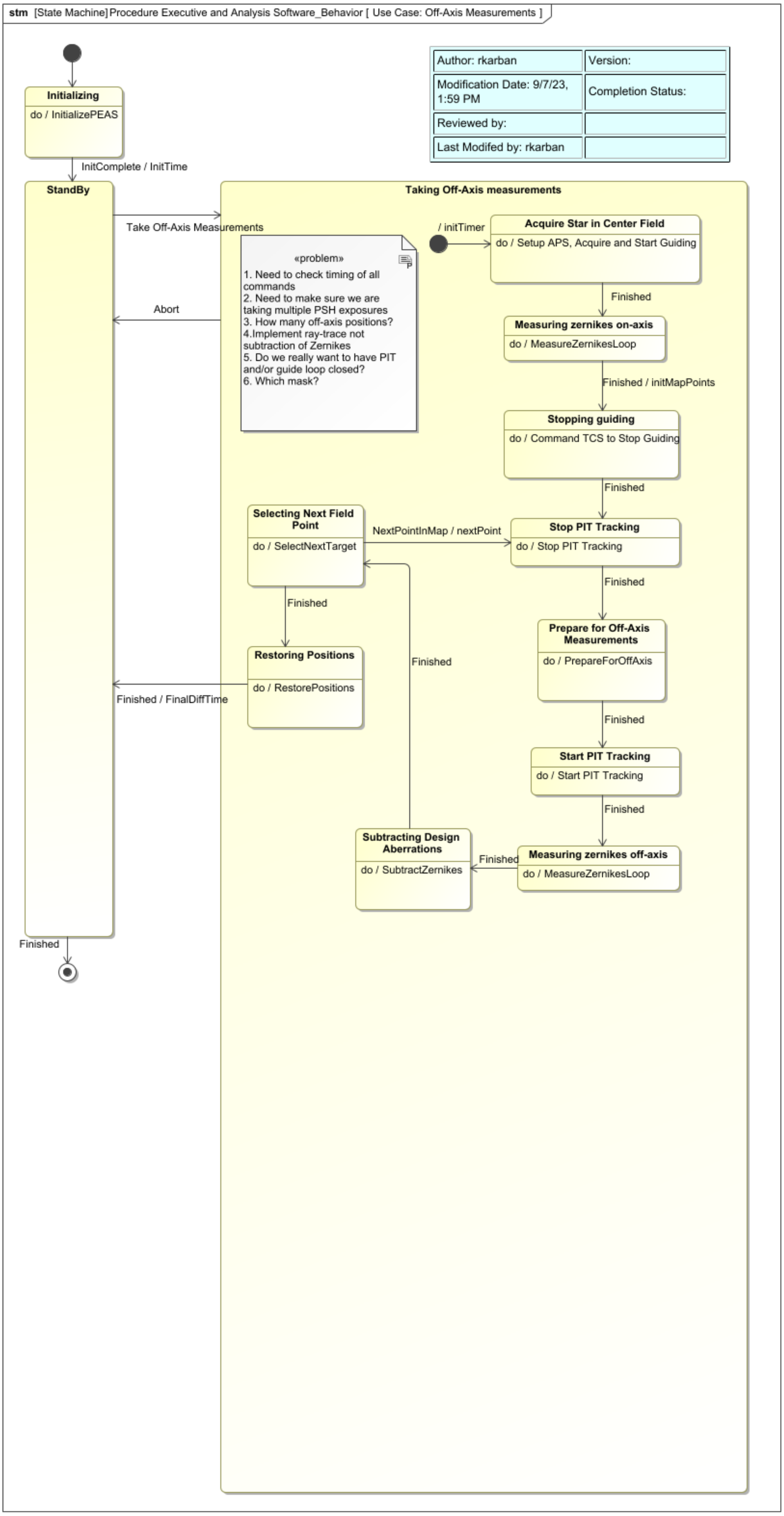
3.4.3 Typical Observing Parameters and Operating Conditions

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.

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



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	

3.5 Calibrate Elevation Dependence of M2 and M3

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.

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.

3.5.3 Typical Observing Parameters and Operating Conditions

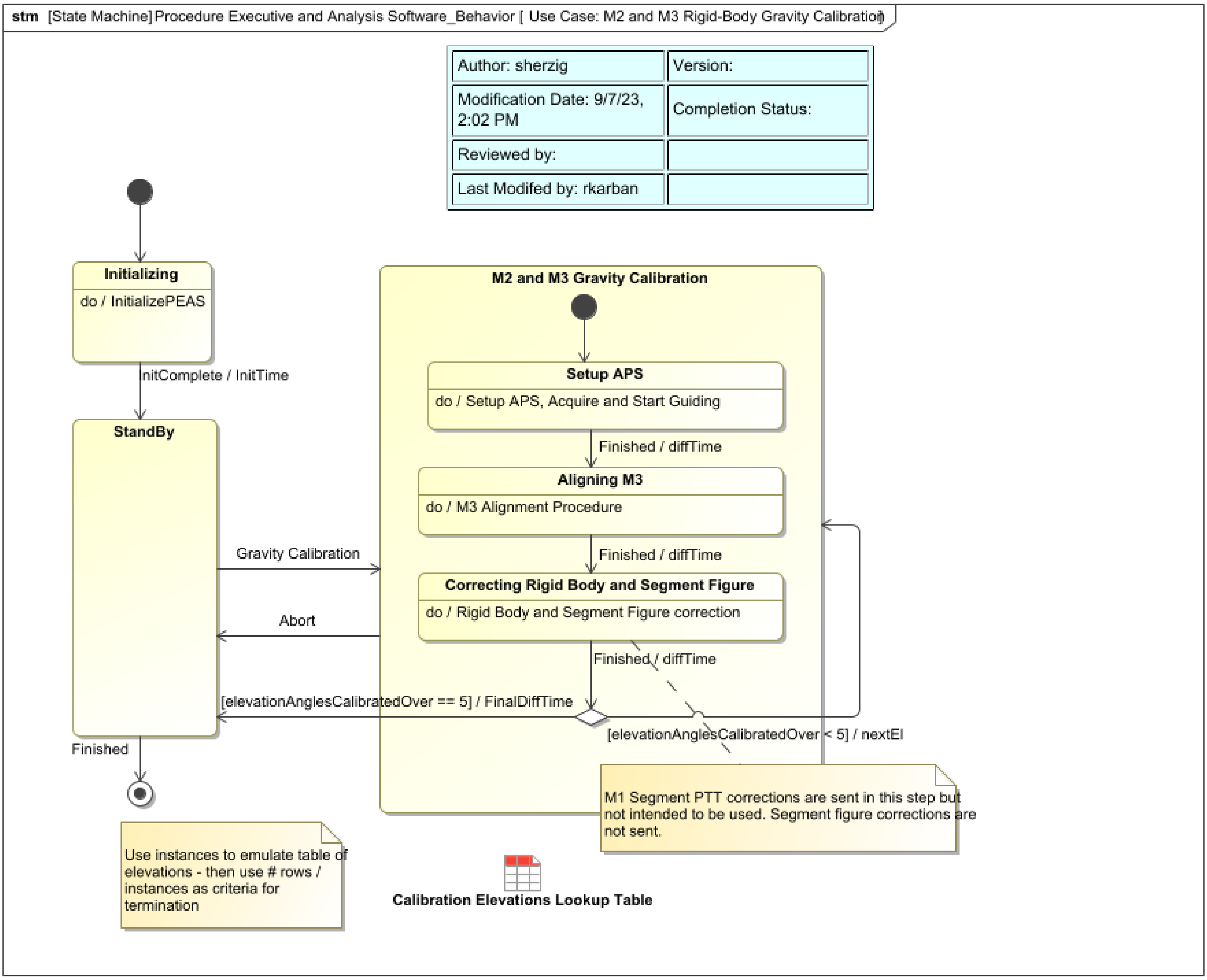
This use case can be executed any time during the night, but no sooner than ~40 minutes after sunset. Stars are usually selected to be ~1 hour to 30 minutes East at a declination of 0 or 40 degrees to minimize changes in telescope elevation. Stars will be acquired at specified telescope elevation angles, 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.

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

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	

3.6 Measurement of Segment Warping Harness Influence Functions

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.

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

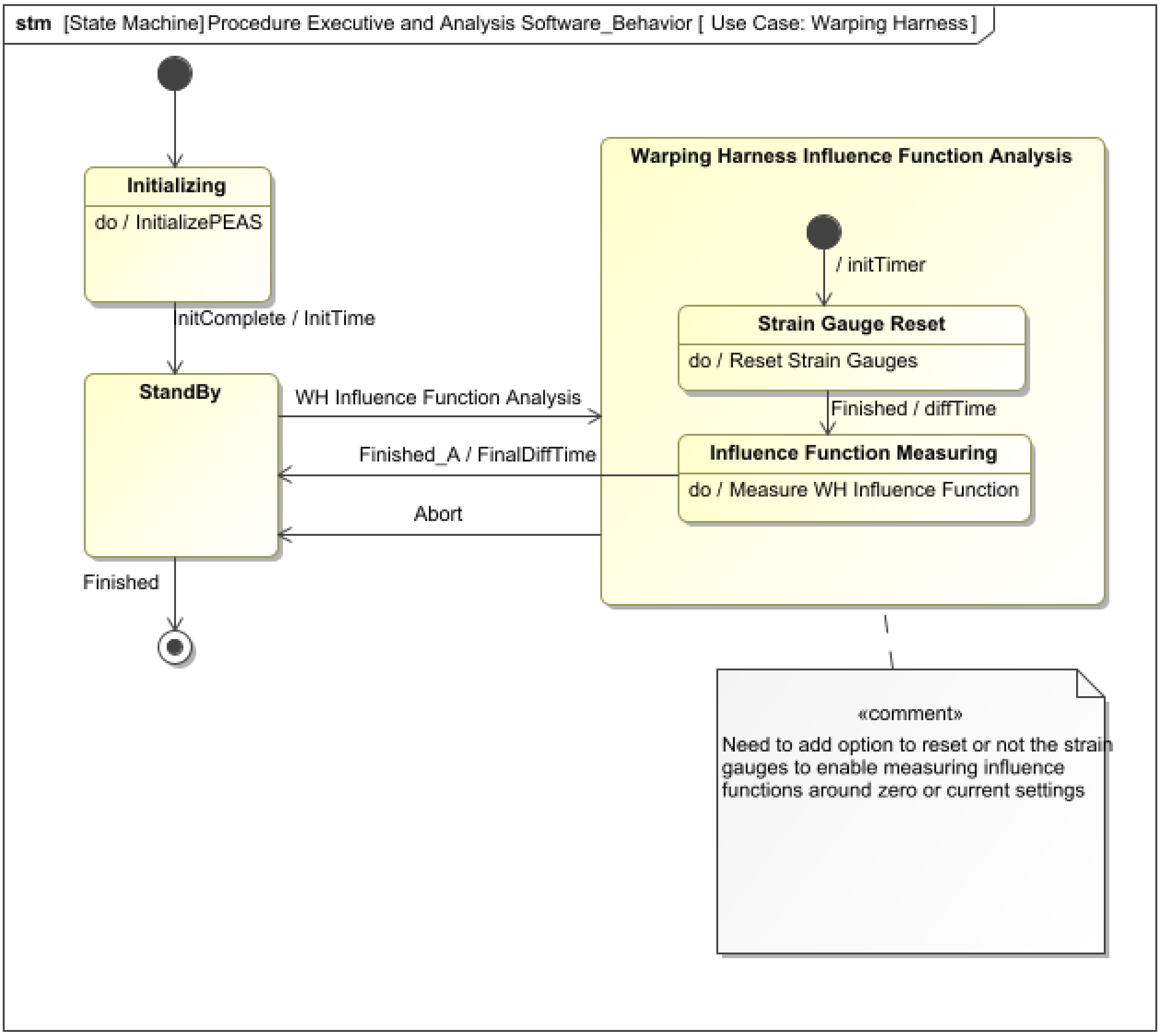
3.6.3 Typical Observing Parameters and Operating Conditions

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.

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" Lower Level Activities. Once the use case is complete the strain values from the start of the use case are restored.

Use Case: Warping Harness



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	

3.7 APS pre-session calibration

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.

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.

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.

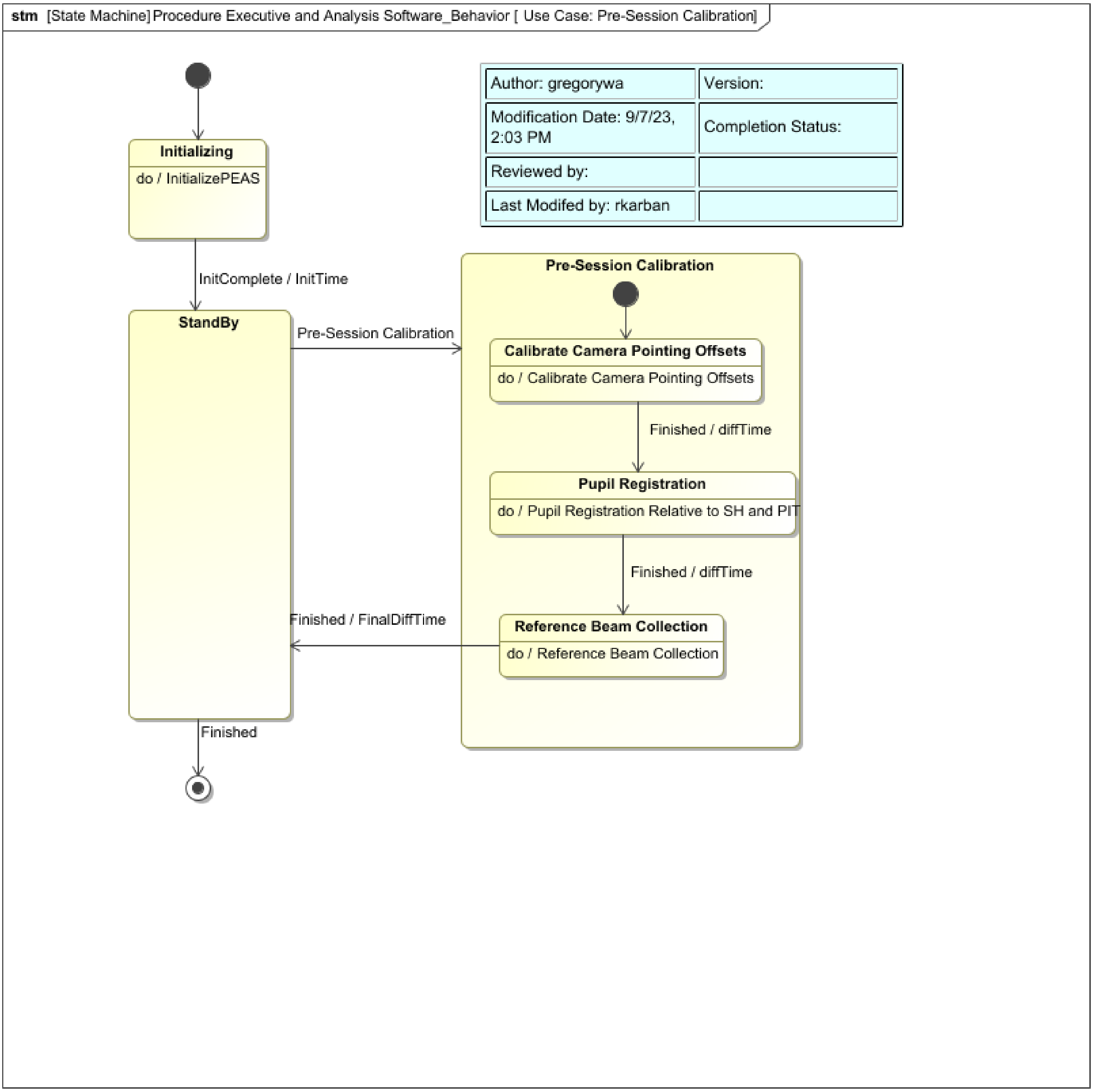
3.7.4 Use Case Activity

The figure below shows the Pre-Session Calibration use case. It starts with APS in standby mode. A series of Section 5 - 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



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

3.8 APS Self Test

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.

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.

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>

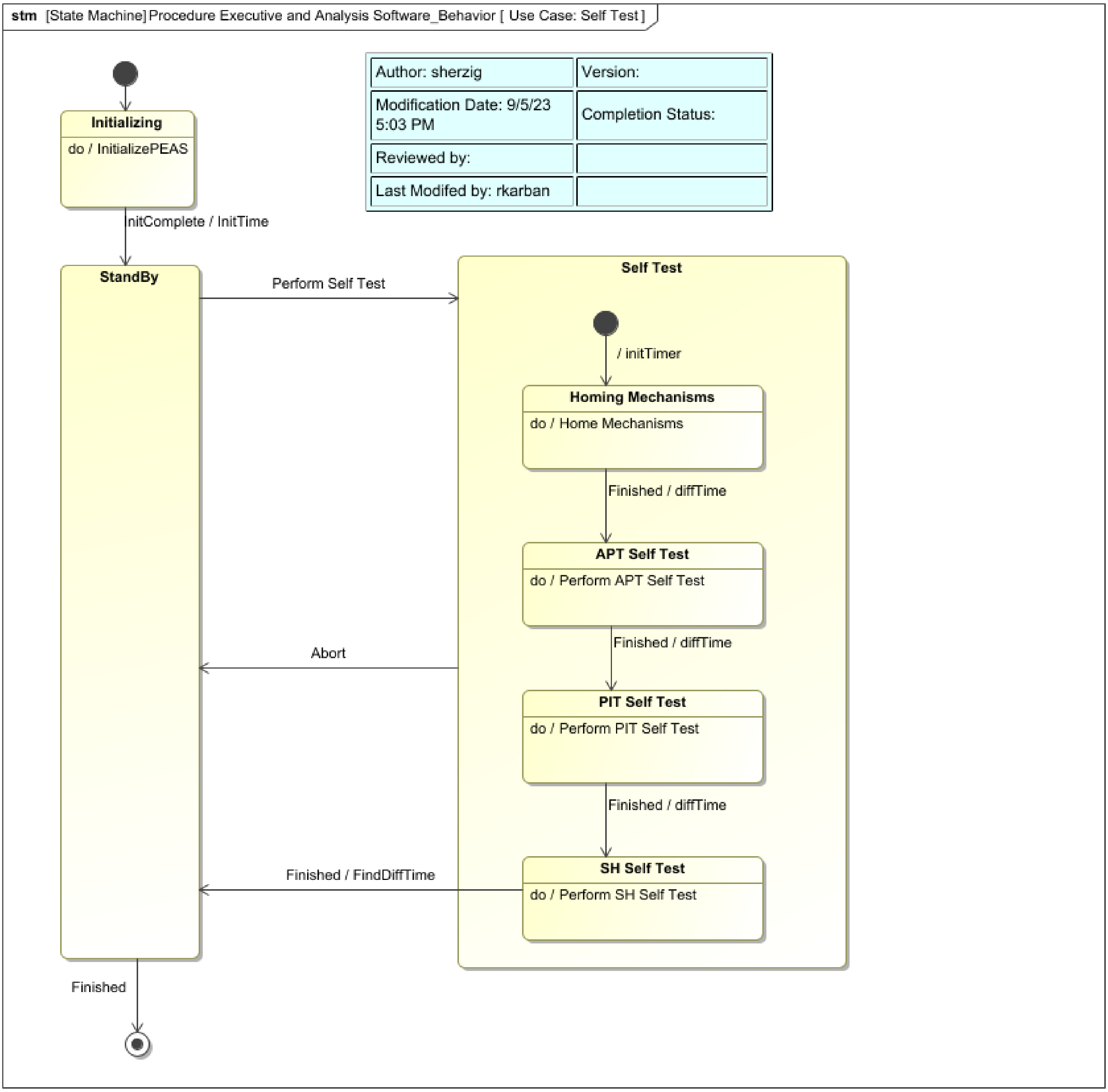
<p>On completion of this use case APS will either report that it passed the self test and is ready to observe, or that an error occurred and provide a description of the error.</p>

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



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 High Level Activities

4.1 Coarse Tilt Alignment

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.

4.1.2 Activity Parameters

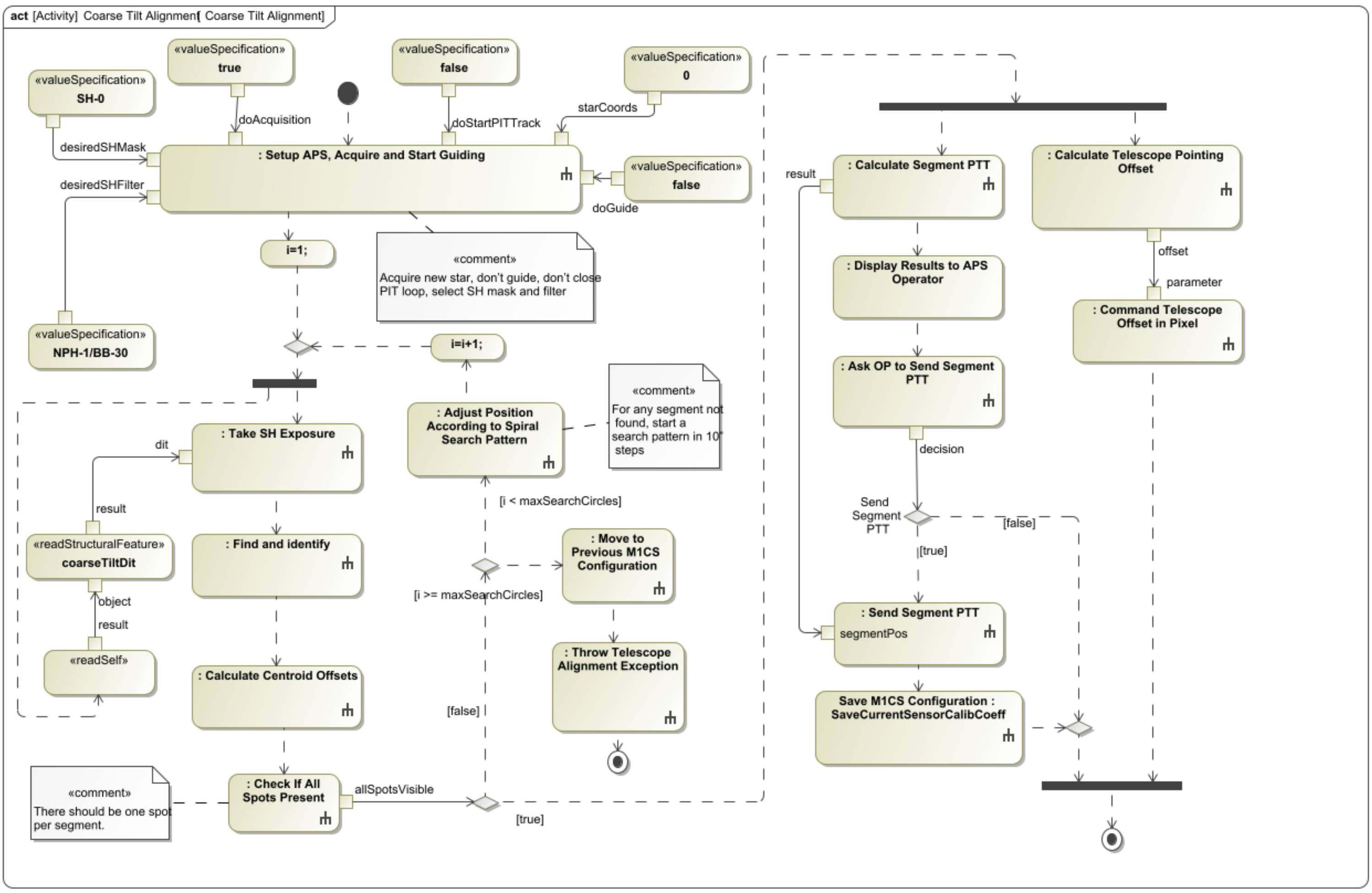
Relevant activity parameters are:

- 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

4.1.3 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



4.2 Rigid Body and Segment Figure Correction

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.

4.2.2 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

4.2.3 Activity Description

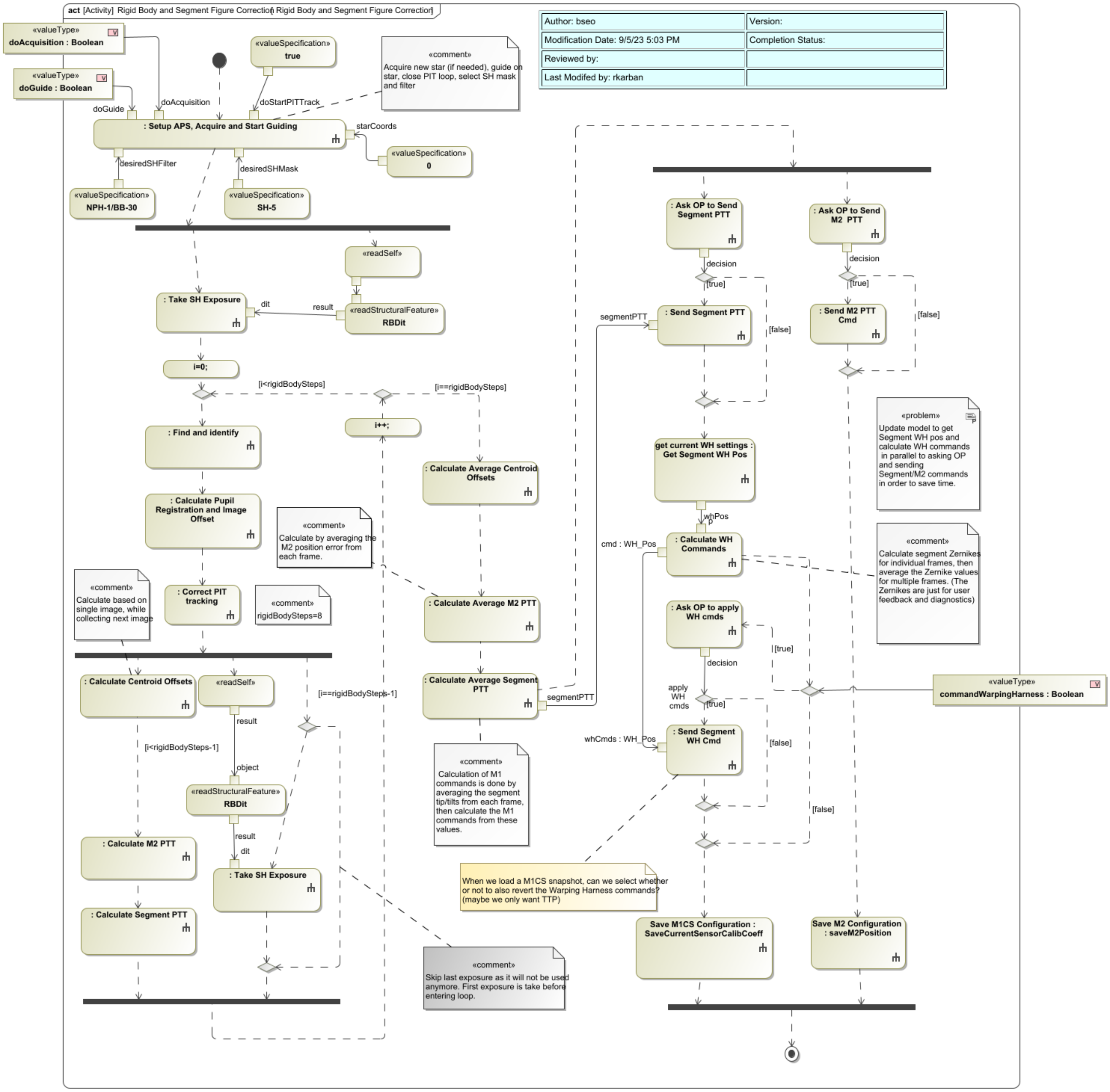
The following figure shows the rigid body and segment figure correction activity. APS first executes the "Setup APS, Acquire and Start Guiding" activity. In this case, the required PSH mask and filter are requested and if requested a star is acquired. The telescope will start guiding, and then the PIT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



4.3 Broadband Phasing

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.

4.3.2 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	

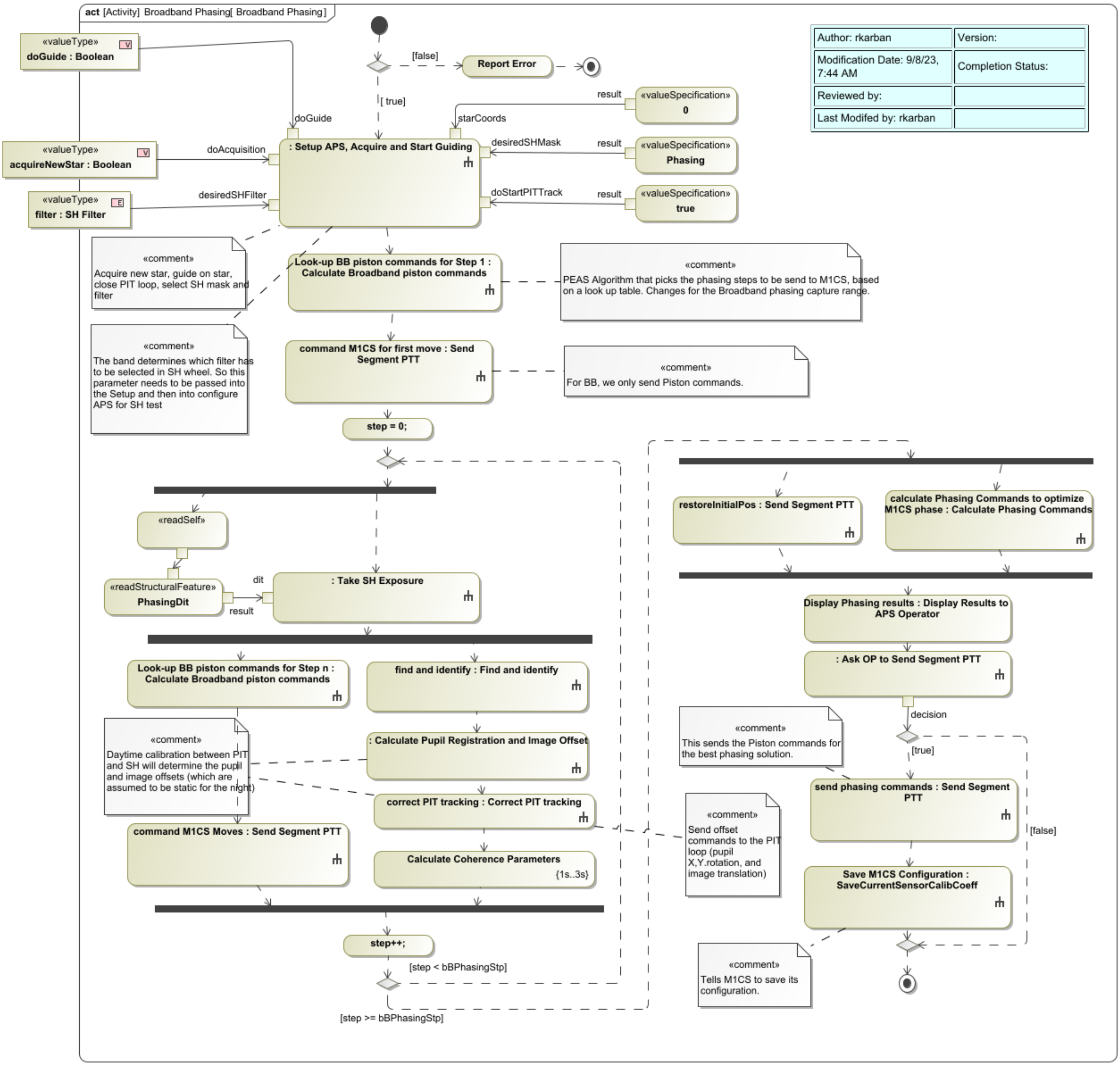
4.3.3 Activity Description

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 Narrowband Phasing

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′, $h' = h - n\lambda/2$

where n is an integer such that: $-\lambda/4 < h' < \lambda/4$. Since the uncertainty in h′ approaches $\lambda/2$ (independent of the formal measurement errors) as h′ approaches $\pm\lambda/4$, 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 $\lambda/4$, 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.

4.4.2 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

4.4.3 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.

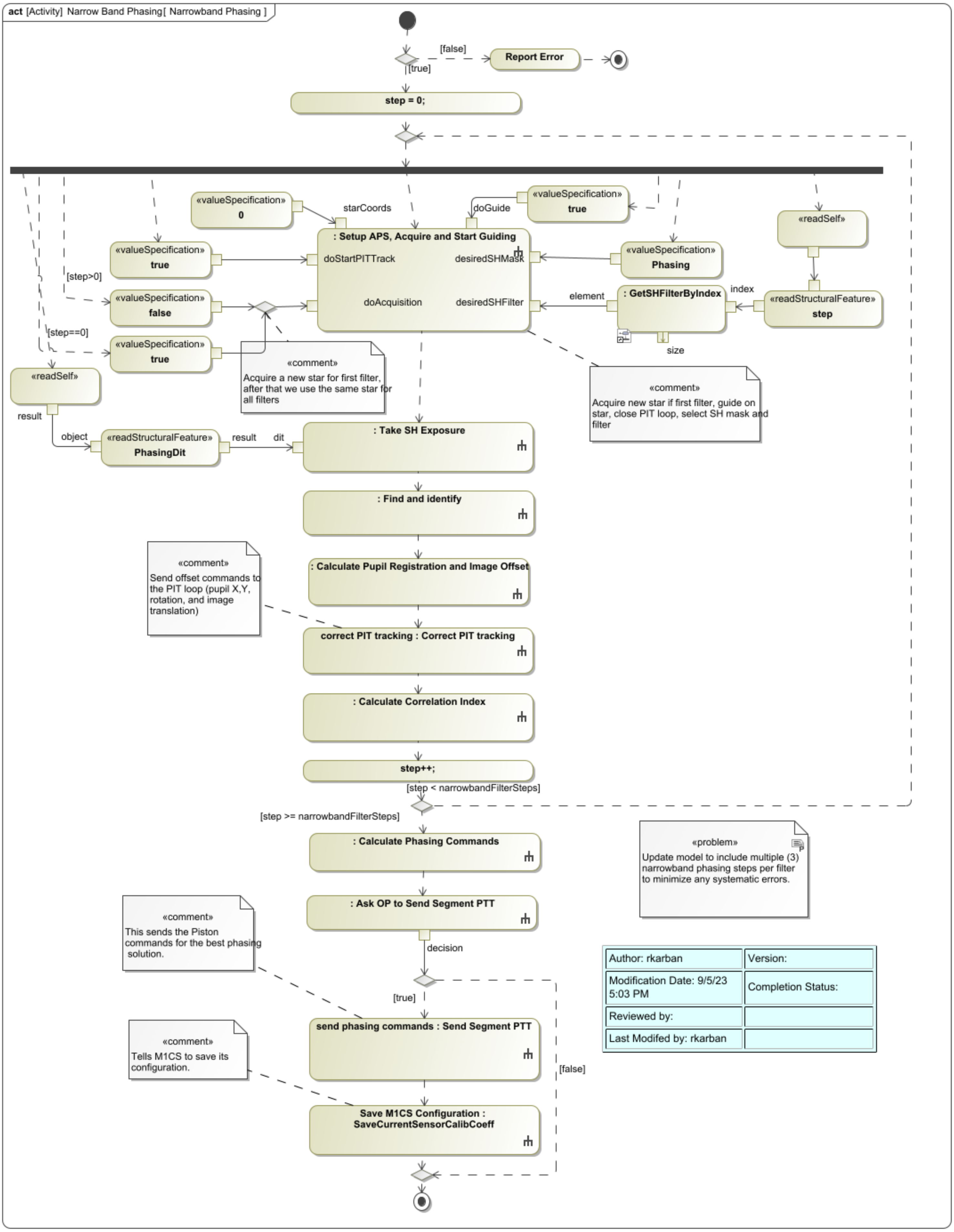
A PSH image is taken, the *Find and Identify* computational routine is called to find the sub-images and pupil registration (*x*, *y*, rotation and scale) and image offset is calculated. These are then sent to the PIT loop to correct the errors. The activity shows the nominal flow, but if the pupil registration 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



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

4.5 Measure Warping Harness Influence Functions

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.

4.5.2 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)

4.5.3 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

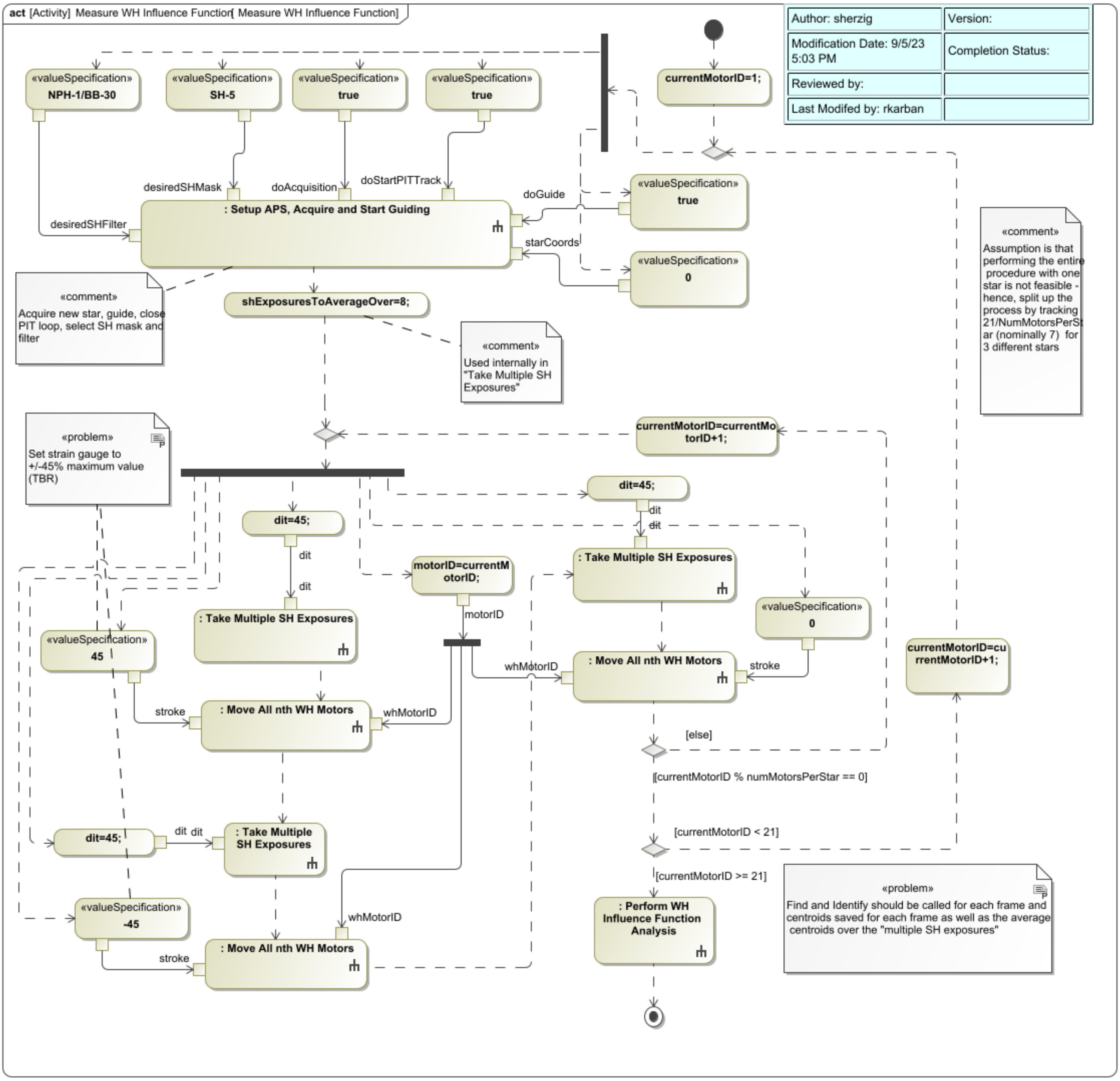
As currently written once all the data has been collected, perform WH Influence function analysis will calculate the centroid offsets for each segment and each set of Shack-Hartmann frames (8 frame average), and store this data in the APS-PEAS database. As noted in the figure this should occur as we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



4.6 M3 Alignment Procedure

4.6.1 Overview of Activity

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.

4.6.2 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

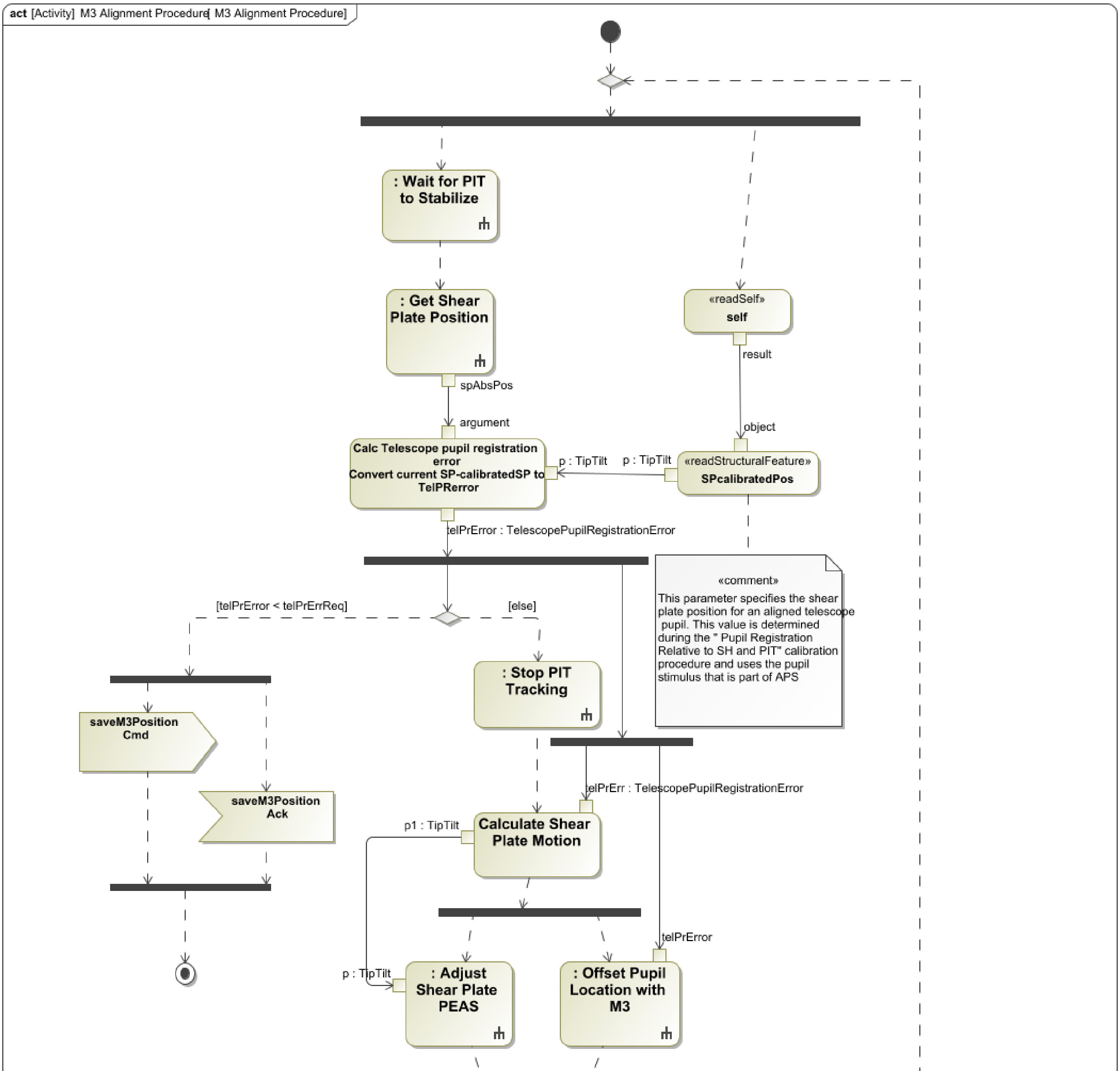
4.6.3 Activity Description

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	

4.7 Prepare for Off-Axis

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.

4.7.2 Activity Parameters

Relevant activity parameters are:

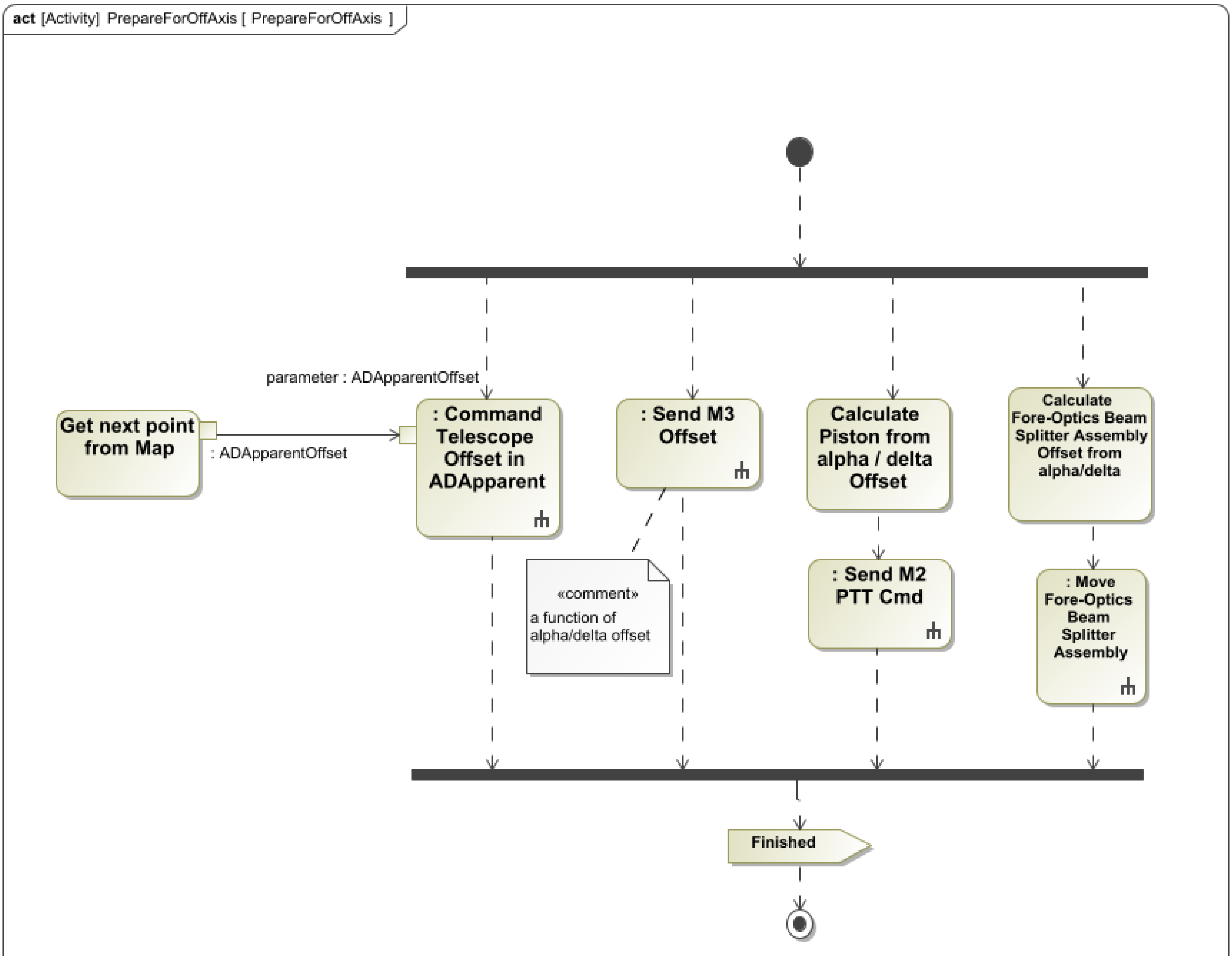
- Entrance requirement: PIT and APT loop should be open
- Exit conditions: The telescope (M1, M2, M3) optics and APS are reconfigured to point at the desired off-axis position.

4.7.3 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	

4.8 Reference Beam Collection

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.

4.8.2 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

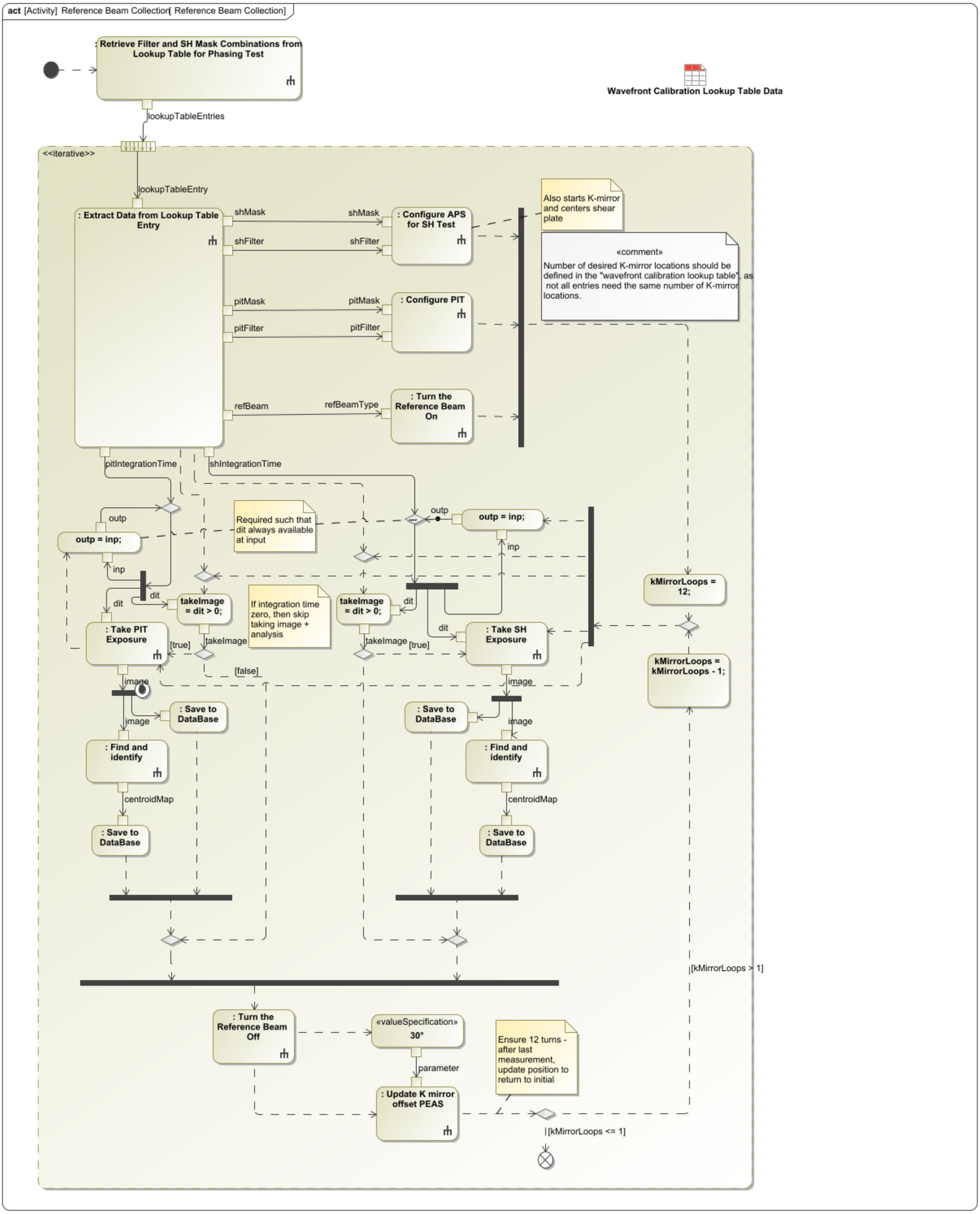
4.8.3 Activity Description

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



4.9 Pupil Registration Calibration

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.

4.9.2 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

4.9.3 Activity Description

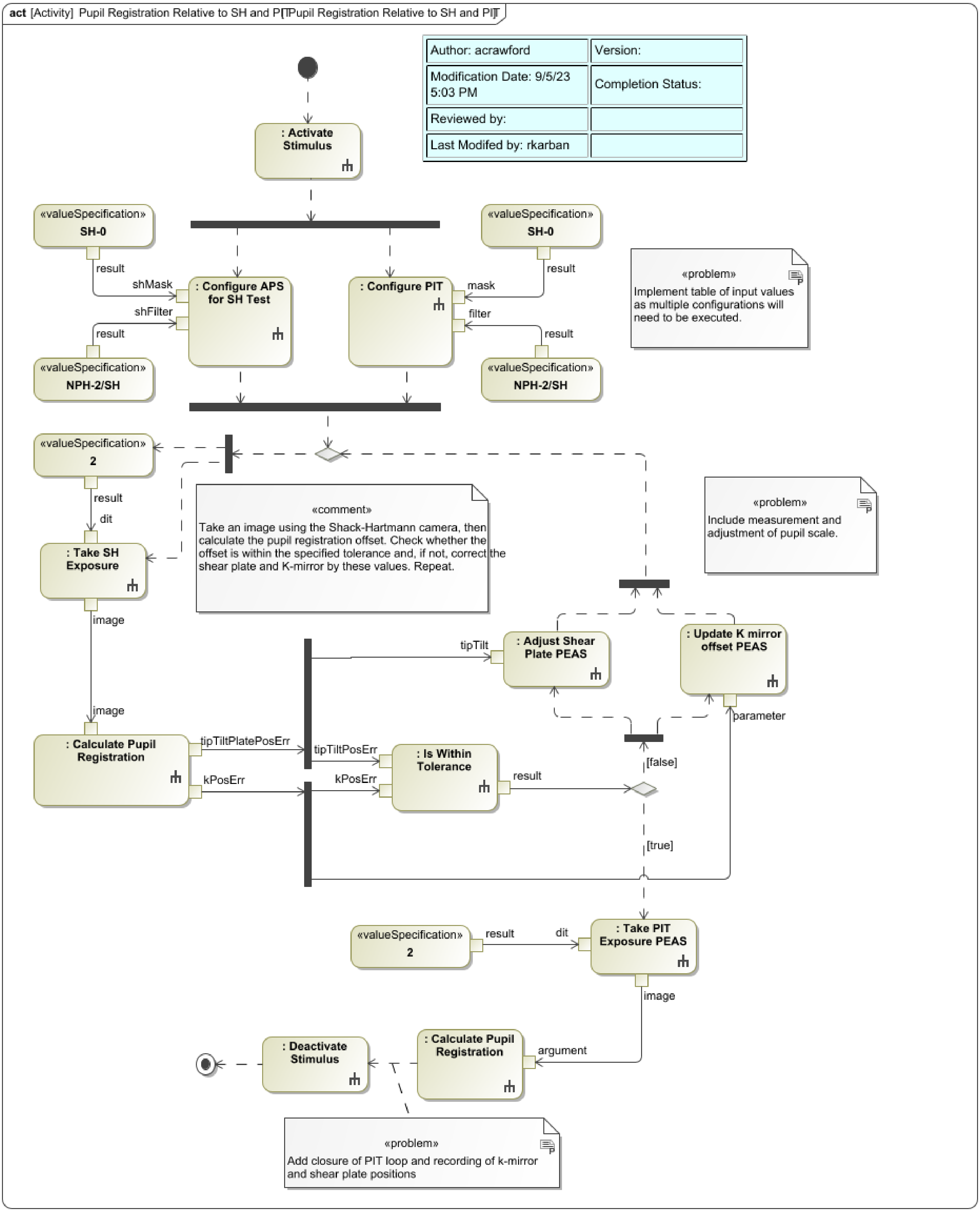
The figure below shows the pupil registration calibration activity:

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



4.10 Calibrate Camera Pointing Offsets

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.

4.10.2 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.

4.10.3 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.

5 Lower Level Activities

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

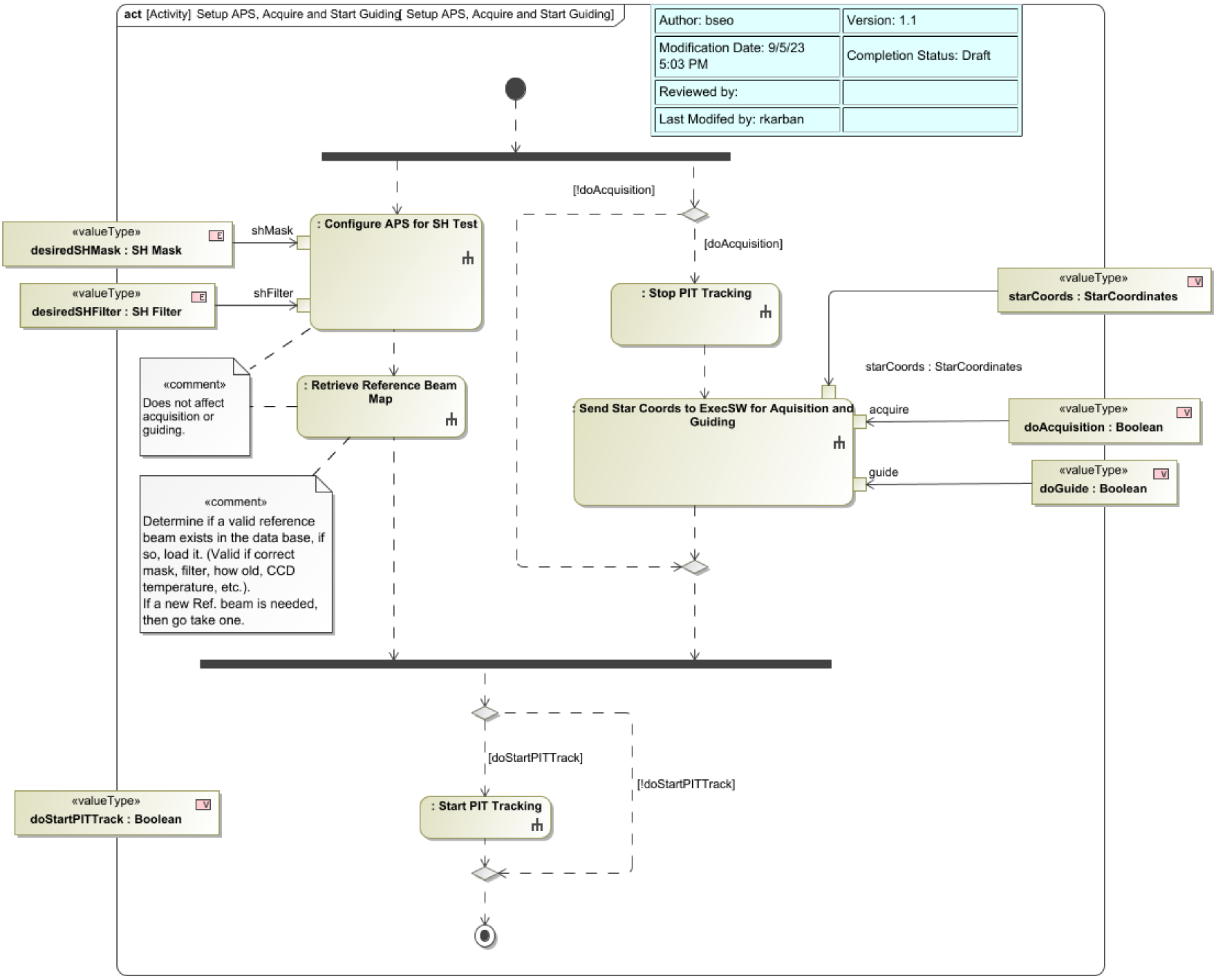
At the end of execution of this activity APS is ready to start data collection and execution of the alignment activity that called this activity.

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



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.

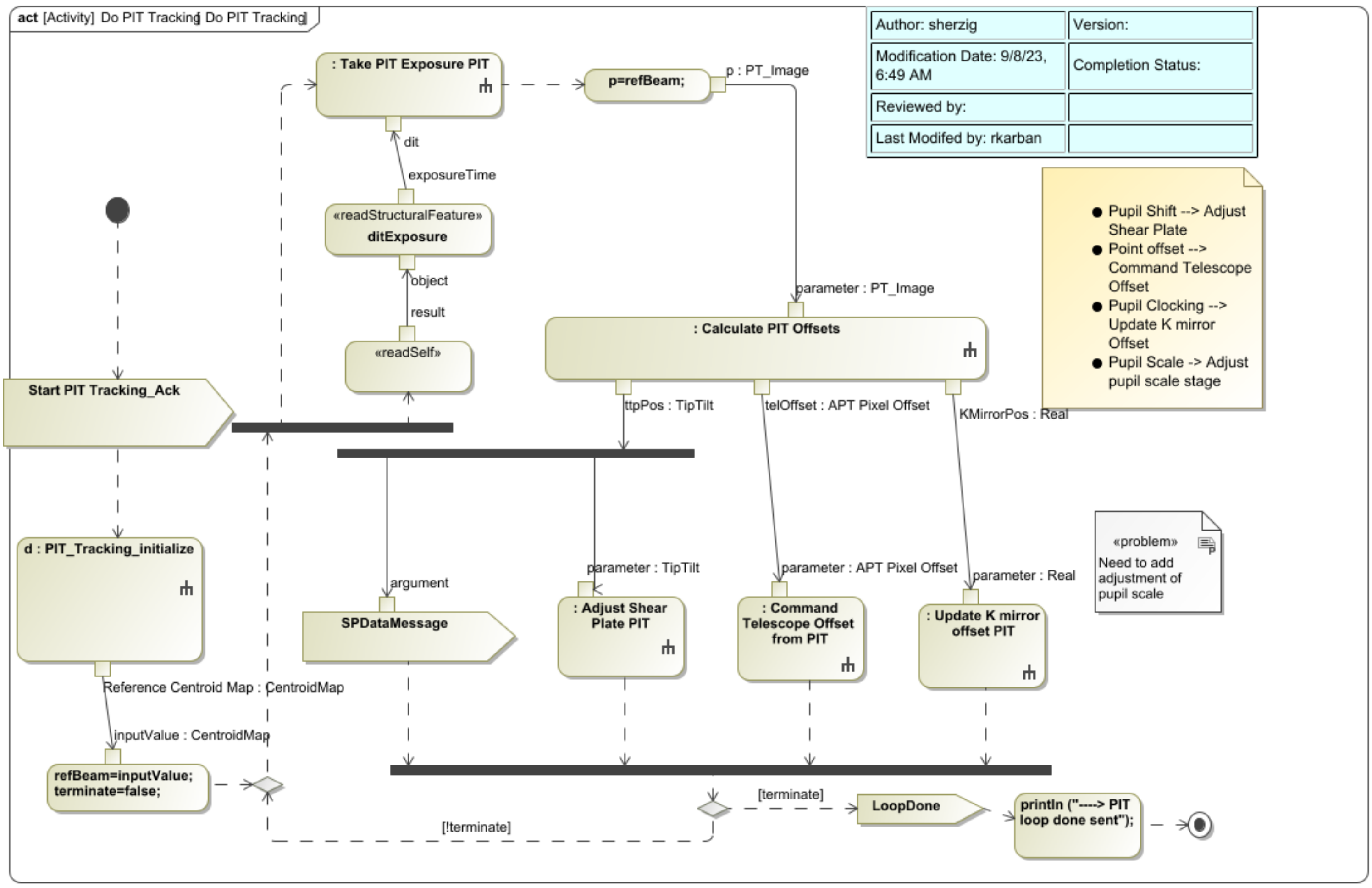
In the figure below we show an activity diagram that describes the baseline activity. The activity starts with the assumption that the telescope is tracking or guiding, and the star has been acquired on the APT CCD within ~5 arcseconds of the desired APS tracking point. This activity will work with the 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

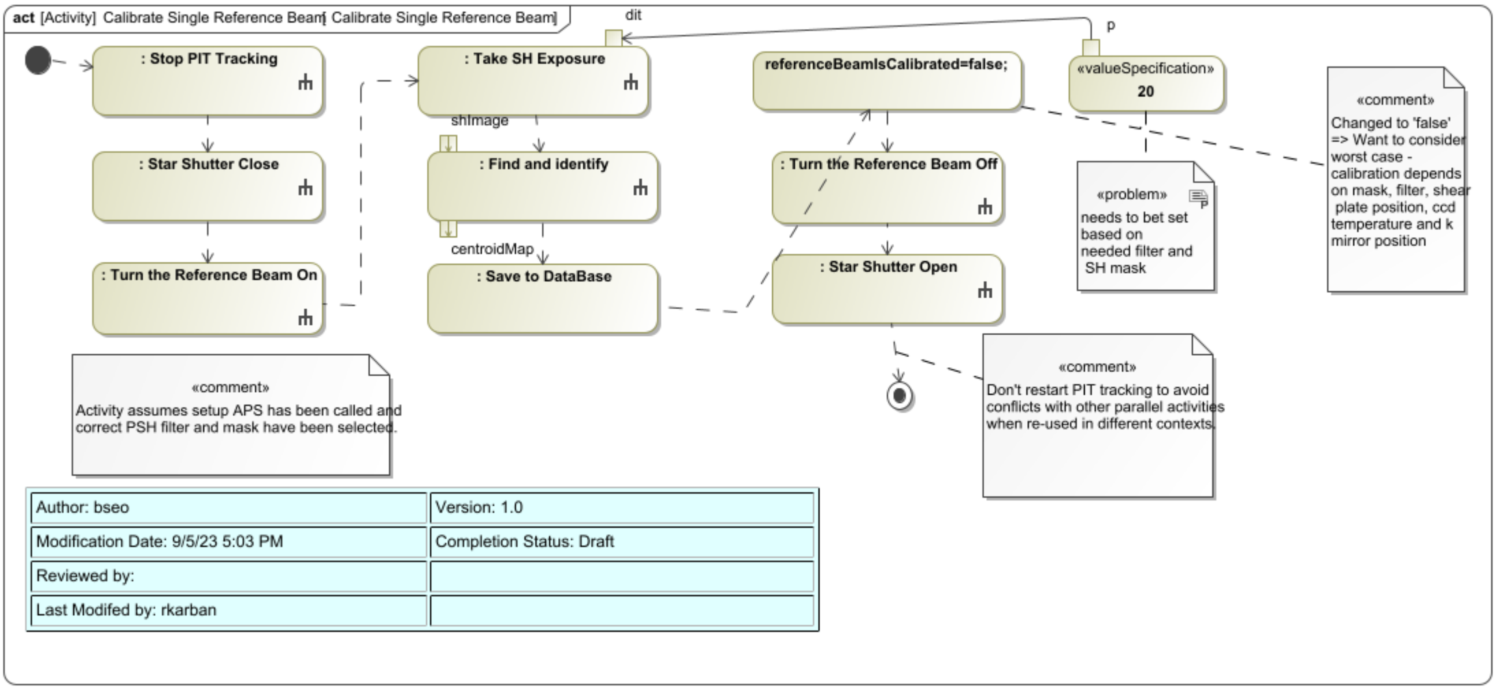


5.3 Calibrate Single Reference Beam

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



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.

6 PFC Use Cases

The PFC will be used before M2 and M3 are installed (or even available), but after the first ~37 segments are installed in TMT. The PFC will be used by TCS to debug and test telescope tracking and guiding, APS-PEAS is not involved in these activities. The APS-PEAS use cases are all in support of M1CS activities and are described in more detail in RD11. These early light use cases are designed to find and correct any M1CS functional or performance issues early in AIV before installation of additional segments. As many of these use cases involve identifying, stacking and aligning the segments it makes sense to perform these operations using the APS-PEAS software which already contains much of the needed functionality. Additionally, this will allow for early testing and debugging of APS-PEAS and its algorithms. The currently identified PFC use cases that use APS are:

1. Measurement of fixed frame installation errors
2. Measurement of edge sensor installation errors
3. Segment stacking
4. Verification of focus mode commands
5. Measurement of piston motion orthogonality with tip/tilt
6. Measurement of M1CS temporal repeatability
7. Measurement of sensor sensitivity to gravity and in-plane motions

The definition of these use cases is in RD11 and the implementation in RD12. Detailed SysML activity diagrams will be developed as part of the FD effort.

7 Future Work

We have identified several areas where improvements should be made to this document as part of the Final Design phase. These include changes to the underlying SysML model to bring it up to a Final Design level. These will be undertaken following the PDR.

- Verify that the nomenclature of software calls to the TCS and M1CS ICDs are up to date.
- Implement nomenclature and activity durations of calls to the APS-ICS once the associated ICD reaches design maturity.
- Add a use case for collecting high-speed data.
- Develop additional use cases for Assembly, Integration, and Verification (AIV) and off-nominal cases as appropriate.
- Various improvements of the activity flows in the SysML model. These changes are marked with the <<problem>> tag in the associated diagrams, and tracked in SysML. We are confident that none of these changes will impact the ability of APS to meet system requirements.