



TMT Observation Workflow

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1 Introduction

1.1 Purpose of the Document

The purpose of this document is to define the sequence of operations or workflow/activities that take place before, during and after a science observation involving the following Observing Modes:

- TMT NFIRAOS NGS AO Observing Mode
- TMT NFIRAOS LGS MCAO Observing Mode
- TMT NFIRAOS Seeing-Limited Observing Mode
- TMT Seeing-Limited Observing Mode

In combination with the followings subsystems:

- Narrow Field InfraRed Adaptive Optics System (NFIRAOS), the TMT AO facility;
- IRIS, IRMS, or WFOS science instruments;
- And/or laser guide star facility (LGSF).

Inputs to this document are the Observatory Requirements Document (ORD) (**AD1**), and the Operations Requirements Document (OPSRD) (**AD2**).

The outputs of the document are level 1 OAD requirements (**RD5**) and by consequence level 2 sub-systems requirements, the time budget for configuring AO System or instruments, the communication ICDs between the relevant systems, as well as the instrument OCDDs (**RD6**), (**RD7**), (**RD8**), (**RD9**) and NFIRAOS OCDD (**RD5**)? etc

The intended audience for this document is:

- The developers of the TMT main sequencers (ESW, TCS, AOESW)
- Telescope Control System (TCS)
- The developers of NFIRAOS and the Laser Guide Star Facility (LGSF) systems,
- The developers of the TMT instruments,
- The TMT science users.

1.2 Overview

A TMT science observation consists of a hierarchical series of linked processes, which are illustrated in Figure 1-1.

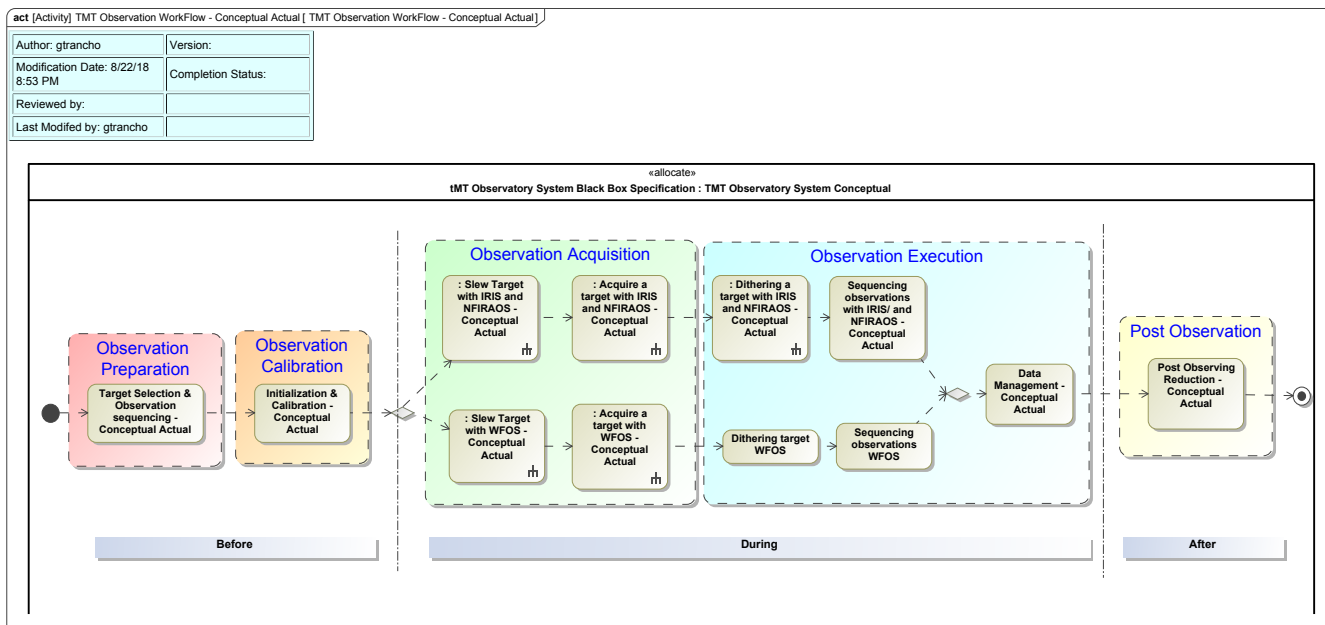


Figure 1. TMT Observation WorkFlow - Conceptual Actual

Figure 1-1. TMT Observation Workflow

Figure 1-1 identifies 3 distinct phases: Before, During, and After Observation

- **Before:** This first observation phase includes the Observation Preparation and System Startup and Calibration. The output of the Observation Preparation includes all of the information necessary to perform the System Startup, Executing Calibration and then Observation, in particular the coordinates of the science object, the coordinates of the natural guide stars, their magnitudes, SEDs and/or color temperature, etc. The Observation Preparation and System Startup and Calibration processes are described in detail in **section 2**.
- **During:** The next observation phase is the Observation Acquisition, which consists of slewing the telescope to the science target, configuring the AO system and/or instrument, acquiring the laser and/or natural guide stars and closing the AO (or aO) loops. This phase is described in detail in **sections 3 and 4** of this document for the TMT AO instruments and WFOS. Once the acquisition process is completed, the next process is the Observation Execution. During this phase, raw science data and required nighttime calibrations are acquired. The Observation Execution process is described in **section 5**, including how to stop the observation when switching to a different target or instrument.
- **After:** Finally, Post Observations Activities such as PSF reconstruction, instrument pipeline data reduction, and data archiving are described in **section 6**.

1.2.1 Supporting Sub-systems

The background information about the Subsystems and Instruments is described herein.

1.2.1.1 Telescope/Enclosure

TMT is a filled-aperture optical-infrared telescope with a 30-m diameter primary mirror. The telescope is designed for observing efficiency. Large Nasmyth platforms hold ~ 8 large science instruments, any of which can be engaged within minutes during the night. A steerable tertiary mirror directs the beam to any of the science instruments or AO systems. This allows targets of opportunity and transient objects to be addressed with minimal delay, and allows switching instruments to best match changing observing conditions. Relatively rapid slewing (2.5 deg/sec in azimuth) makes it possible to change science objects within five minutes anywhere in the sky. High efficiency optical coatings and only three warm reflections provide high throughput and low thermal background. The field of view is 20 arcmin, with 15 arcmin unvignetted (maximum vignetting at the edge of the 20 arcmin field is 11%).

The enclosure is an innovative Calotte design that includes a large area of vents that can be independently adjusted to control the amount of ventilation across the telescope during the night. The reflective low-emissivity coating on the exterior of the enclosure and the daytime thermal management system keep the telescope at nighttime temperatures during the day. The observing aperture is round with minimal clearance around the telescope beam.

The telescope control system (TCS) computes positioning demands for all the mechanisms in NFIRAOS, LGSF, instrument, etc. that depend on the telescope pointing angle (zenith angle, pupil rotation). The TCS treats the mechanisms as ideal, and the positioning demands are x/y/z coordinates in the focal plane, angle and power of ADC, etc. (TBC). It is the responsibility of each mechanism's owner to provide the calibration necessary to drive the mechanisms. There may be feedbacks from such mechanism controllers to TCS for corrections in the position calculation.

1.2.1.2 NFIRAOS

The TMT facility AO system, NFIRAOS, enables NGS AO, LGS MCAO and Seeing-Limited observing mode (see description in section 2.2.1)

NFIRAOS includes two deformable mirrors conjugated to 11.8 km (DM11) and 0 km (DM0) situated in a 4 OAP relay. The mount for DM0 also serves as a Tip Tilt Stage (TTS).

Each NFIRAOS science instrument provides up to three low order on-instrument wavefront sensors (OIWFS) and (for IRIS only) multiple on-detector guide windows (ODGW) to provide high precision tip/tilt, and (only in the case of 2x2 mode) focus and astigmatism measurements. When running at high speed, the OIWFS or ODGW measurements are used for tip/tilt, focus and plate scale control. When running at low speed, they can compensate for flexure between NFIRAOS and the science instrument. The ODGW additionally compensate for flexure of the OIWFS because they are directly located on the science focal plane.

NFIRAOS has three instrument output ports. An Instrument Selection Mirror (ISM) is used to feed light to any of these three ports.

At first light, these three ports are expected to be occupied by 1) IRIS, an imager and integral field spectrograph, 2) IRMS, a multi-object slit spectrograph and wide field imager that can work with modest or no AO correction, and 3) NSEN, a non-science instrument that contains an acquisition camera (NSEN ACQ) and a diffraction-limited NIR camera.

The NFIRAOS Real-Time Controller (NRTC) is comprised of the hardware and software responsible for controlling wavefront correctors. In particular, the RTC reads the pixels from various WFSs, compute gradients, and finally reconstruct DM/TTS commands, at rates up to 800 Hz. The RTC also controls other mechanisms (e.g., in NFIRAOS or LGSF) to maintain maximal AO performance.

NFIRAOS Optical Layout - 2018-04-27 - v1

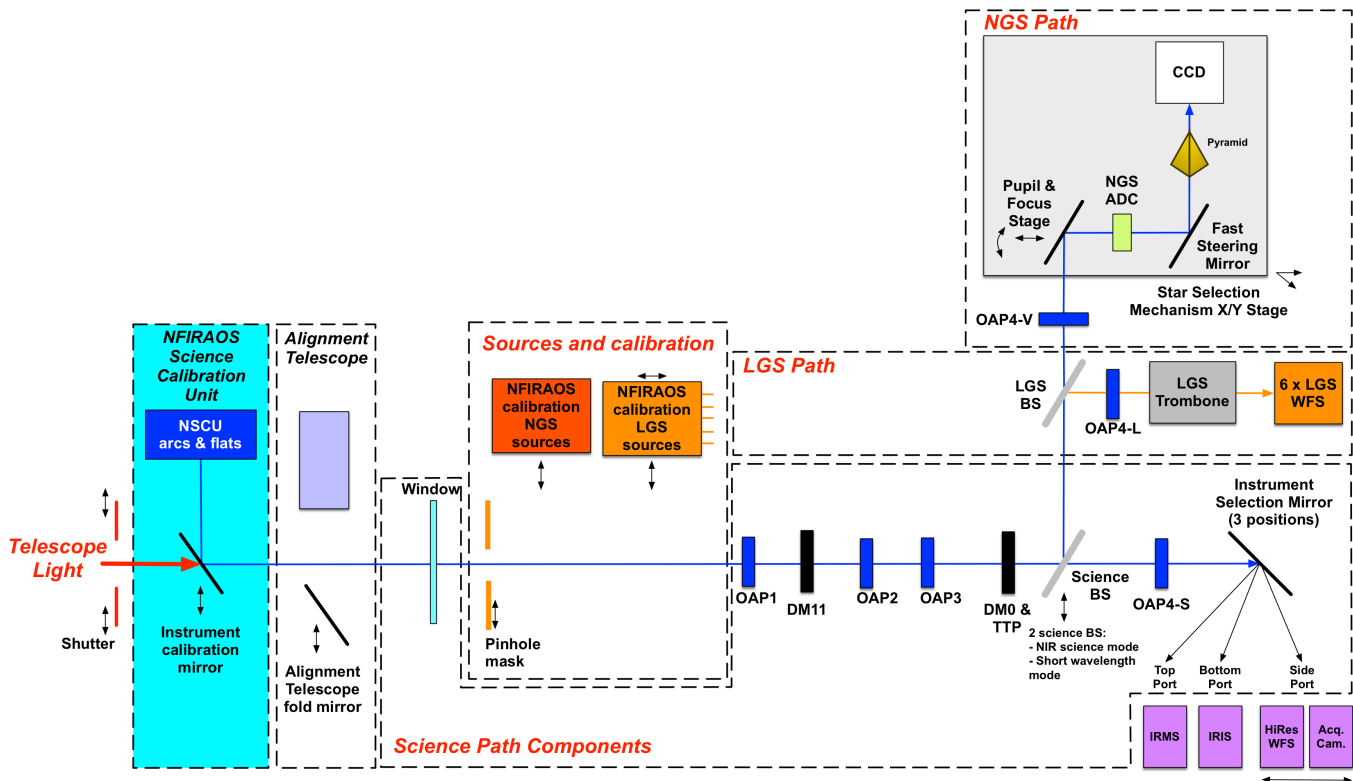


Figure 2. Figure 1-2. NFIRAOS layout

1.2.1.2.1 NFIRAOS Operating Modes

The following operational modes are defined for NFIRAOS:

1. NFIRAOS NGS AO mode,
2. NFIRAOS LGS MCAO mode,
3. NFIRAOS Seeing-limited mode
4. Stand-alone mode,
5. Parked mode,
6. OFF mode.

These modes are described hereafter.

Table 1 shows NFIRAOS plus IRIS guide star requirements. When used as low order truth WFS, the OIWFS and ODGW guide star magnitude limit can be relaxed by up to 4 magnitudes. However star catalogs may not contain stars at this dim brightness.

Table 1. NFIRAOS and IRIS/IRMS guide stars requirements

WFS	Observing mode	NFIRAOS + IRIS (Number of guide stars)	NFIRAOS + IRMS (Number of guide stars)	Magnitude Vega limits
LGSWFS	NFIRAOS LGS MCAO	6	6	(20W each Laser)
PWFS	NFIRAOS NGS AO	1	1	R=16
	NFIRAOS LGS MCAO (as TWFS)	1	1	R=20 (RD3)
	NFIRAOS LGS MCAO (as TTF)	1	1	R=18 (RD4)
	NFIRAOS Seeing-Limited	1	1	R=20 (TBC)
OIWFS	NFIRAOS LGS MCAO	1-3	1	J=22
	NFIRAOS NGS AO	0-1	0-1	J=22
	NFIRAOS Seeing-Limited	0-1	0-1	J=22
ODGW	NFIRAOS LGS MCAO	0-4	0	J=22
	NFIRAOS NGS AO	0-1	0	J=22

1.2.1.2.1.1 NFIRAOS LGS MCAO Mode

In NFIRAOS LGS MCAO mode, NFIRAOS expected nominal use case uses six LGS WFS and the PWFS located within NFIRAOS, as well as up to three OIWFS and/or up to four ODGW provided by client instruments.

The PWFS is generally used as a Truth WFS (TWFS) running at low frame rate for correcting aberrations rising from changes in the sodium layer profile.

The OIWFS are generally used to provide tip/tilt, focus, and plate scale control. ODGW can be used as well if bright guide stars are available within the imager focal plane to provide tip/tilt measurements. If faint guide stars are available within the imager focal plane, the ODGW can be used as tip/tilt truth WFS running at lower speed, to provide flexure compensation between OIWFS and instrument focal plane.

There are also cases when a fast TTF OIWFS measurement cannot be used due to reasons like 1) vignetting science target, or 2) lacking bright enough guide stars (extended object require higher brightness), the PWFS may be used instead to provide high speed but less accurate tip/tilt/focus control. The TTF OIWFS could then be used as tip/tilt/focus truth WFS with a faint guide star while other TT OIWFS and/or ODGW may be used as tip/tilt truth WFS.

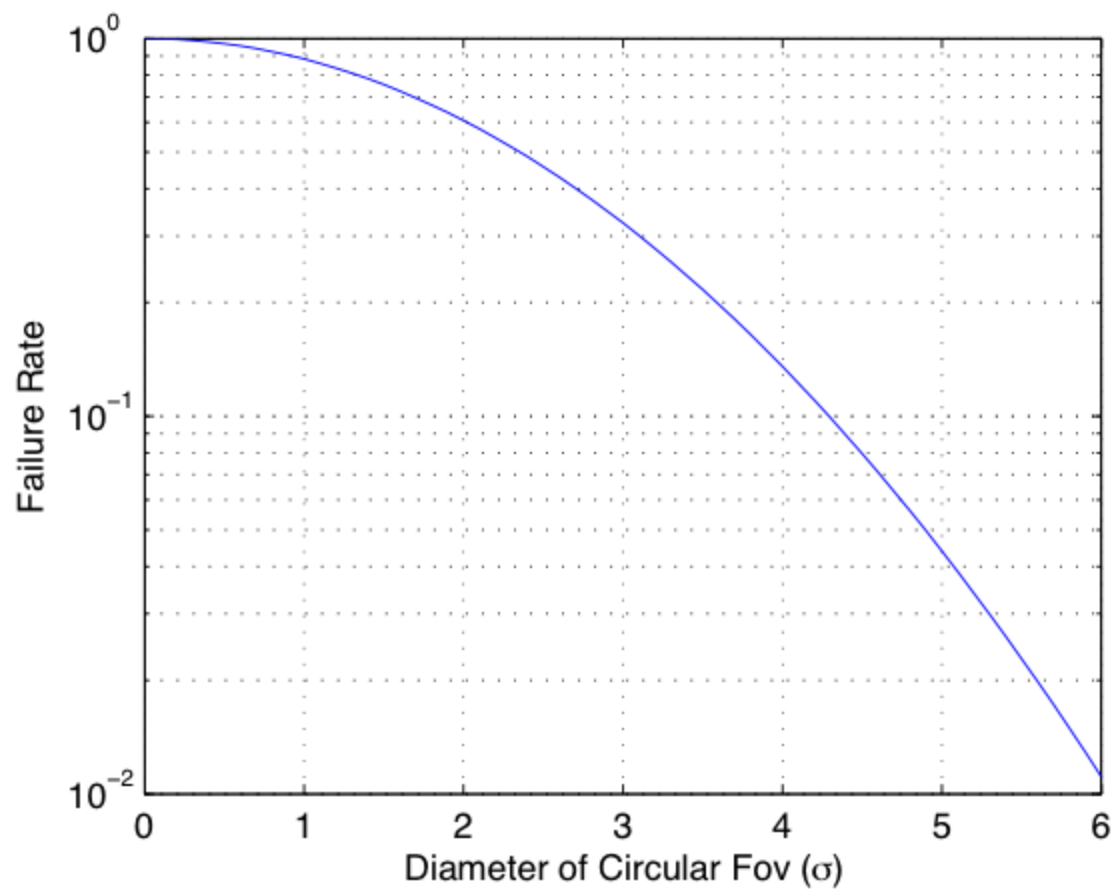


Figure 3. Figure 1?3. Probability of failed acquisition as a function of diameter of the circular FoV in terms of telescope pointing accuracy. $P(D) = \exp(-D^2/8)$

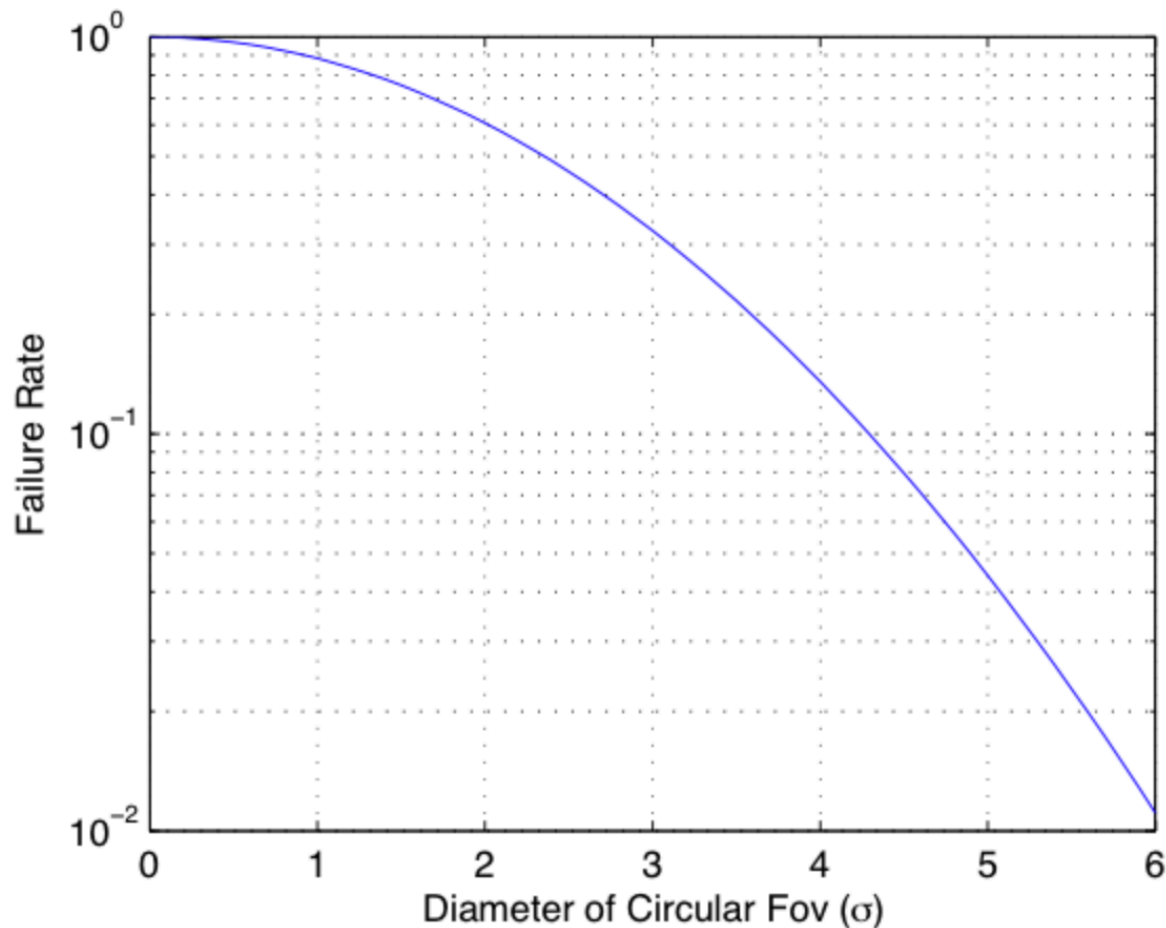


Figure 1-3. Probability of failed acquisition as a function of the ratio of the FoV and telescope pointing accuracy. $P(D) = \exp(-D^2/8)$

1.2.1.2.1.2 NFIRAOS NGS AO Mode

In NGS AO mode, NFIRAOS uses the PWFS with a bright visible natural guide star, and optionally a TTF OIWFS and/or an ODGW, to close the AO loops. The NGS is usually a star but can be a small extended object. The PWFS running in 96x96 mode has an effective sub-aperture size of 0.31 meters and a magnitude limit of $R \sim 13.5$ (RD1) for an on-axis H-band Strehl ratio of 50%. With a bright NGS ($R < 11$), the NGS AO mode provides superior on-axis performance to that of LGS mode. But the performance degrades for guide stars that are dimmer or at distances greater than about 5 arcsec from the science object.

The diameter of the PWFS field stop is less than 2 arcsec. Therefore the probability of missing the spots on the PWFS is greater than 60% as shown in Figure 1-3, which warrants the use of the acquisition camera.

1.2.1.2.1.3 NFIRAOS Seeing-Limited Mode

In the case of IRMS, there are science cases where NFIRAOS is used as an active Optics system. This is called NFIRAOS Seeing-Limited mode. This mode is implemented as degraded NGS AO mode with PWFS binned down and operating at lower frame rate, and an optional TTF OIWFS in IRMS. No ODGW is used in this configuration.

1.2.1.2.1.4 Stand-alone Mode

In Stand-alone mode, NFIRAOS uses light either from an internal calibration source or from the NSCU. There are a number of different functions performed in stand-alone mode. All functions of NFIRAOS (operating the DMs, LGS WFS, PWFS), the OIWFSs and the NFIRAOS-client instruments are exercised in this mode, with control commands from the AOSQ.

1.2.1.2.1.5 Parked Mode

In this mode, all the loops are stopped, all mechanisms are parked, the entrance shutter is closed, and the DM high voltage amplifiers and VCAM are turned off.

1.2.1.2.1.6 OFF Mode

In this mode, all mechanisms and functionalities are set according to the Parked mode. In addition, the enclosure is warmed to the ambient temperature. Panels on NFIRAOS can be opened for internal maintenance and repair.

1.2.1.2.2 Acquisition Sensors

- NSEN ACQ

The NFIRAOS near IR (NIR) Acquisition Camera (in target acquisition mode) is part of the NSEN unit mounted on the side port of NFIRAOS. It has a field of view of 20 arcsec, with a pixel scale of 0.08 arcsec/pixel and can patrol the whole 2° FoV within 30 seconds. The NIR detector is capable of detecting $J < 20.5$ [1] magnitude seeing-limited point source in a 10 s integration, with a 5 sigma confidence in ?bad? conditions. There is no ADC in front of the NSEN ACQ, so the impact of atmospheric dispersion has to be corrected when calculating telescope offset from NSEN ACQ images.

- IRIS/IRMS

When the third instrument is ready to be installed on the side instrument port, NSEN is removed. When this happens, the IRIS or IRMS imaging mode is used as the acquisition camera, with comparable or larger FoV than the current NIR acquisition camera. The pixel scales of the two imaging modes are about 0.004 and 0.06 arcsec, respectively.

It takes 30 seconds to fully open up the IRMS reconfigurable slit unit to put IRMS in imaging mode for acquisition purposes. The filter wheel in IRIS may also need depending on the brightness of the potential objects in field go to a narrowband or ND filter. The goal is to balance acquisition time vs. detector saturation. Moving the IRIS filter wheel can take up to 30 seconds.

[1] All magnitudes quoted in reference to NFIRAOS are Vega, not AB, magnitudes.

1.2.1.2.3 Calibration Sources

- NFIRAOS Science Calibration Unit

The NFIRAOS Science Calibration Unit (NSCU) is formally not part of NFIRAOS, but is permanently mounted in front of the NFIRAOS entrance window.

The NSCU provides daytime and nighttime calibrations to NFIRAOS-fed science instruments. Four main sets of calibrations are provided by the NSCU: uniform (flat) illumination for (1) pixel-to-pixel sensitivity corrections, (2) wavelength scale mapping, (3) point-spread-function mapping and (4) characterization of the on-instrument wavefront sensor pointing model.

The NSCU consists of: an integrating sphere fed by a set of lamps; a deployment mechanism or mirror to inject light into the beam to NFIRAOS; and a light-tight enclosure with an input shutter. The NSCU is mounted at the front of NFIRAOS.

During daytime calibrations, the NSCU is under control of the AOSQ for calibrating various NFIRAOS functionalities.

- Deployable Focal Plane Pinhole Mask

NFIRAOS includes a deployable focal plane pinhole mask, which is back-illuminated by the NSCU with both arc lamps and broadband light. It creates reference asterisms for calibrating pointing models for the PWFS SSM, instrument selection mirror (ISM), and for the client instrument OIWFSs and rotators. It also provides a reference for calibrating image distortion. The focal plane mask simulates pupil illumination onto the DMs, the WFSs and the instrument cold stops. It includes the following holes:

1. Isolated 25-micron (~11 mas) pinhole on axis and scattered over IRIS imager FoV (at every rotator angle) for alignment and PSF or NCPA calibration.
2. A dense grid of 25 mas pinholes, separated by 0.45 μ m, covering the FoV of the IRIS imager for astrometric calibration of IRIS.
3. An array of 250-micron pinholes along x/y axis and perimeter of NFIRAOS FoV for HRWFS.

The focal plane mask can be dithered in two dimensions by small, precise amounts during the astrometric calibration process.

Notice that there is no pupil mask in NSCU or NFIRAOS.

- Source Simulators

NFIRAOS source simulators include the following deployable artificial sources:

1. A single NGS source patrolling along the y axis.
2. LGS source simulator at range distance from 85 km to 235 km.

1.2.1.3 LGSF

The LGSF is responsible for generating artificial guide stars in the mesospheric sodium layer with the brightness, beam quality and asterism geometries required by both the NFIRAOS early light AO system and later AO instruments. Figure 1?4. LGSF block diagram gives a block diagram of the LGSF.

The baseline LGSF consists of 3 primary sub-systems:

- The Laser System, which includes up to nine 20 W?25 W CW or pulsed sodium lasers mounted on inside of the ?X_ECRS telescope elevation journal.
- The Beam Transfer Optics and the Laser Launch Telescope (BTO/LLT) system, which is responsible for taking the beams at the output of the laser system and transferring them up the telescope elevation structure and then launching them from the LLT located behind the TMT secondary mirror.
- The Laser Safety System, which provides interlocks to prevent laser damage to personnel, the TMT observatory or the LGSF itself. In addition, the LGSF provides safety systems to avoid accidental illumination of aircraft and satellites, and to avoid beam collision with neighboring telescopes.

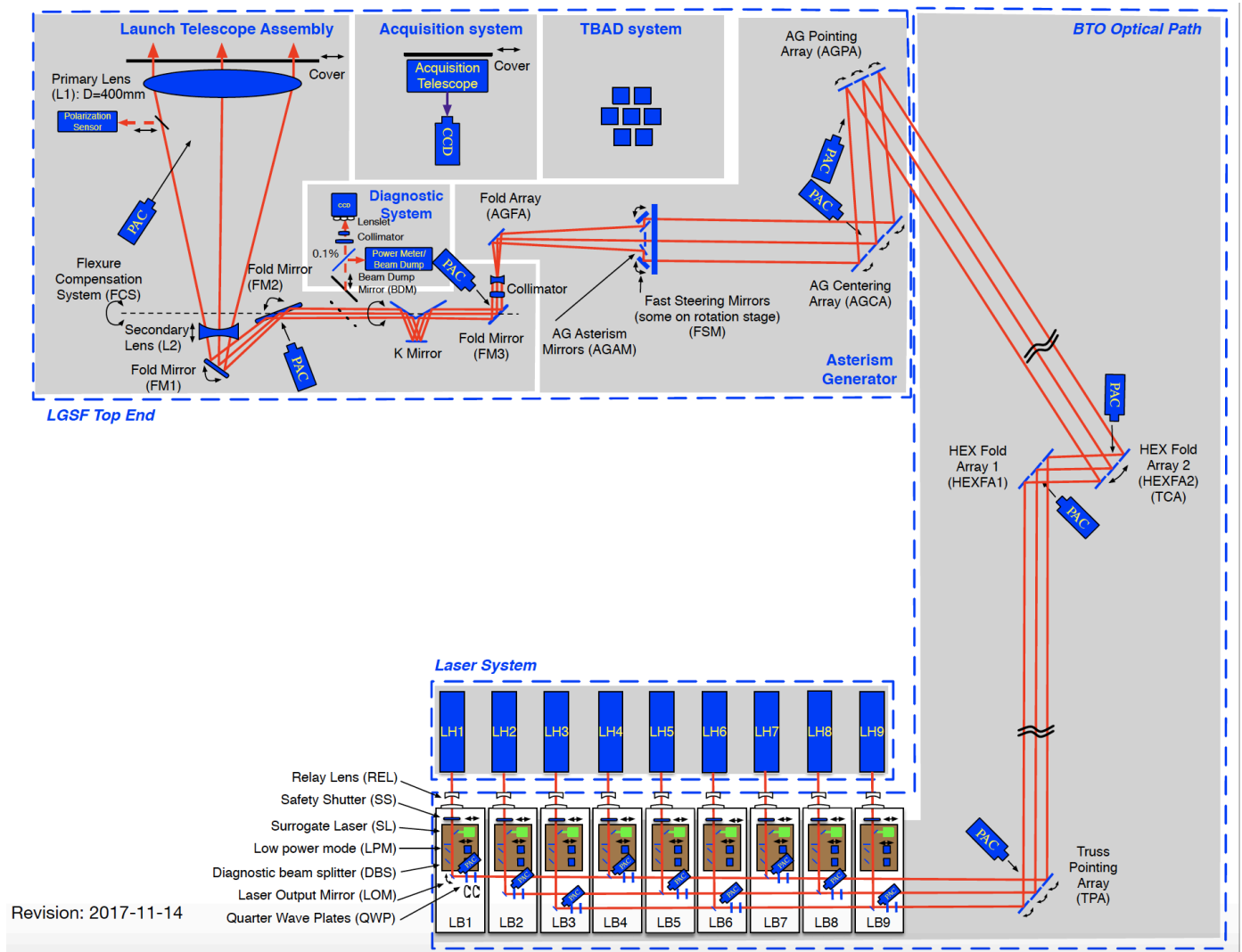


Figure 4. Figure 1?4. LGSF block diagram

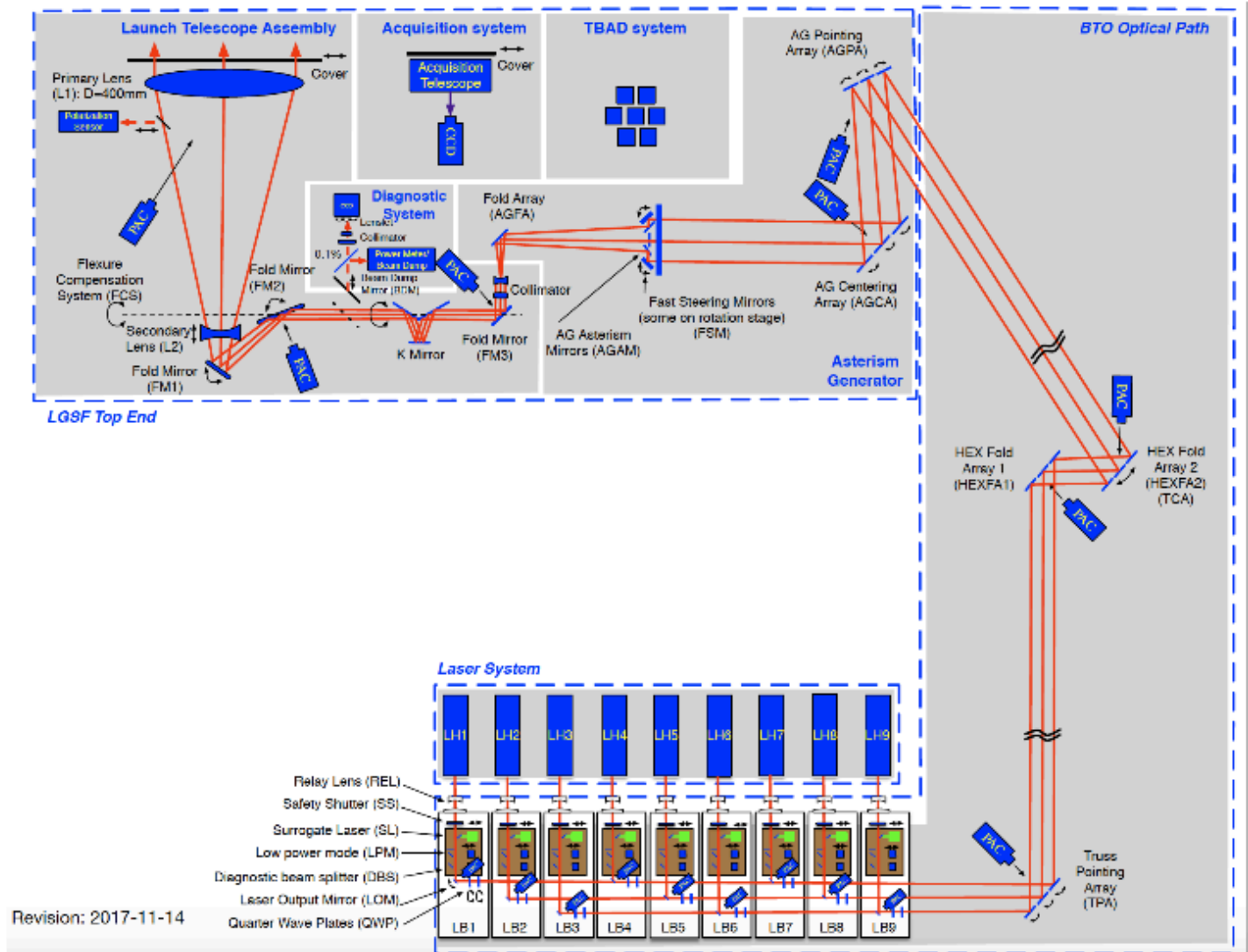


Figure 1?4. LGSF block diagram

The following operating modes are defined for the LGSF:

- ?Off mode?: The lasers are turned OFF, all the shutters are closed, and all the mechanisms are turned off.
- ?Shuttered mode?: The lasers are turned ON and the laser shutters are closed, as are the safety shutters and the Beam Dump Mirror (BDM). The LLT cover can be opened (at night) or closed (during the day).
- ?Standby mode?: The laser beams are propagated up to the BDM with an asterism already selected in the asterism generator, laser and safety shutters open and the active array loops closed. The LLT cover can be open (at night) or closed (during the day).
- ?Propagation mode?: The beams are propagated to the sky with the active arrays controlled in closed loop to compensate for flexure. The uplink tip/tilt loops may be open or closed (controlled by the NFIRAOS RTC).
- ?Alignment modes?: The purpose of these modes is to align the BTO and to build the LUT based on the telescope elevation angle and temperature.
 - Using the surrogate laser: In this mode, the lasers are turned OFF and the laser and safety shutters are closed. The BDM is not inserted. The LLT cover is closed. The surrogate laser is turned ON and inserted into the BTO. The pre-alignment cameras (PACs) are used to adjust the positions of the different arrays and perform a rough alignment of the BTO.
 - Using the low power mode: In this mode, the lasers are turned ON, the laser and safety shutters are open, and the 1/2 wave plate and thin film polarizer are inserted to reduce laser beam power. The BDM is inserted. The LLT cover is closed. The DOB cameras and PACs are used to build the active array control LUT.

1.2.1.4 IRIS

IRIS is a diffraction-limited integral field spectrometer and imager fed by NFIRAOS. IRIS operates over the wavelength range $0.8\text{ }\mu\text{m}$ to $2.4\text{ }\mu\text{m}$. The field of view of the IFU in its coarsest spatial sampling mode (50mas) is up to $3''$ along one spatial direction, and the field of view of the imager is $32.8'' \times 32.8''$. The IFU is located at the center of the imager FoV, and the imaging and spectroscopic channels can be operated in parallel. The plate scale of the IFU is adjustable to values of 4, 9, 25 and 50 mas/pixel. The IFU can provide resolutions of 4,000 and 8,000 and includes modes where the spectral resolution will be $R=4000$ over the entire Y, Z, J, H and K bands, one band at a time.

IRIS provides three OIWFS riding on pick off arms (POA) using infrared guide stars sharpened by the AO system. Each OIWFS can be configured in TTF (2 x 2 SHWFS) or TT mode. Each OIWFS POA is able to patrol slightly over a third of the full $2''$ corrected field produced by NFIRAOS.

The IRIS OIWFS has a wide band-pass that includes J, H, and Ks bands. The magnitude limit for each of the IRIS OIWFS natural guide stars is about $J = 22$. The pixel angular size is 6 mas. The instantaneous field of view is $1.5''$ with newly proposed APD detector (was $5''$ for a $1\text{ k} \times 1\text{ k}$ HIRG detector). With a telescope pointing accuracy of 1 arcsec RMS, the probability of seeing some light in one OIWFS is only 24.5% as illustrated in Figure 1-3. This mandates telescope pointing correcting using NSEN or IRIS imager.

IRIS also provides four ODGW, one in each quadrant of the imager focal plane. The ODGW pixel angular size is 6mas TT and 12 in TTF, and the ODGW utilizes the same pass-band selected for the science observation. The ODGW acquisition follows sub-window read out sequence, with a maximum window size defined as a percentage of the frame rate.

1.2.1.5 IRMS

The Infrared Multi-Slit Spectrometer (IRMS) is based on the Keck MOSFIRE, which was designed for the same f/ratio as the TMT Nasmyth foci. Its spectrograph mode uses the center $2'' \times 1''$ FoV whereas the imaging mode covers the entire $2''$ diameter FoV. The multiplexing capability of IRMS comes from a set of 46 movable cryogenic masking bars in the Reconfigurable Slit Unit (RSU), each $2.43''$ long on sky. These bars can be remotely retracted in 30 seconds to form an imager that covers the entire NFIRAOS FoV with a spatial sampling of 60 mas. IRMS has spectral resolutions of $R = 3000$ to 5000 over the Y, J, H and K bands ($0.97\text{ }\mu\text{m}$ to $2.45\text{ }\mu\text{m}$).

IRMS has only one tip/tilt/focus OIWFS. The patrol field is on one side of the rectangular FoV of the IRMS detector. If proved necessary (misidentified OIWFS during preparation), the whole instrument can be rotated by 180 degrees to reach guide stars on the opposite side.

IRMS does not provide any ODGW.

1.2.1.6 WFOS

The Wide-Field Optical Spectrograph (WFOS) enables multi-object spectroscopy with a high multiplexing capability (several hundreds of spectra). WFOS consists of two channels, which feed blue and red camera arms to simultaneously cover the wavelength range $0.34\text{ }\mu\text{m}$ to $1.0\text{ }\mu\text{m}$ with atmospheric dispersion correction. The total field of view is 40.3 square arcmin over a contiguous rectangular field of view of 9.6 by 4.2 arcmin (TBC). WFOS provides spectral resolutions up to $R = 7500$ (TBC) with a total slit length of 500 arcsec.

The AGWFS or OIWFS component in WFOS includes an acquisition camera, multiple guide cameras, and a low order wavefront sensor. The purpose of the acquisition camera is to align the telescope pointing with the WFOS focal plane. The guide cameras provide guide information to the telescope control system to keep the telescope pointing, and resulting focal surface position, correctly aligned on the mask while the WFOS observation is made. Multiple guide cameras provide image rotation information, which is also required to align the mask. The wavefront sensor provides low order (7×7 subaperture sampling, TBC) information to the telescope alignment and phasing system, to correct low order telescope alignment errors including focus.

1.3 Top Level Requirements

The TMT acquisition sequence includes the following processes:

1. Preset process: includes not only slew time but also the time to configure the telescope, enclosure, instrument, and/or AO system.
2. Acquisition process: includes the Guide Star Acquisition process and Science Target Acquisition process.

The top-level requirements for the observation preparation, the observation acquisition, the observation execution and the post observation activities are defined in the ORD (**AD1**) and OpsRD (**AD2**).

In particular, the following requirements are defined for the acquisition sequence and are summarized here:

- **[REQ-1-ORD-1805]** The TMT Observatory shall perform the complete target acquisition sequence in less than 5 minutes when an instrument change is not needed.
- **[REQ-1-OPSRD-3022]** TMT Observatory shall acquire an object from anywhere on the sky within five (5) minutes
- **[REQ-1-ORD-1800]** Within 3 minutes, the telescope and enclosure shall be able to point from any one position on the sky to any other in a way ensuring the uninterrupted execution of the next observation, and settle control loops and structural dynamics sufficiently to be ready for object acquisition.

Note: To ensure the uninterrupted execution of the next observation, the telescope motion may include un-wrapping the cables running from the observing floor to the azimuth structure.

- **[REQ-1-ORD-2656]** The TMT Observatory average slew time between science targets shall be less than 60 seconds
- **[REQ-1-OPSRD-3023]** TMT Observatory target acquisition and alignment onto an instrument aperture or long slit required to achieve final alignment shall be under two (2) minutes, and under three (3) minutes for multi-aperture instruments.
- **[REQ-1-ORD-1810]** The TMT Observatory shall be able to change from one instrument to another instrument already installed on the telescope in less than 10 minutes, starting from the end of an observation in one instrument to the start of observation in the other.
- **[REQ-1-ORD-1815]** The TMT Observatory shall be able to perform a major instrument reconfiguration in less than 10 minutes, starting from the end of an observation in one configuration to the start of observation in another.

Note: The meaning of "major instrument reconfiguration" must be defined for each instrument. This is envisioned to include such things as changes from imaging to spectroscopy. It is not intended to include minor changes such as movement of guide probes, changing filters etc.

The TMT Preset and Acquisition sequences presented in this document demonstrate that the TMT systems are flexible enough to accommodate a diversity of acquisition/observation sequences. This flexibility should be adequate to tackle more complex sequences not studied here that some programs might need. However, it should be emphasized that added complexity leads to greater risk of exceeding the 5-minute time budget.

1.4 Assumptions

1.4.1 Guide Star Catalogs and Astrometry

The efficiency of the preset and acquisition sequences presented here depend on how well target/guide star fields are characterized prior to TMT observations. In particular, the availability of precise astrometric solutions measured from high-quality imaging and/or catalogs is of prime importance to determine the relative positions of suitable natural guide stars relative to the science target. However, this is not always possible, especially for targets of opportunity such as gamma-ray bursts and other transient phenomena that may occur in previously unobserved regions of the sky.

Preset and acquisition sequences for Targets of Opportunity (ToO) may therefore include additional steps and may require more time to complete. Large surveys covering most of the sky (i.e., Vista Hemisphere Survey or the Large Synoptic Survey Telescope, albeit only from the southern hemisphere) may alleviate this problem.

For the TMT preset and acquisition sequences described below, we have included the path with/without prior knowledge of the target field. The prior knowledge of the target field is defined as:

- Objects suitable as natural guide stars. Extended objects ($> 1.7''$) should not be included in this list, however compact binary stars or other objects may be used if star separation is less than $1.7''$.
- Astrometric solutions applicable at the wavelength of the wavefront sensors. For instruments such as IRIS and IRMS, astrometric solutions should be obtained from near-IR observations.

1.4.2 Sequencing Architecture

Observations result in complex sequences involving the telescope (with or without AO) and the instruments. As described in the Software Architecture in the OAD (RD5), it is assumed that the ESW tasks the sequencing work during the observation to the appropriate sequencers:

- Telescope Control System (TCS)
- Adaptive Optics Sequencer (AOSQ) (In AO observations only)
- Instrument Sequencer (One per instrument)

1.4.2.1 TCS

The Telescope Control System controls the following sub-systems:

- The Enclosure (including dome, shutters, vents?)
- The Structure Mount Control System
- M1S and M1CS (including the M1 segments and the warping harness system)
- M2S
- M3S (including tracking)

Additionally, it is expected that the TCS implements the following functions:

- **Pointing kernel:** The TCS converts target position (right ascension and declination) into pointing and tracking demands in the appropriate coordinate system for use by the telescope mount; instrument and WFS/guiders probes or ODGW, atmospheric dispersion correctors, rotators; LGSF K-mirror; and the enclosure cap and base.
- **Wavefront Control:**
 - The TCS in Seeing-Limited operations, the correction module receives and processes tip/tilt and other corrections from the guider and wavefront sensors on Natural Seeing Instruments like WFOS.
 - The TCS in NFIRAOS NGS AO, NFIRAOS LGS MCAO and NFIRAOS Seeing-Limited modes, the corrections are based on an offload of the time average position of the AO tip/tilt stage and the DM; up to 100 modes can be offloaded in this configuration.

1.4.2.2 AOSQ

The Adaptive Optics Sequencer controls the following sub-systems:

- The Reconstructor Parameter Generator (RPG) and Point Spread Function Reconstructor (PSFR) of AOESW
- The NFIRAOS Real Time Controller (NRTC)
- The NFIRAOS Component Controller (NCC)
- The On Instrument Wavefront Sensor (OIWFS) Component Controllers (CC) elements of the NFIRAOS instruments
- The On Detector Guide Window (ODGW) of the NFIRAOS instruments
- The LGSF elements (BTO/LLT, Laser, and the Laser Safety System)
- The NSCU

1.4.2.3 IS

The Instrument Sequencers (IS) control the instruments. There is one instrument sequencer per instrument:

- InfraRed Imaging Spectrograph (IRIS) Instrument Sequencer
- InfraRed Multi-slit Spectrometer (IRMS) Instrument Sequencer
- Wide Field Optical Spectrograph (WFOS) Instrument Sequencer

The scenarios described in [Section 3.1](#) and [Section 3.2](#) are implemented within the sequencers (ESW, TCS, AOSQ and IS). However, it is expected that some of these sequences are only used either before or after the Observatory operations have achieved a steady state.

1.5 Applicable and Reference Documents

1.5.1 Applicable Documents

AD1 [Observatory Requirement Document \(ORD\)](#), (TMT.SEN.DRD.05.001.CCR28)

AD2 [Operations Requirements Document \(OPSRD\)](#), (TMT.OPS.MGT.07.002.CCR12)

1.5.2 Reference Documents

RD1 [NFIRAOS Pyramid WFS Trade Study](#), (TMT.AOS.TEC.14.140)

RD2 [AOESW PSFR Algorithm Description Document \(AOESW PSFR ADD\)](#), (TMT.AOS.CDD.14.003)

RD3 [Optimizing LGS WFS Pixel Processing in the Context of Evolving Turbulence and Sodium Profile](#), (TMT.AOS.TEC.15.014)

RD4 [Pyramid WFS as T/T Sensor for NFIRAOS](#), (TMT.AOS.TEC.15.105)

RD5 [Observatory Architecture Document \(OAD\)](#), (TMT.SEN.DRD.05.002)

RD6 [NFIRAOS Operations Concept Definition Document \(OCDD\)](#), (TMT.AOS.CDD.05.001)

RD7 [Initial Operational Concept Design Document \(OCDD\) for the Laser Guide Star Facility \(LGSF\)](#), (TMT.AOS.CDD.05.033)

RD8 [TMT Infrared Imaging Spectrograph \(IRIS\) Initial Operational Concepts Definition Document \(OCDD\)](#), (TMT.INS.DRD.06.002)

1.6 Acronyms

aO	Active Optics
ACQ	Acquisition Camera
ADC	Atmospheric Dispersion Corrector
ADD	Algorithm Definition Document
AGCM	Asterism Generator Centering Mirror
AGFA	Asterism Generator Fold Array
AGPM	Asterism Generator Pointing Mirror
AGWFS	Acquisition, Guiding, and Wavefront Sensing
AIV	Assembly, Integration and Verification
AO	Adaptive Optics
AOESW	AO Executive Software
AOSQ	Adaptive Optics Sequencer
arcmin	arcminute
arcsec	arcsecond
BDM	Beam Dump Mirror
BS	Beam Splitter
BTO	Beam Transfer Optics
CC	Component Controller

CCD	Charge Coupled Device
CW	Continuous Wave
CoG	Center of Gravity
DC	Detector Controller
DM	Deformable Mirror
DM0	Deformable Mirror Ground Conjugate
DM11	Deformable Mirror Conjugate to 11.8 km
DOB	Diagnostics Optical Bench
e.g.	Exempli Gratia (Latin for the sake of example)
EI	Electronics
FF	Far Field
FoV	Field of View
FSM	Fast Steering Mirror
FWHM	Full Width at Half Maximum
GUI	Graphical User Interface
H2RG	Hawaii 2k with Reference rows and Guide window
HCD	Hardware Control Daemon
HEXFA	Hex Fold Array
HPF	High Pass Filter
HRWFS	High Resolution Wavefront Sensor
IFU	Integral Field Unit
ICD	Interface Control Document
IR	InfraRed
IRIS	InfraRed Imaging Spectrograph
IRMS	InfraRed Multi-slit Spectrometer
IS	Instrument Sequencer
ISM	NFIRAOS Instrument Selection Mirror
IMF	Initial Mass Function
km	kilometer
LGS	Laser Guide Star
LGSF	Laser Guide Star Facility
LLT	Laser Launch Telescope
LUT	Lookup Table
m	meter
M1	Primary Mirror Optics System
M2	Secondary Mirror System
M3	Tertiary Mirror System
mas	milliarcsecond
MCAO	Multi-Conjugate Adaptive Optics
MOS	Multi Object Spectroscopy

NCC	NFIRAOS Component Controller
NCPA	Non Common Path Aberration
NF	Near Field
NFIRAOS	Narrow Field InfraRed Adaptive Optics System
NGS	Natural Guide S`tar
NIR	Near Infrared
NRTC	NFIRAOS Real Time Controller
NSCU	NFIRAOS Science Calibration Unit
NSEN	NFIRAOS Sensor
NRTC	NFIRAOS RTC
OAD	Observatory Architecture Document
OCS	Observatory Control System
OAP	Off Axis Parabola
OCDD	Operational Concept Definition Document
ESW	Observatory Control System
ODGW	On Detector Guide Window
OIWFS	On Instrument Wavefront Sensor
OPSRD	Operations Requirements Document
ORD	Observatory Requirements Document
OSW	Observatory Software
PAC	Pre-Alignment Camera
POA	Pick Off Arm
PSFR	Point Spread Function Reconstructor
RA/dec	Right Ascension/declination
RMS	Root Mean Square
RPG	Reconstructor Parameter Generator
PWFS	Pyramid WaveFront Sensor
RSU	Reconfigurable Slit Unit
RTC	Real Time Controller
SCMS	Site condition monitoring system
SED	Spectrum Energy Density
SLODAR	Slope Detection and Ranging
SMBH	Super Massive Black Holes
S/N	Signal to Noise Ratio
SOSS	Science Operations Support Subsystem
SSM	Star Selection Mechanism
SW	Software
TBAD	Transponder Based Aircraft Detection
TBC	To Be Confirmed
TCA	Truss Centering Array

TCS	Telescope Control System
TMT	Thirty Meter Telescope
TNO	Trans-Neptunian Object
ToO	Target of Opportunity
TPA	Truss Pointing Array
TT	Tip Tilt
T/T	Tip/Tilt
TTF	Tip Tilt Focus
TTP	Tip Tilt Platform
TTS	Tip/Tilt Stage
TWFS	Truth Wavefront Sensor
VCAM	Visible Camera (for LGS or NGS)
WFS	Wavefront Sensor
WFOS	Wide Field Optical Spectrograph
w.r.t	With respect to

2 Observation Preparation

2.1 IRIS/IRMS And NFIRAOS Observation Preparation

2.1.1 Observation Preparation Tools

In order to make efficient use of TMT, NFIRAOS and the science instruments, the observer needs to prepare their observation in advance, as described in the next section. To make these preparations, the observer needs access to guide star catalogues and the observation preparation software tools, including the integration time calculators and AO performance modeling tools.

The Strehl ratio delivered by NFIRAOS depends most critically on the seeing at the time of the observation. However, other factors may also have a significant impact on the system performance. These factors include air-mass, sky transparency and background (moon phase), brightness and location of natural guide stars, etc. There may also be other trade-offs to be made; for example, is the system better with a mildly extended tip-tilt source close to the target or using a known star that is located at the outermost limits of the tip-tilt guide field?

To properly identify the observing conditions that are required for a successful NFIRAOS with IRIS/IRMS observation, and make informed decisions regarding guide stars, the observer uses the PWFS, OIWFS and ODGW selection tool (as part of SOSS), which includes the NFIRAOS LGS MCAO/NGSAO and Seeing-Limited performance modeling tool to select the optimal WFS guide asterism ahead of the observation using known star catalogue information, or available images. If the selected guide stars have not been used before, backup stars should also be selected in case the stars are not point source or have wrong magnitude. TMT keeps a database for guide stars that have been successfully used.

The guide star selection tool could also be used during the acquisition step with acquisition images taken by the NFIRAOS acquisition camera or science instruments. The guide stars selection tool should be able to select a near optimal asterism in less than 5?20 seconds (TBC).

2.1.2 Inputs to the Observation Execution

Observing programs need to provide the following inputs for the successful execution of the observations:

- Coordinates (RA/Dec, epoch) of science object/field
- Rate of apparent motion for non-sidereal targets
- AO mode (NFIRAOS NGSAO, NFIRAOS LGS MCAO or NFIRAOS Seeing-Limited) and corresponding coordinates (RA/Dec, epoch), magnitudes and colors or spectrum energy density (SED) of natural guide stars
- Instrument configuration
- Sequence of science and nighttime calibration exposures (arc, flats, darks, off?source)
- Type and sequence of daytime calibrations
- Spectrophotometric or photometric standard stars observations
- Radial velocity standard star (if needed)
- Weather, minimum image quality (Strehl ratio, enclosed energy, PSF FWHM, etc.) ,and Sky Background under which observations should be conducted.
- Pattern for dithering..

This list may not be complete and additional observation input parameters may be required. However, for certain observations, such as a new field or target of opportunity, some of the information, such as guide star choice, may not be available. In such instances, the acquisition may require longer time.

These inputs need to be provided by observers in a detailed format that can be stored in the observing database so that observing programs can be efficiently sequenced. Sequencing is key in meeting the required acquisition time budgets.

For AO observations, a backup plan should be always prepared in case:

- NFIRAOS LGS MCAO observations are not possible,
- NFIRAOS NGSAO not suitable for planned target,
- Image quality or Strehl requirement cannot be met,
- An AO instrument is not available,

- NFIRAOS is not available, etc.

The backup plan should ideally include NFIRAOS NGS AO mode and NFIRAOS Seeing-Limited mode operations. Backup science targets may also be prepared, e.g. standard stars. Detailed parameters should be provided for each AO mode in the backup plan.

2.1.3 Startup

In late afternoon, all the components in the AO systems go through initialization and self-test to prepare for day/night time calibration and night time observations.

All the server computers remain on 24/7 once installed and configured. So the daily start up process does not involve turning on those computers, but the software components may need to be re-initialized and run self-tests.

The following describes the start up procedure for each AO subsystem, which may be executed in parallel. These procedures are initiated from the AOESW engineering GUI or the ESW.

The startup operations do not contribute to the time required to start an observation. They are only carried out in the afternoon if AO observations with NFIRAOS are planned.

2.1.3.1 Laser Guide Star Facility (LGSF)

The AOSQ initiates an LGSF initialization command, followed by a self-test on all the mechanisms and functionalities of the LGSF and check that the LGSF is in a ?health? state. The mechanisms and functionalities include but may not be limited to:

1. BTO: laser bench mechanisms, truss pointing/centering arrays, pre-alignment cameras, quarter wave plate rotator, beam dump mirror, fast steering mirrors (FSM), asterism generator pointing/centering mirrors, k-mirror, etc.
2. LLT: zoom lens, cover, flexure compensation system, etc.
3. Acquisition system: acquisition camera.

The AOSQ turns on the lasers with all the shutters in closed condition (no propagation in BTO).

Note: the laser beams cannot be propagated without the BTO elevation dependent loop turned on.

2.1.3.2 NFIRAOS

The AOSQ does the following in series:

1. Initialize all NFIRAOS assemblies, followed by a self-test on all the mechanisms and functionalities of NFIRAOS and check that NFIRAOS is in a ?healthy? state.
2. Turn on the DM high voltage and run a self-test on DM electronics, e.g., look for possible short, open circuits, etc. The high voltage is turned off after calibration is finished.
3. Check the NSCU entrance shutter status to make sure it is closed. Then turn on the LGS and NGS (PWFS) VCAM if they are off.
4. Initialize the RTC with the default AO configuration.

2.1.3.3 IRIS or IRMS OIWFS

The AOSQ initializes and runs a self-test on all the mechanisms in all the OIWFS, and turns on the cameras.

2.1.3.4 RPG

The AOSQ initializes the RPG with default configurations.

2.1.3.5 PSFR

It will be possible (TBC) to run PSFR in automatic mode in day/night time unless engineering mode is enabled manually.

2.1.3.6 IRIS, IRMS

Initialize these instruments with their respective instrument sequencers.

2.1.4 Calibration

All LGSF, NFIRAOS and Instruments OIWFS/ODGW calibration procedures should be fully implemented in the AOSQ if they are used after the AIV stage. Some procedures may be developed and used internally in NFIRAOS during INT/AIV stage and finally merge into AOSQ.

The NFIRAOS and OIWFS/ODGW calibration procedures are initiated from the AOESW engineering GUI. Detailed diagnostics tools are provided in an advanced mode in the AOESW engineering GUI and/or command line interface.

2.1.4.1 Instrument Daytime Calibration

This is discussed in the Instruments OCDD and/or Instruments Calibration Plan (RD10)

2.1.4.2 NFIRAOS Calibration During INT/AIV Stage

NFIRAOS calibration procedures during INT/AIV stage that are not needed after AIV are not listed in this document. Please refer to the NFIRAOS calibration plan.

2.1.4.3 NFIRAOS Infrequent Day Time Calibration

The following procedures do not need to be carried out daily, but are executed during initial AIV, periodically (frequency TBD), and after major services.

2.1.4.3.1 PWFS SSM Pointing Model

Turn on the broadband light in NSCU and deploy the NFIRAOS focal plane mask.

Move the SSM to zero out the pupil misregistration and pointing error iteratively with error signal provided by the RTC. The pupil misregistration is measured using the PWFS (quadrant averaged) illumination pattern with a matched filter algorithm, and the pointing error is measured by the global tip/tilt.

Repeat for all locations of NGS source and build the SSM pointing model.

During observation, the pupil misregistration determined by the PWFS is fed to the TCS to fix the M2/M3 pointing error.

2.1.4.3.2 DM to LGS WFS Interaction Matrices

Activate the LGS calibration source in NFIRAOS, with location corresponding to telescope at the specified zenith angle. Set LGS Trombone accordingly. Set the LGS WFS integration time according to the brightness of the calibration sources.

Ask the RTC to apply a series of patterns on DM0 or DM11 as provided by the RPG. Trigger the LGS WFS VCAM to take one (or multiple, TBD) exposure after each DM command. The RTC sends averaged gradients to the RPG, which then computes the interaction matrix based on these measurements.

Distortion/misregistration parameters are extracted from the measured interaction matrices. These parameters are incorporated in an interaction matrix model to compute the interaction matrix that is used in the RPG to compute the RTC control matrix.

Repeat for various zenith angles.

2.1.4.3.3 DM to PWFS Interaction Matrices

The method is similar to the DM0 to LGS WFS interaction matrices with telescope at zenith, although no model based interaction matrix are computed. The patterns applied to the DM0 consist of Karhunen-Loeve modes.

2.1.4.3.4 DM to Science Pupil Distortion (TBC)

Set the ISM to HRWFS (NSEN) position. Use the on-axis artificial NGS source in NFIRAOS. Apply a series of TBD patterns on each DM and measure the gradients in HRWFS. Misregistration/distortion parameters can be extracted in a similar way as the DM to LGS WFS interaction matrix case. Repeat with a different artificial NGS source within the instrument FoV. The parameters obtained here are used in the RPG DM fitting model when computing the control matrix.

2.1.4.3.5 NCPA Calibration

Due to hysteresis and other non-linear effects of the DM, the LGS WFS gradient offset is used during all NCPA calibrations to maintain DM figure, and loaded during operation to flatten the DMs. The HRWFS and PWFS use sources on the FPM illuminated by the NSCU in high visible flux mode, with the IRIS shutter closed. As an example, the IRIS imager and OIWFS use sources on the FPM with the NSCU in low flux mode. The LGS WFS uses NFIRAOS calibration LGS sources.

NCPA within NFIRAOS is calibrated by zeroing out HRWFS measurements, with the gradient offset of LGS and PWFS (at many locations) measured and recorded. It is possible to do tomographic correction by patrolling HRWFS along multiple directions.

NCPA in IRIS is calibrated after NCPA in NFIRAOS has been fully calibrated and applied to the LGS AO loops. Only ADC-induced aberrations (at the pupil) within IRIS are calibrated in this procedure as other surfaces are either not conjugated to the ground or DM11 (e.g., TMAs) or have negligible effects (e.g., filters) on image quality.

Closed-loop phase diversity is carried out to minimize the wavefront error on-axis by applying additional gradient offsets for the LGS WFS. The defocus can be applied to DM0 by applying a focus offset to the LGS WFS gradient reference vector. The PWFS gradient offset is recorded on-axis with the IRIS shutter closed (while LGS WFS is maintaining DM figure) so that brighter sources can be used. Instrument image quality (Strehl ratio, FWHM, enclosed energy, etc.) is also recorded in addition to the WFS gradient reference vectors for use in PSF reconstruction. TTF OIWFS focus is also recorded which may arise due to differential focus error between the OIWFS and the science focal plane.

The additional component in WFS gradient reference vectors due to NCPA in IRIS is reconstruction into OPD and then converted to gradient reference vectors for different IRIS rotator angles.

2.1.4.4 NFIRAOS Daily Day Time Calibration

The following procedures are carried out daily.

2.1.4.4.1 PWFS Dark Frame

With the NSCU shutter closed, take an exposure with the PWFS at typical NGS AO frame rates (from 10 to 800 Hz) and TWFS frame rates to determine the dark frame caused by NFIRAOS alone. Determine the readout noise, dark current and background from the data. The night sky contribution to the PWFS is negligible in NGS AO mode but may not be in TWFS or TTF mode for LGS MCAO.

2.1.4.4.2 Check NFIRAOS and Instrument Alignment

With artificial NGS sources, the tip/tilt measurement from OIWFS and ODGW should be within tolerance. If not, TBD diagnostics are carried out.

2.1.4.4.3 DM to WFS Registration Verification

With artificial guide star sources turned on for each WFS, apply DM patterns and measure gradients using each WFS. Compare against results obtained by multiplying the interaction matrix with the applied DM patterns to determine the change in misregistration. This additional misregistration can be used to update the parameters for DM to WFS interaction matrix computation (TBC). TBD diagnostics are carried out if the misregistration is too large.

2.1.4.4.4 Exercise the RTC with NCPA using the DM

Activate the LGS calibration source in NFIRAOS and NSCU. Set the corresponding trombone position for LGS WFS. Configure RTC for LGS MCAO operation mode. RPG sends to the RTC WFS gradient offsets and DM system flats obtained during NCPA calibration for each instrument, and computes the control matrix for the RTC. Inject turbulence by DM command offsets via the RTC.

Close the AO loops and assess the image quality (Strehl ratio, FWHM, or Enclosed energy) using the corresponding instrument and compare with the values obtained during NCPA calibration. Smoothly vary simulated telescope zenith angle from 0 to 60 degrees, rotate instrument rotator, adjust LGS trombone, and update RTC parameters (control matrix, NCPA gradient offset, etc., by RPG). Assess the image quality during the process.

Repeat in NGS AO mode and for each instrument and a few selected operation modes.

The mechanism to convert telescope zenith angle to instrument rotator and LGS trombone position is TBD. During night-time observation, this is done by the TCS, but during day time, TBD needs to provide this function.

2.1.4.5 LGSF Infrequent Daytime Calibration

The follow procedures do not need to be carried out daily, but are executed during initial AIV, periodically (frequency TBD), and after major services.

2.1.4.5.1 Calibrate LGSF Optical Path LUT

Calibrations here use laser in low power mode.

The interaction matrix between the mirror actuator and the pre-alignment camera (PAC) measurements is calibrated by moving the actuators and computing beam displacement in the following mirror and PAC along the optical path.

The optical path look up table is calibrated as follows. Use the pre-alignment cameras (PAC) to detect beam locations on the optical path mirrors, and then optimize actuated mirror mounts to center beams in select locations. Populate the LUT by repeating the process for different zenith angles.

2.1.4.5.2 Calibrate LGSF Asterism Generator and K-mirror

2.1.4.5.3 Calibrate LGSF Quarter Wave Plates

2.1.4.6 LGS Daily Daytime Calibration/Test

2.1.4.6.1 LGSF BTO/LLT Alignment Verification

Enable LGSF BTO TCA/TPA follow LUT mode. Propagate low power laser up to BDM. Close PAC loops. Check images from pre-alignment cameras while varying telescope zenith angle from 0 to 65.

2.1.4.7 NFIRAOS Night Time Calibration

The nighttime calibrations are generally required after major system maintenance or as part of a dedicated engineering run or observation.

2.1.4.7.1 Telescope to LGS WFS Lenslet Array Pupil Distortion

Tilt a number of telescope primary segments. LGS WFS subapertures behind these segments are blacked out. Compare the subaperture illumination pattern against the theoretical value to derive subaperture coordinate displacement.

The telescope to LGS WFS lenslet pupil distortion may not be negligible due to the finite distance to the LGS. The wavefront reconstruction algorithm can compensate this distortion partially by altering ray tracing.

2.1.4.7.2 Telescope to PWFS Pupil Misregistration/Magnification

With the telescope pointing to multiple preselected bright natural guide stars at various zenith angles, compute the pupil magnification/misregistration in PWFS by comparing the WFS pupil illumination pattern to reference values determined at daytime calibration. The TCS alignment tables is optimized to null the difference.

This procedure may need to be done regularly.

2.1.4.7.3 Instrument Image Distortion Calibration with Natural Starlight

The distortion effects caused by NFIRAOS and IRIS optics are calibrated during daytime using the NSCU and NFIRAOS pinhole grid, but additional distortion effects due to telescope optics and the NFIRAOS window need to be calibrated with natural star light, with the AO loop closed in LGS MCAO mode.

2.1.4.7.4 Telescope NCPA Calibration

The telescope optics, such as M3, can induce non-common path aberrations that cannot be calibrated during daytime using calibration sources. The PWFS (LGS WFS TBD) gradient reference vector needs to be updated using on sky calibrations.

Start NFIRAOS acquisition in LGS MCAO mode with ISM set to HRWFS (on axis). Point the telescope to a guide star for HRWFS and acquire it. Acquire another guide star at various field angles for the PWFS. Adjust the PWFS reference vector to null the HRWFS gradients (after its reference vector subtraction, time averaged). Record the time-averaged gradients in PWFS as the updated reference vector.

2.1.4.7.5 AO Performance Checkout

At night time, with laser guide stars and/or bright natural guide stars, a routine AO test may be necessary to verify the system stability and AO performance. The telemetry collected during this test is recorded for long-term AO performance analysis.

2.1.4.7.6 Vibration Spectrum

With NFIRAOS in NGS AO mode, close the AO loops with a bright NGS on axis and a TTF OIWFS on the same star. Run the OIWFS at a high frame rate (800 Hz). Run PSD analysis on the collected global tip/tilt measurement to determine the vibration spectrum. This can be used to diagnose possible observatory problems and/or tune the vibration suppression algorithm.

This procedure may be done together with the AO performance checkout.

2.1.4.8 LGSF Night Time Calibration

2.1.4.8.1 Calibrate LGSF Flexure Compensation System

Point the telescope to a bright natural guide star and acquire and guide on it using APS. Acquire the same natural guide star on the LGSF acquisition camera (LACQ) along with the laser beam. Adjust the flexure compensation system (FCS) to align the laser beam with the natural guide star.

Populate the LUT by repeating the process for natural guide stars at different zenith angles.

2.1.5 Pre-imaging to Determine Guide Stars and AO Mode

For new star fields that haven't been observed in detail before and a guide star catalogue doesn't exist, pre-imaging the field may be required to determine guide stars and/or the preferred AO mode. The TMT baseline is to have guide star catalogues available, so the time used to **pre-image is not taken into account in the overall Preset and Acquisition time requirement of 5 minutes.**

The procedure to obtain TMT pre-imaging is as follows:

- First, close the LGS loop without OIWFS. If IRIS or IRMS is online, the ESW asks the IRIS or IRMS instrument sequencer to take an image, otherwise the ESW asks the NSEN ACQ camera to take an image centered on the science target and a few additional images surrounding the target by offsetting the telescope. The integration time is set by the limiting guide star magnitude of the OIWFS/ODGW. Non-destructive readout may be carried out and analyzed as integration is continuing if supported by the camera.
- The ESW-ACQ module displays the acquired images for the astronomer to identify the guide stars. The choice of AO mode normally is made based on the following rules:
 1. If there is a bright enough natural guide star very close to the target and the required science FoV is small, NFIRAOS NGSAO mode is used with this guide star.
 2. If weather conditions (no strong cirrus or cloud) and laser traffic control and satellite predictive avoidance permit laser propagation, and $J < 22$ guide stars for OIWFS/ODGW are available, NFIRAOS LGS MCAO mode is used.
 3. If laser propagation is not permitted and there is a natural guide star suitable for NGSAO mode albeit with degraded performance, NFIRAOS NGSAO mode is used with this guide star.
 4. Otherwise, if there is at least a guide star for seeing-limited mode, the NFIRAOS seeing-limited mode of IRMS/IRIS is used.
 5. The choice of instrument (IRIS or IRMS) depends on the target and scientific purpose.

2.2 WFOS Observation Preparation

TBA

3 Observation Preset and Guide Star Acquisition

In most cases, the timing of this **Preset Sequence** should be dominated by the time needed to configure the telescope and enclosure. This time is defined in [REQ-1-ORD-1800] and [REQ?1?ORD?2656] in the ORD (AD1) and shall not exceed 3 minutes and a long term average of less than 60 seconds. See sections 3.1.1 and 3.2.1 for more details.

The **Guide Star Acquisition Sequence** consists of acquiring the guide stars and closing the aO and/or AO loops. This task consists of several sub-tasks, which are interleaved and depend upon the required instrument configuration and the observation. The time defined shall not exceed 4 minutes average. See sections 3.1.2, 3.1.3, 3.1.4 and 3.2.2 for more details.

Finally, the **Science Target Acquisition Sequence** consists of additional fine-tuning alignment of the science target onto the instrument (MOS alignment, IFU ...etc). This task also consists of a set of sub-tasks, which depend on the careful characterization of the instrument and associated wavefront sensors as well as the nature of the target. This third task is defined in detail in the instrument OCDDs (See section 4.0 for details) and are not counted in the 5 minute overall acquisition time.

This document describes in full detail the Preset and Guide Star Sequence Acquisition timing.

3.1 IRIS/IRMS and NFIRAOS Preset and Guide Star Acquisition Sequences

All plausible preset and guide star acquisition scenarios for each instrument/configuration/mode of NFIRAOS and IRIS are summarized in (RD10) and described in detail in the following sub-sections.

We grouped all these plausible scenarios (53 for LGS MCAO and 12 for NGS AO) by commonalities into a total of 6 groups for LGS MCAO and 1 for NGS AO, using the TIER definition in (RD10).

We modeled all these scenarios and groups with activity and sequence diagrams using Model-Based Systems Engineering (MBSE). We ran timing simulations of all these different scenarios in a Monte-Carlo statistical sense with probabilistic flows. Sections 3.1.2.8 and 3.1.3.1 show the results of these timing simulations.

3.1.1 Preset Sequence for IRIS/IRMS and NFIRAOS

For all instruments in all configurations (NFIRAOS Seeing limited, NFIRAOS NGS AO or NFIRAOS LGS MCAO), the Preset Sequence of an acquisition consists of the three TMT main sequencers performing the following actions almost in parallel (Figure 3-1):

- **(Task S1)** The Telescope Controls System (TCS) points the telescope and enclosure to the science target and configures the telescope sub-systems (including guide stars coordinates).
- **(Task S2)** The Instrument Sequencer (IS) configures the Instrument.
- **(Task S3)** The AO Sequencer (AOSQ) configures the AO sub-systems.

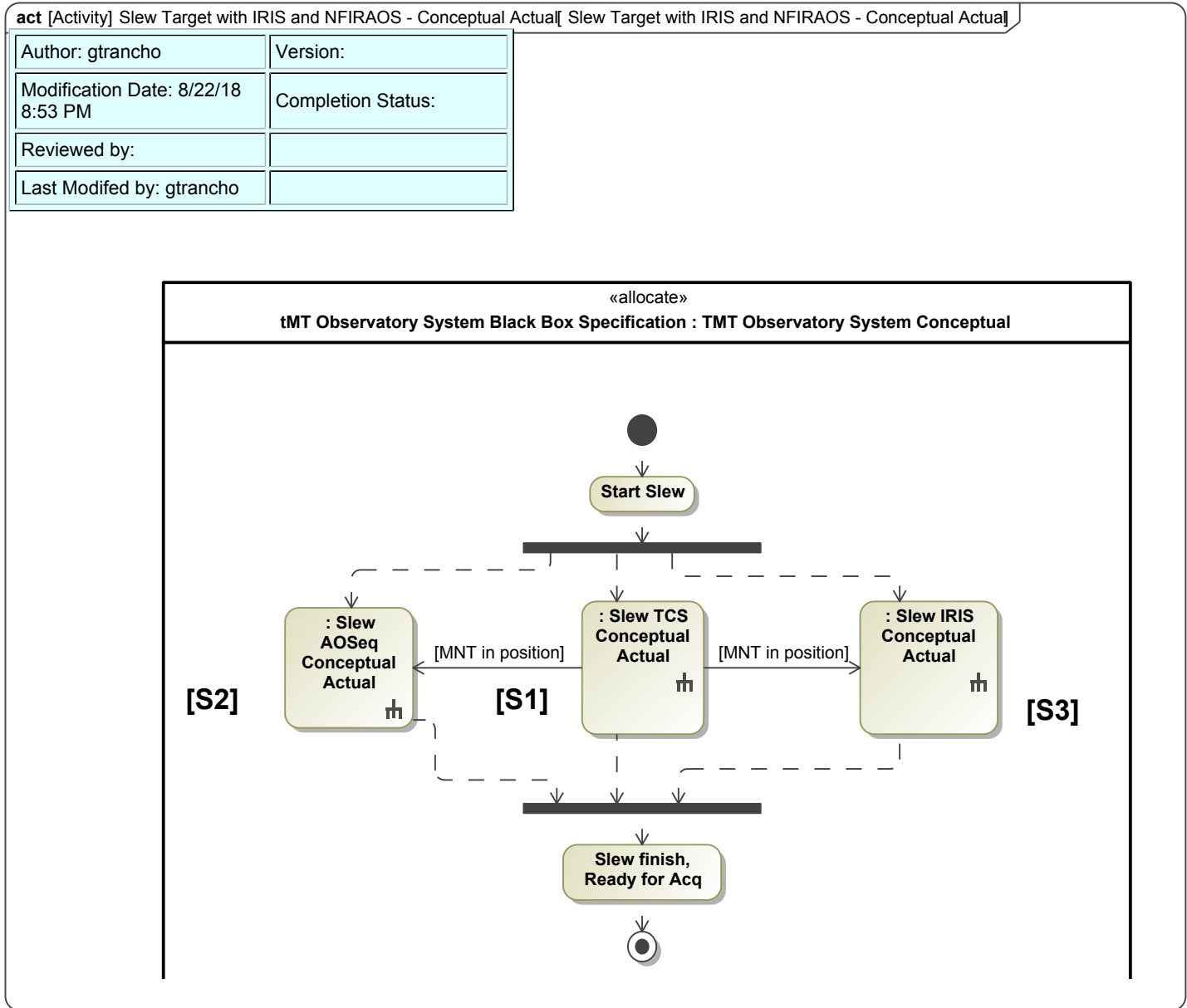


Figure 5. Slew Target with IRIS and NFIRAOS - Conceptual Actual

Figure 3-1: Preset Sequence for IRIS and NFIRAOS

Task S1: The ESW tasks the TCS to Preset the science target coordinates and configure the telescope for LGS operation (Figure 3-2):

The TCS performs the following tasks in parallel:

- Rotate the enclosure.
- Configure the telescope (mount, M1, M2, M3) for target position.
- Compute and provide elevation angle and position demands for LGS trombone (if LGS is used), OIWFS POA, ODGW position, PWFS SSM, instrument rotator, and various ADCs, based on the telescope destination position. These values are updated in real time as telescope tracks.

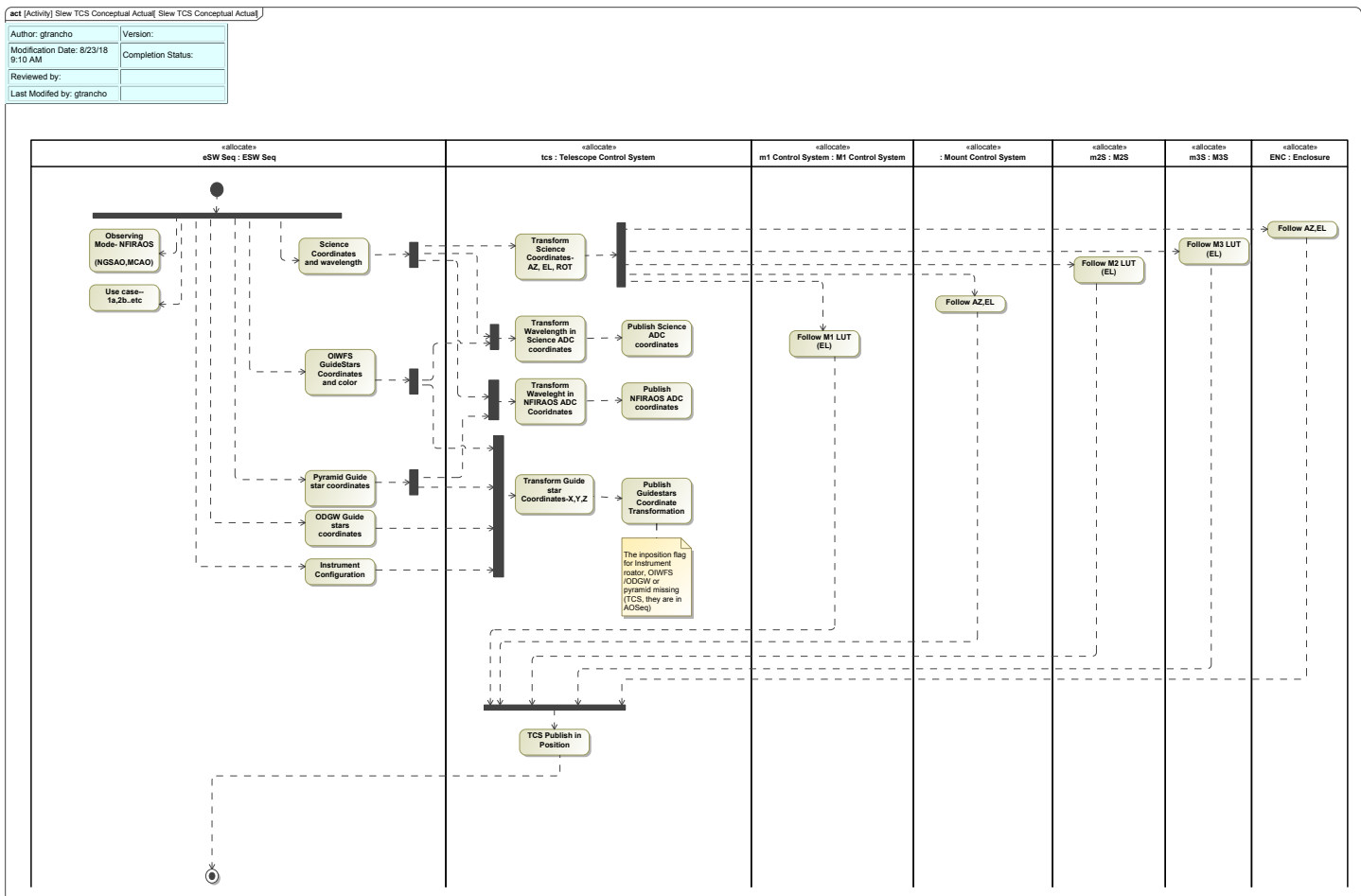


Figure 6. Slew TCS Conceptual Actual

Figure 3-2: Task S1-Preset TCS

Task S2: The ESW tasks the AOSQ to configure the AO systems for NFIRAOS NGSAO or LGS MCAO or NFIRAOS Seeing-Limited operation (**Figure 3-3**). The TCS computes and provides elevation angles and position demands for the LGS trombone (if LGS is used), OIWFS POA, ODGW position, PWFS SSM, instrument rotator, and various ADCs, based on the telescope destination position. These values are updated in real time as the telescope tracks.

Many of the following steps take less time if the last observation was done in the same mode.

The AOSQ performs the following tasks in parallel:

- Configure NFIRAOS for NFIRAOS NGSAO or LGS MCAO mode.
 - Set the ISM to the desired acquisition sensor position (NSEN ACQ camera if online or IRIS/IRMS otherwise) for acquiring OIWFS/PWFS as the TTF WFS.
 - Select the science beam splitter.
 - Enable PWFS ADC and SSM follow mode.
 - Enable LGS zoom follow mode (telescope elevation angle) (LGS MCAO only).
 - Configure the PWFS VCAM.
 - Configure the LGS VCAM (LGS MCAO only).
 - Configure the NFIRAOS NSEN ACQ if used.
 - Configure the NFIRAOS RTC for NGSAO or LGS MCAO operation.
 - Configure the timing generator (LGS VCAM) (LGS MCAO only).
 - Configure the timing generator (OIWFS, ODGW).
- Configure the LGSF for LGS observations (LGS MCAO only).
 - Configure the BTO for the NFIRAOS asterism based on the available lasers.
 - Start the BTO elevation dependent loops based on LUT.
 - Start the LLT flexure compensation system based on LUT.
 - Enable the K-mirror and quarter wave plate follow mode.

- Initialize the Fast Steering Mirrors (FSM) control source.
 - Start the FSM to AGPM/CM and flexure compensation system offloading process.
 - For pulsed laser only: configure the laser trigger box to trigger the pulse at specific start time and period.
 - Put the LGSF in standby mode by opening laser shutters with BDM inserted, and enabling TPA/TCA active control using diagnostic sensors.
 - Configure the LGSF ACQ camera.
- Configure the OIWFS Component Controller
 - Set which OIWFS is used and the mode (TT or TTF).
 - Select the neutral density filter and/or color filter if implemented.
 - Enable OIWFS POA, ADC and instrument rotator follow mode.
 - Enable continuous readout mode.
- Configure the IRIS ODGW (If used)
 - Initialize sub-window stepping sequence table for each ODGW.
 - Enable continuous read out mode.
- Configure the RPG module for LGS operation
 - Obtain Cn2 profile, sky transparency, etc. from SCMS (or use previous value from RTC).
 - Start generating reconstruction parameters. Send to RTC when ready.
 - Configure for listening to new data from RTC and send to RTC updated reconstruction parameters.

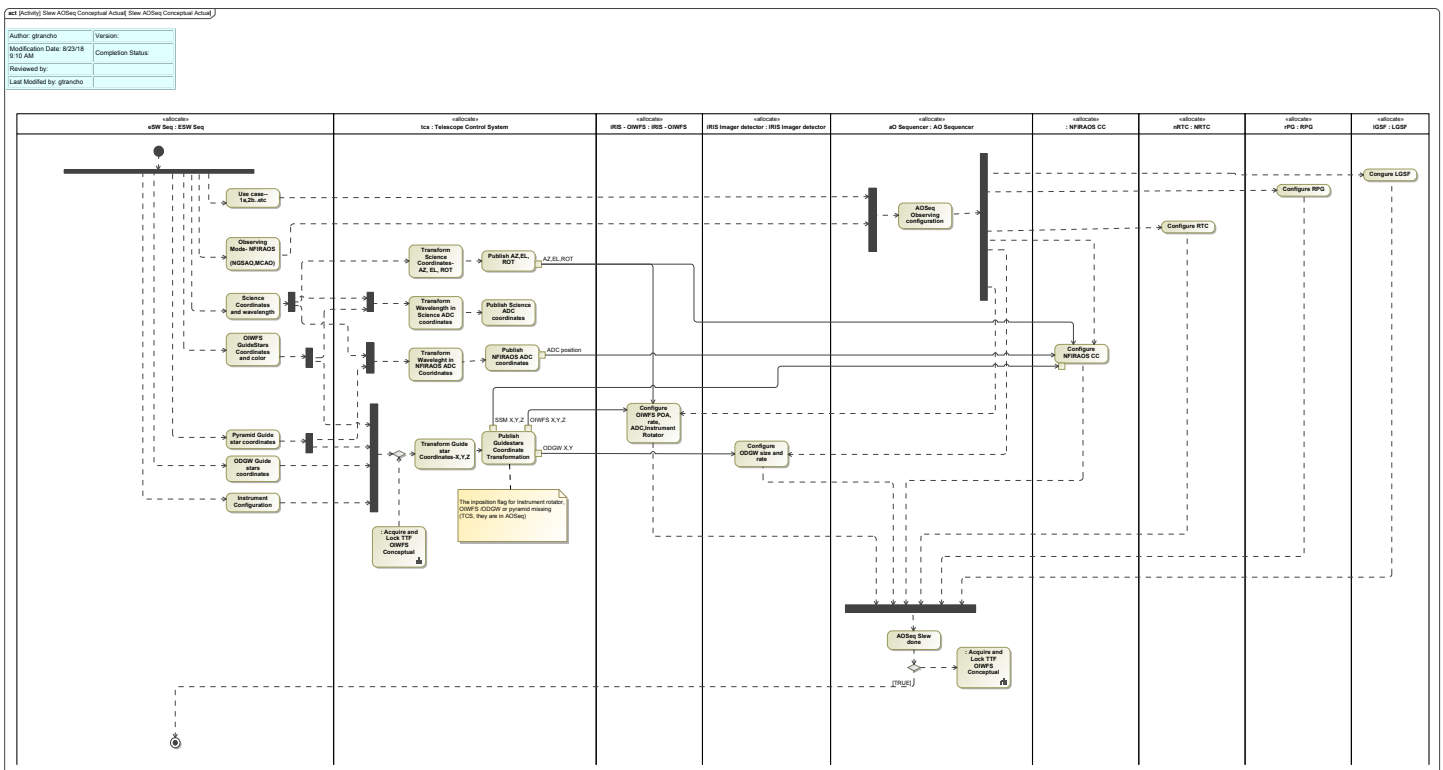


Figure 7. Slew AOSeq Conceptual Actual

Figure 3-3: Task S2- Preset AOSQ

Task S3: The ESW tasks the Instrument Sequencer to configure IRIS/IRMS for the observation (**Figure 3-4**)

The Instrument Sequencer performs the following tasks in parallel:

- When NSEN ACQ is not in use, the instrument is responsible for Checking Telescope Pointing (**Task A1**).
- Configure and enable follow for: gratings, selected periscope/mirror, selected slicer or mirror, science ADC, rotating Lyot stop, filter wheel, etc.

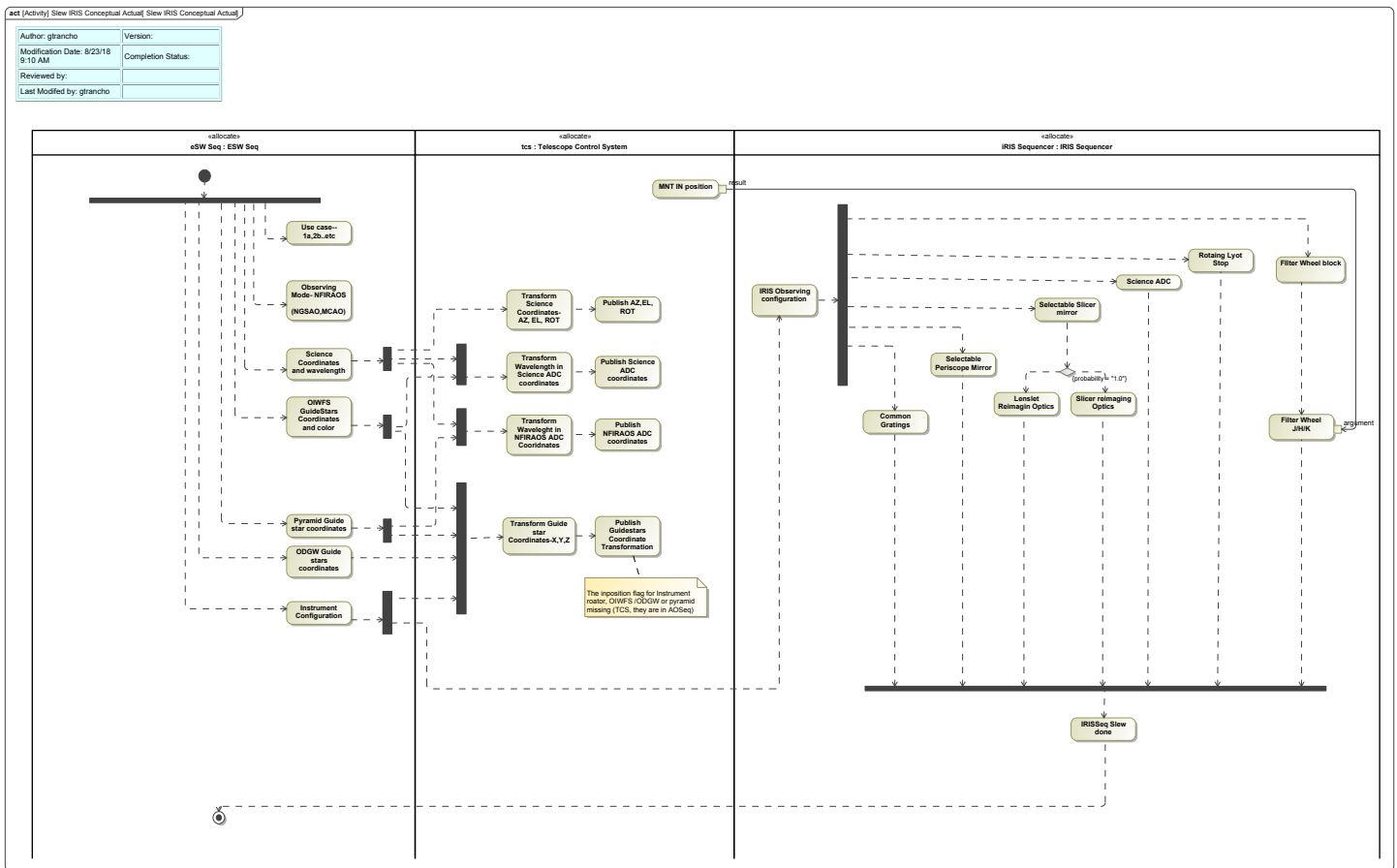


Figure 8. Slew IRIS Conceptual Actual

Figure 3-4: Task S3- Preset Instrument Sequencer

3.1.2 Guide Star Acquisition Sequences for IRIS/IRMS and NFIRAOS LGS MCAO Observations

The NFIRAOS LGS MCAO Guide Star Acquisition Sequences with IRIS and IRMS instruments are very similar. Up to three OIWFS and four ODGW can be used with the IRIS instrument, whereas only one OIWFS is used with the IRMS instrument. From now on, we refer to NFIRAOS and IRIS sequences only for simplicity.

The PWFS may use a different guide star from the OIWFS/ODGW, or it may reuse one of the OIWFS/ODGW guide stars. The brightest OIWFS guide star (adjusted by Strehl ratio) is generally used for the TTF OIWFS. The full list of combination of guide stars is shown in RD10.

The overall NFIRAOS LGS MCAO Guide Star Acquisition Sequence is given in Figure 3-5, showing all possible groups. These groups are triggered by the combination of the different tasks shown in Figure 3-5. We describe each of these tasks below [A1 to A9].

act [Activity] Acquire a target with IRIS and NFIRAOS - Conceptual Actual[Acquire a target with IRIS and NFIRAOS - Conceptual Actual]

Author: rkarban	Version:
Modification Date: 8/23/18 9:19 AM	Completion Status:
Reviewed by:	
Last Modified by: gtranco	

tMT Observatory System Black Box Specification : TMT Observatory System Conceptual

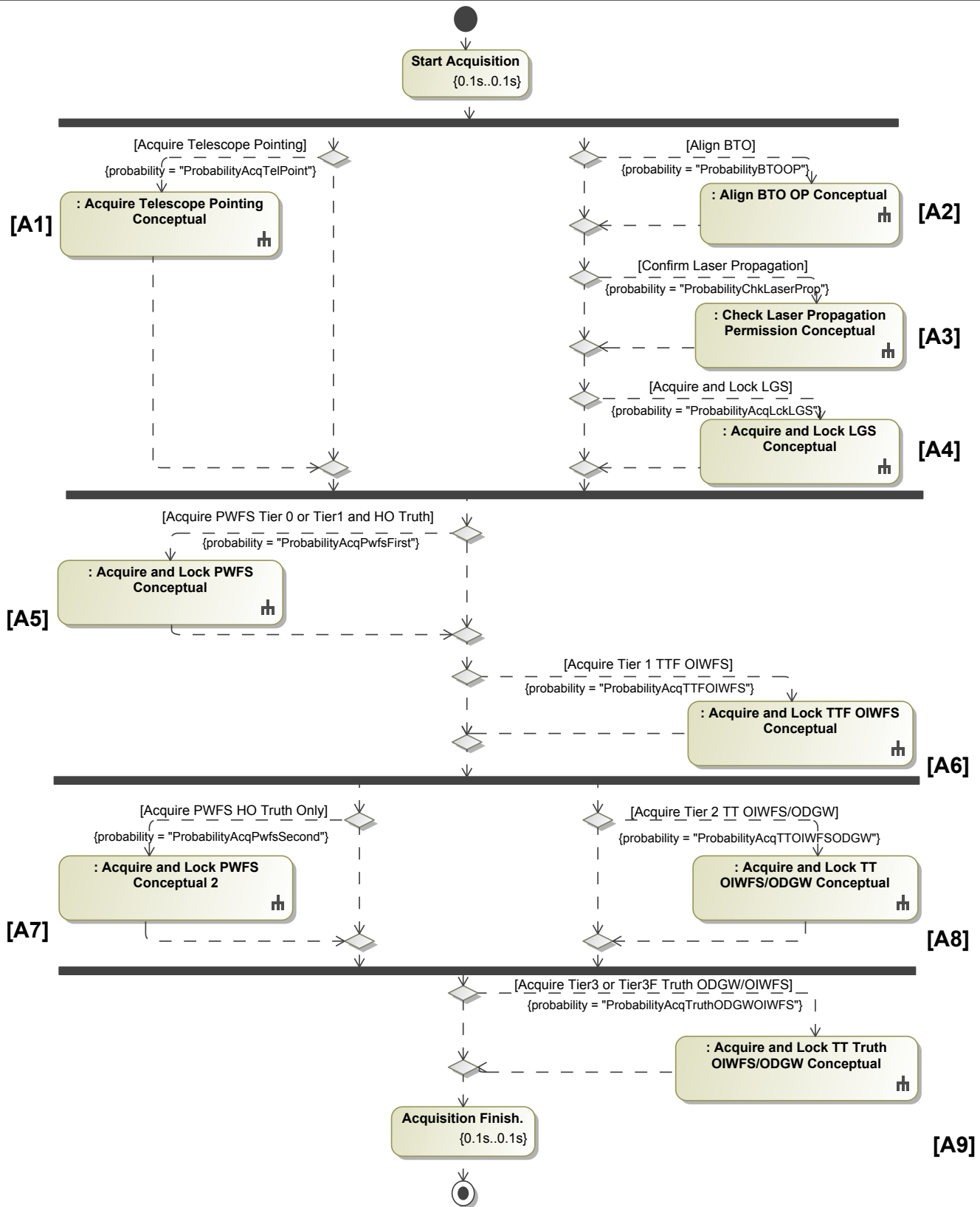


Figure 9. Acquire a target with IRIS and NFIRAOS - Conceptual Actual

Figure 3-5. IRIS and NFIRAOS LGS MCAO Mode Guide Star Acquisition Sequence

3.1.2.1 Task A1: Acquiring Telescope Pointing

Task A1: Acquiring Telescope Pointing

Depending on the achieved performance of the telescope pointing, there are two different choices for initial acquisition to fix pointing and focus error:

1. When telescope blind focus error is expected to be more than $1''$ (i.e., $> \text{seeing}$, e.g., during commissioning, at the beginning of night, or after a large slew), the ESW configures the TCS to point the telescope to a $J < 19$ bright star (which can be either the TTF guide star or a nearby one) for pointing and focus correction (see Figure 3-6a and b).
2. When the telescope blind focus error is expected to be less than $0.2''$, the blind pointing error is expected to be better than $1''$ (TCS meets the $1''$ RMS pointing error requirement, or after a short slew), and the OIWFS is used as the fast TTF sensor, the acquisition camera step is skipped, and the telescope is blind pointed to place guide stars on OIWFS and PWFS.

The telescope pointing acquisition is presented in Figure 3-6, representing the case 1 above, using IRIS as the pointing check camera. A similar sequence is generated for NSEN (not shown). Details on this task are describe below:

1. The ESW asks the AOSQ to trigger an acquisition camera exposure if NSEN ACQ or IRIS is used; otherwise asks the IRIS/IRMS sequencer to take an image.
2. A dedicated ESW ACQ and TCS module retrieves the image. ESW ACQ displays the image.
3. In automatic mode:
 - the TCS module identifies the coordinate of the object with a pattern matching or box search algorithm. Fall back to manual mode if automatic identification fails.
4. In manual mode:
 - the ESW ACQ module displays the message and lets the operator select the object.
5. The TCS module then computes the telescope offset based on the object position in the ACQ image, corrects atmospheric dispersion, and applies the offset demand.
6. Stop images from NSEN or IRIS
7. Move ISM back to the instrument (if needed)

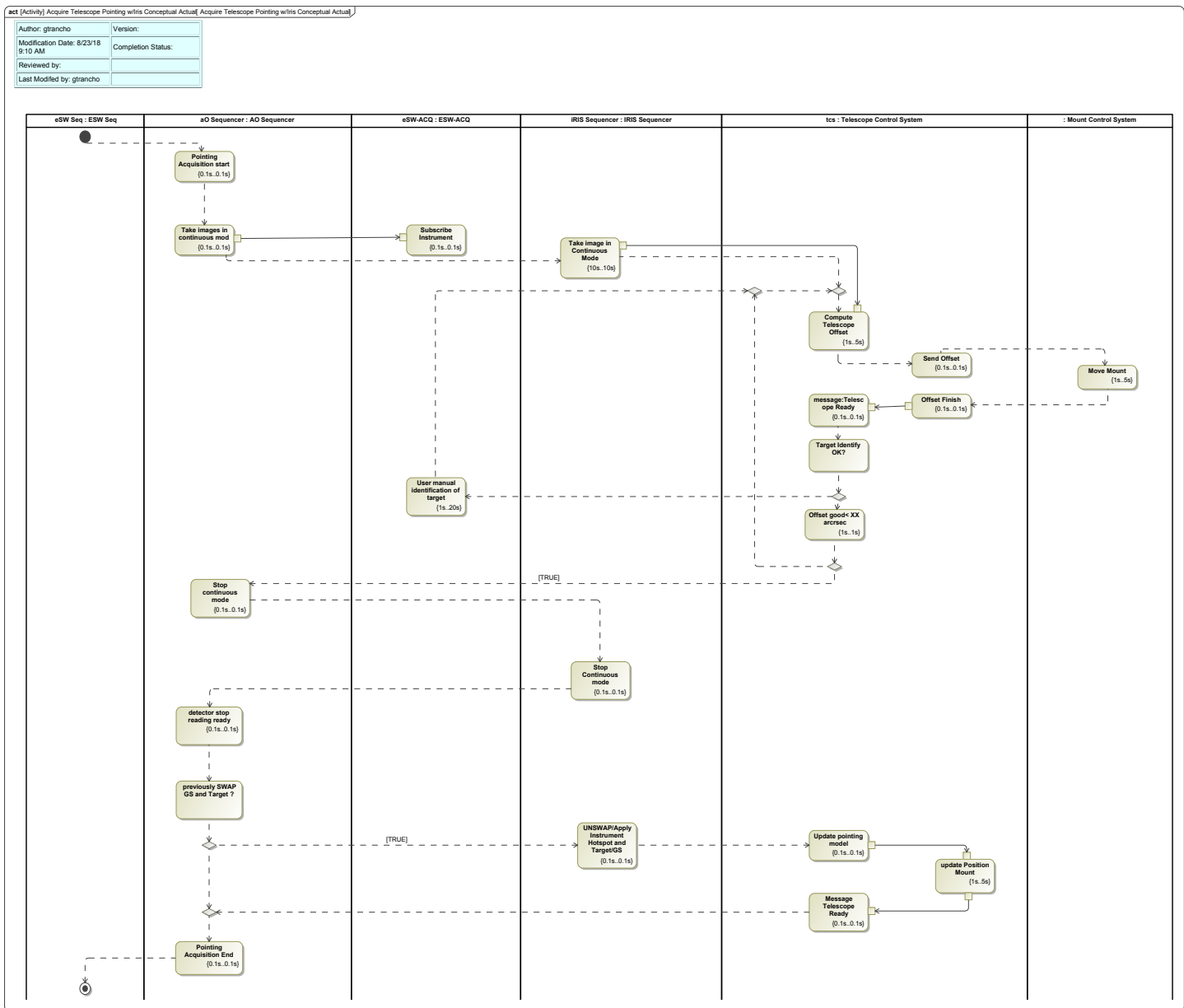


Figure 10. Acquire Telescope Pointing w/Iris Conceptual Actual

Figure 3-6: Task A1-Telescope Pointing Acquisition with IRIS

3.1.2.2 Task A2, A3 & A4: Align Laser thru BTO, Check Laser Propagation Permission and Acquire and Lock Laser Guide Star

Task A2, A3 & A4: Align Laser thru BTO, Check Laser Propagation Permission and Acquire and Lock Laser Guide Star.

The ESW tasks the AOSQ to propagate the laser, acquire the LGS, and close LGS loops (Figures 3-7a and b).

The AOSQ does the following in series:

1. Check alignment of BTO laser to beam dump (Figure 3-7a):

- Using PAC cameras and laser low power.
- Switch to high power when alignment is completed.

2. Confirm permission to propagate laser to the sky when condition (weather, space command, LTCS, etc.) permits (Figure 3-7b).
3. Configure the BTO/LLT control system (Figure 3-7c):
 - Propagate the LGS asterism
 - Check the asterism geometry with LGS acquisition camera.
 - Ask the RTC to acquire the LGS using the Rayleigh backscatter pattern. Proceed to the next steps when it converges.
 - Ask the RTC to close the uplink FSM and trombone loop.
 - The RTC starts computing CoG gradients from illuminated subapertures (flux above TBD threshold, but exclude those that are affected by Rayleigh backscatter, determined using algorithm), and closes the uplink FSM and trombone loops.
 - The LGS WFS focus HPF is set to zero pass during this process.
 - Fine tune the LGS WFS parameters:
 - Based on LGS WFS flux reported by the RTC, the AOSQ may choose to change the main sampling frequency by programming the LGSF and LGS WFS VCAM trigger sources.
 - Ask the laser controller to briefly detune the laser and then ask the RTC to perform the Rayleigh background calibration.
 - Command the RTC to close the LGS loop:
 - Enable LGS WFS pixel processing background processes (dithering and matched filter update, drift mode computation, etc.).
 - Start LGS WFS reconstruction.
 - Start wavefront corrector control to close the high order loop. The loop is expected to converge within 10 frames.
 - Start TCS mode offloading process 1) from persistent DM shape 2) scalloping mode from gradients.
 - Collect and send statistics (including PSD, SLODAR) to the RPG at specific interval and listen for new parameters from RPG.

act [Activity] Align BTO OP Conceptual Actual[Align BTO OP Conceptual Actual]

Author: gtranco	Version:
Modification Date: 8/23/18 9:10 AM	Completion Status:
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Last Modified by: gtranco	

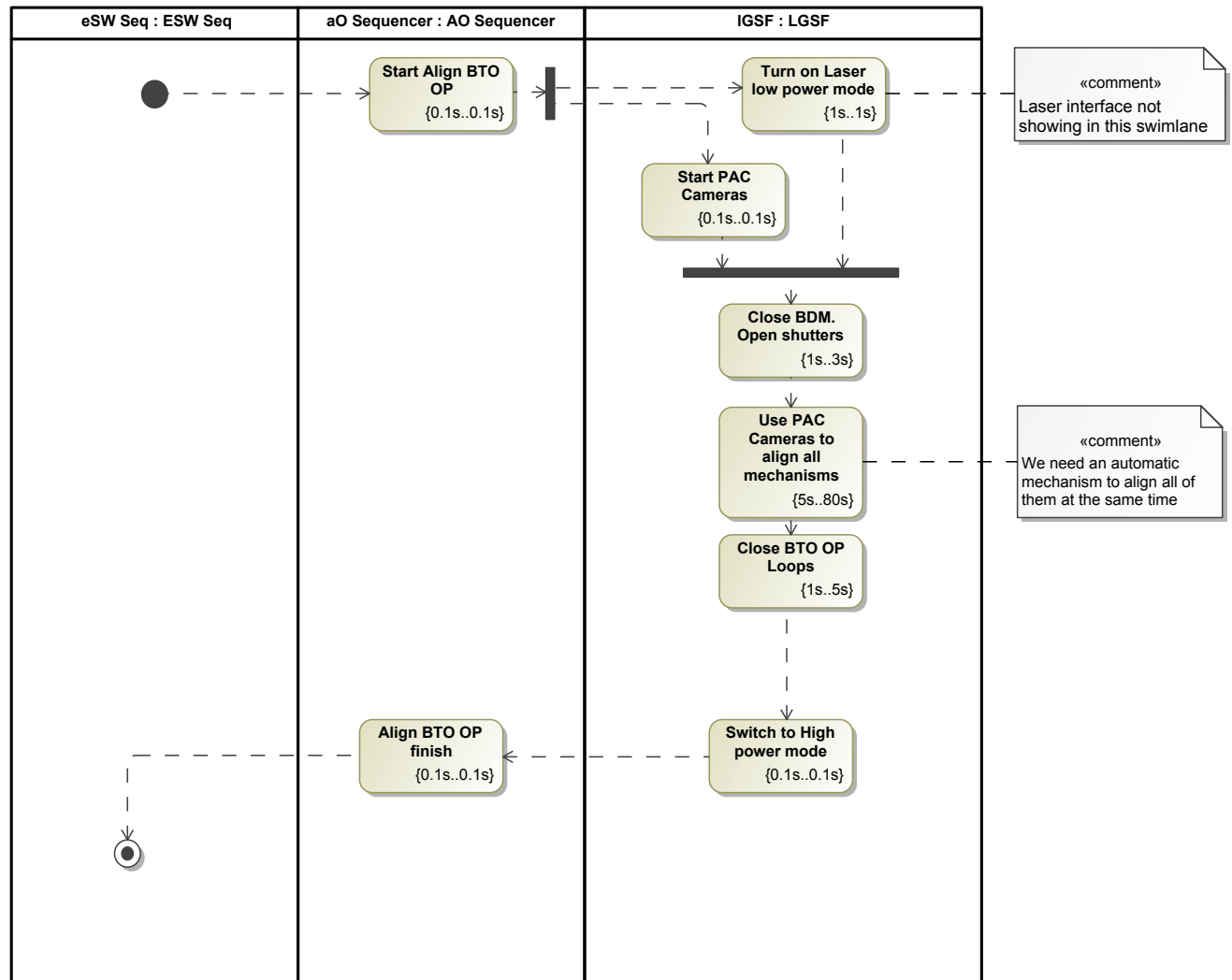


Figure 11. Align BTO OP Conceptual Actual

Figure 3-7a: Task A2-BTO Acquisition

act [Activity] Check Laser Propagation Permission Conceptual Actual[Check Laser Propagation Permission Conceptual Actual]

Author: gtranco	Version:
Modification Date: 8/23/18 9:10 AM	Completion Status:
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Last Modified by: gtranco	

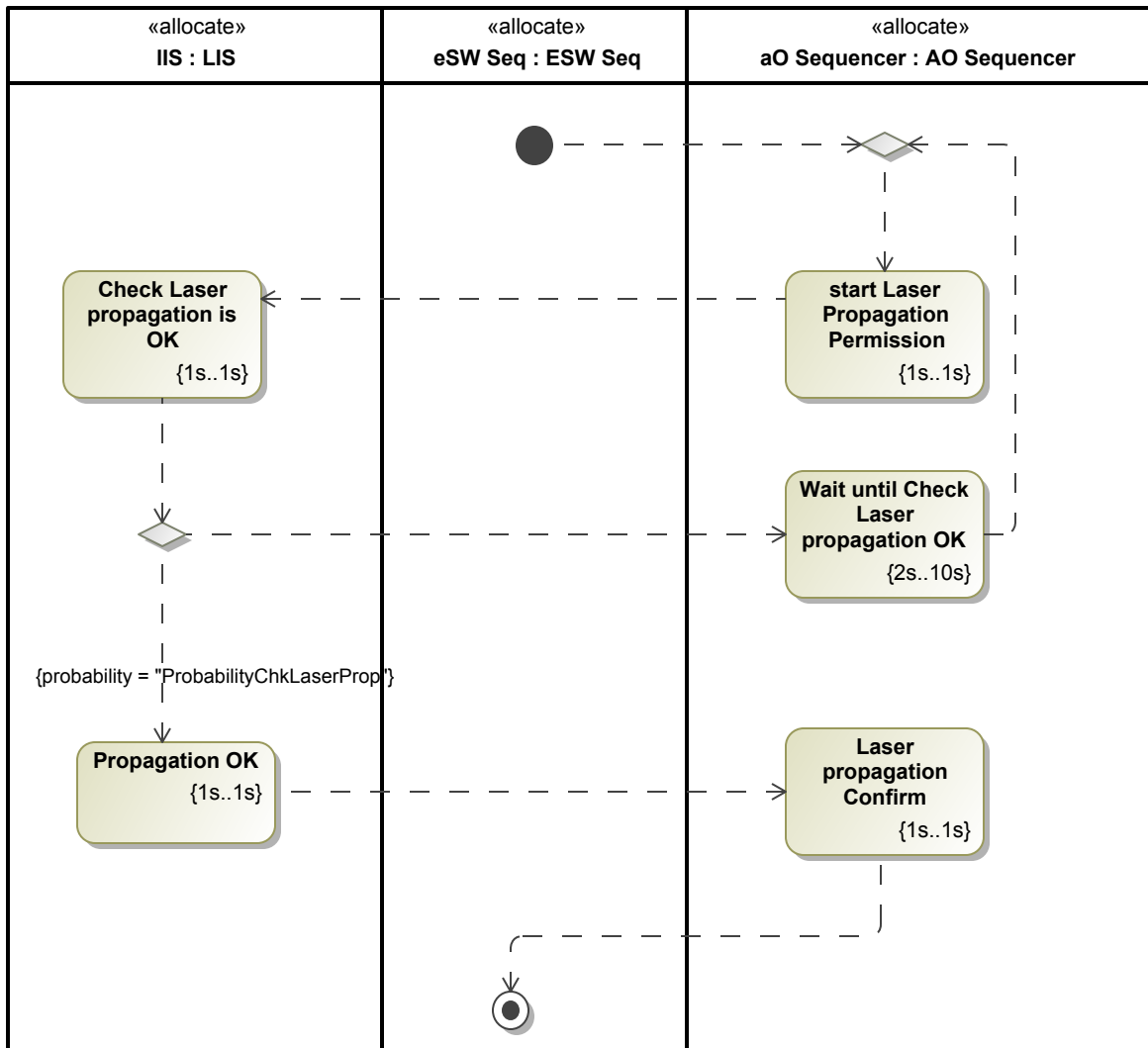


Figure 12. Check Laser Propagation Permission Conceptual Actual

Figure 3-7b: Task A3-Check Laser Propagation Permission

act [Activity] Acquire and Lock LGS Conceptual Actual [Acquire and Lock LGS Conceptual Actual]

Author: gtranco	Version:
Modification Date: 8/23/18 9:10 AM	Completion Status:
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Last Modified by: gtranco	

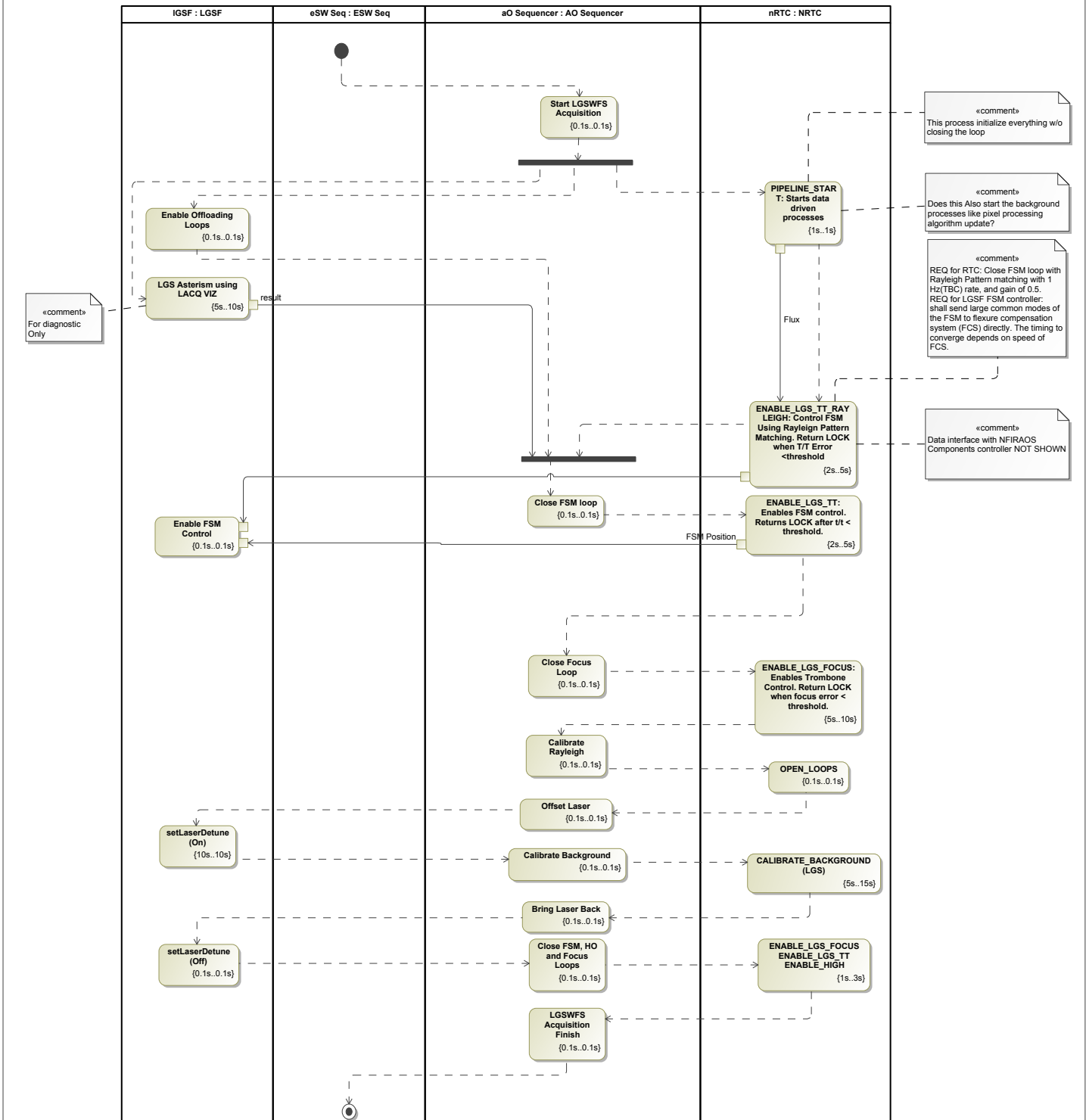


Figure 13. Acquire and Lock LGS Conceptual Actual

Figure 3-7c: Task A4-Acquire and Lock LGS

3.1.2.3 Task A5: Acquire and Lock TT or TTF and HO PWFS

Task A5: Acquire and Lock TT or TTF and HO PWFS

The ESW tasks the AOSQ to acquire and lock the PWFS (Figure 3-8):

1. The AOSQ checks whether the flux reported by the RTC for PWFS is correct according to the brightness and weather conditions. It should be correct most of the time, especially if it is reusing one of the OIWFS guide stars. If not, do a spiral search using the SSM until the guide star is acquired, or timeout. Report failure and abort the acquisition if this fails.
2. If needed, briefly offset the PWFS SSM and ask the RTC to take a dark image and calibrate the PWFS.
3. If needed, ask the PWFS VCAM to adjust the PWFS frame rate based on S/N computed from the flux.
4. Ask the RTC to start computing gradients and adjust reference vectors from PWFS pixels. Report the telescope pupil centering error estimated from PWFS illumination pattern to the TCS.

act [Activity] Acquire and Lock PWFS Conceptual Actual[Acquire and Lock PWFS Conceptual Actual]

Author: gtranco	Version:
Modification Date: 8/23/18 9:29 AM	Completion Status:
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Last Modified by: gtranco	

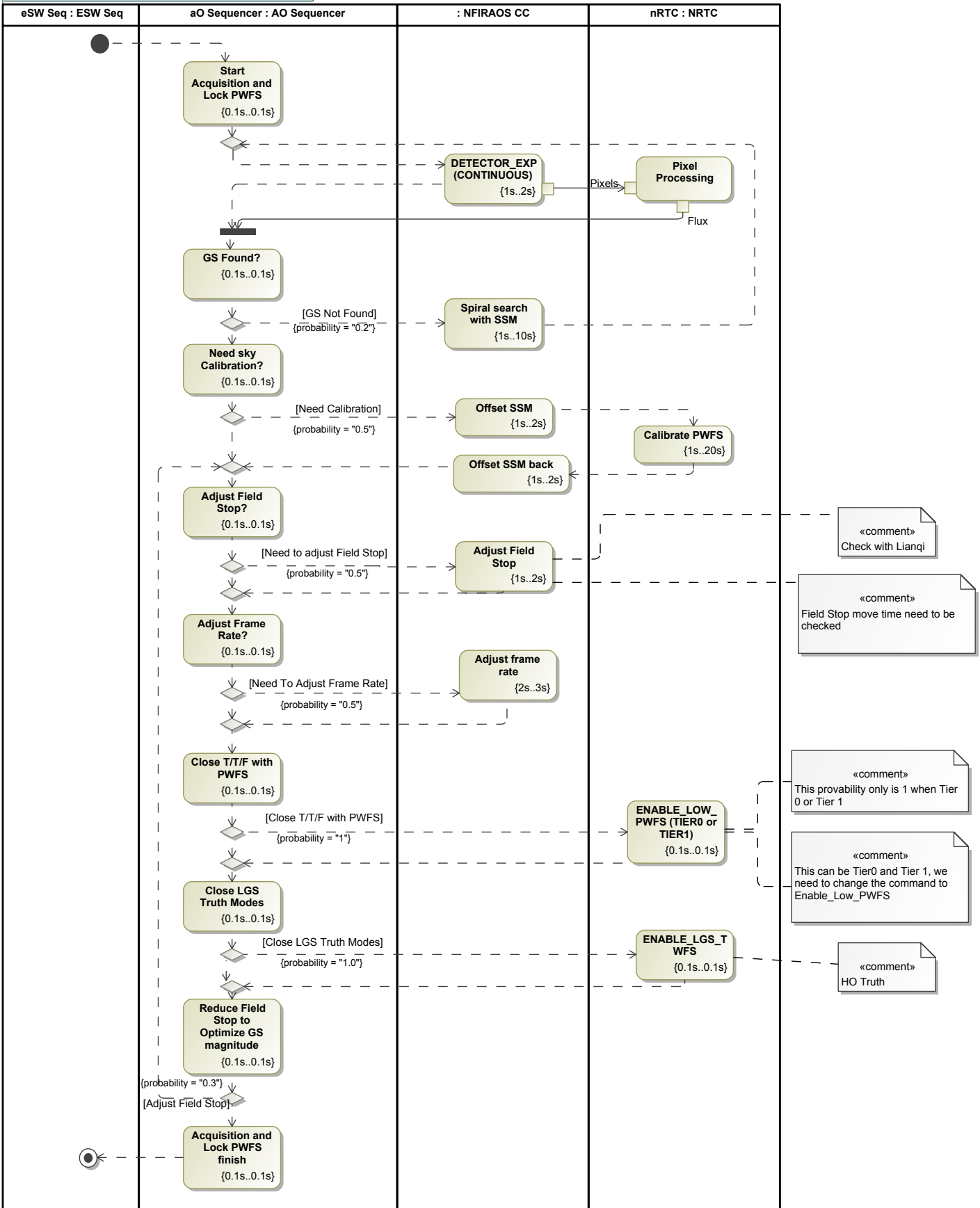


Figure 14. Acquire and Lock PWFS Conceptual Actual

Figure 3-8: Task A5-Acquire and Lock PWFS

3.1.2.4 Task A6: Acquire and Lock TTF OIWFS

Task A6 : Acquire and Lock TTF OIWFS

The ESW tasks the AOSQ to acquire the low order WFS and close the low order loops (Figure 3?9). This may happen before or after step A5.

The AOSQ does the following:

- 1. Acquire the TTF OIWFS if it is used:
 - Check if the TTF OIWFS flux is correct according to the estimated Strehl ratio, TTF guide star brightness, and weather conditions. For guide stars that are used for the first time on TMT, differences may be caused by catalog error. The guide star is used as long as it meets magnitude requirements.
 - If the TTF OIWFS has not captured the guide star, request the TCS to do a spiral search using the telescope (or OIWFS POA).
 - Compute gradients using CoG (or brightest pixel with median filter, based on information in the acquisition table) with center of FoV as the reference point.
- 2. The sky background of the OIWFS/ODGW is determined using an algorithm (e.g., median) on the first exposure. Telescope offsetting is not required. Start the T/T and focus mode reconstruction and close these loops.

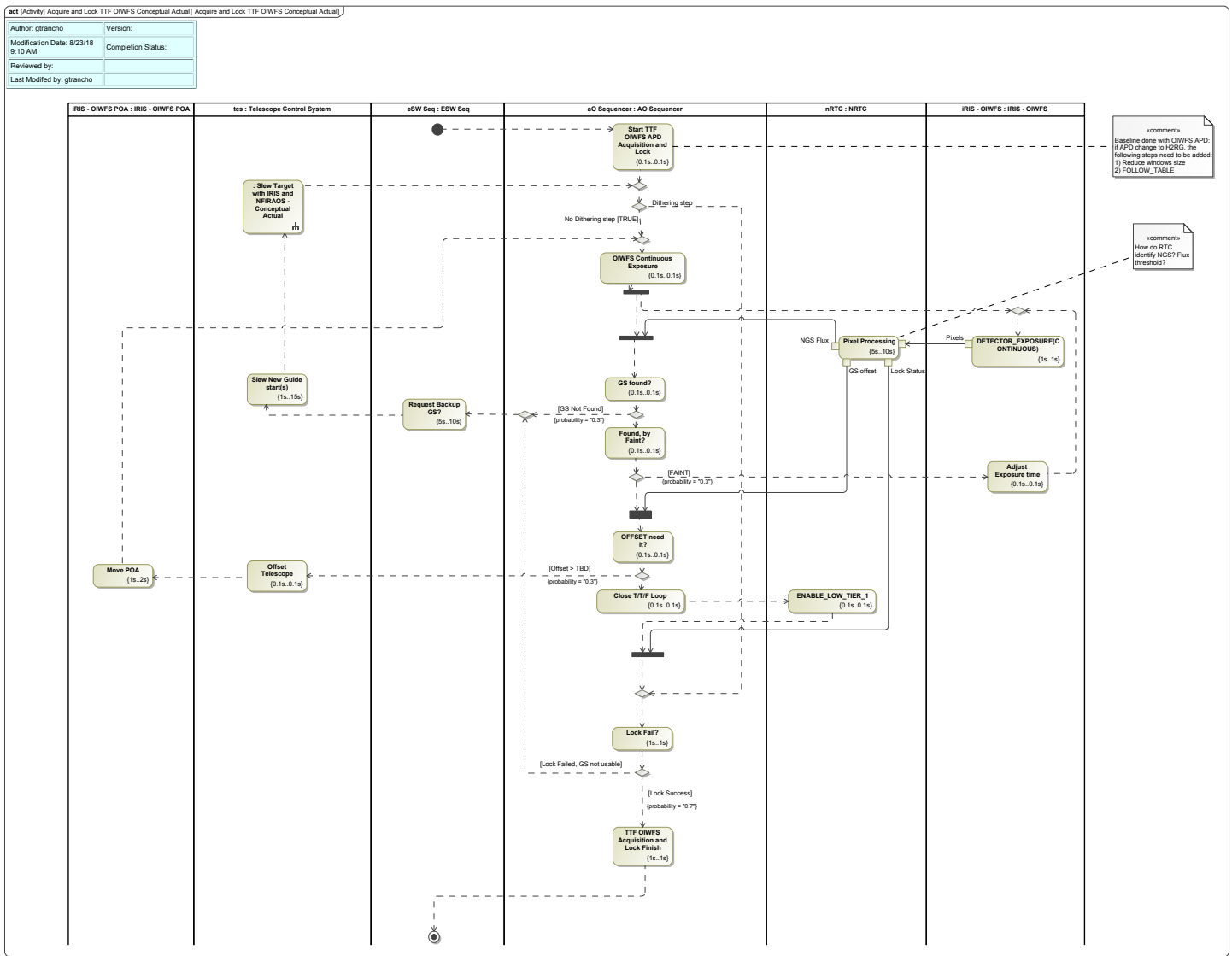


Figure 15. Acquire and Lock TTF OIWFS Conceptual Actual**Figure 3-9: Task A6-Lock and Acquire TTF OIWFS**

3.1.2.5 Task A7: Acquire and Lock PWFS for High Order Only

Task A7: Acquire and Lock PWFS for High Order Only.

The ESW tasks the AOSQ to acquire the PWFS using the procedure in A5 (Figure 3-8), with the exception that only the HO loops are closed.

3.1.2.6 Task A8: Acquire and Lock TT OIWFS/ODGW

Task A8: Acquire and Lock TT OIWFS/ODGW

The ESW tasks the AOSQ to acquire the low order WFS and close the low order loops (Figure 3-10). This may happen in parallel with A7.

1. Acquire the tip/tilt wavefront sensors (TT OIWFS and any high speed ODGW) in parallel, if used:
 - Check if flux is correct according to the estimated Strehl ratio, corresponding guide star brightness, and weather conditions.
 - If the OIWFS has not captured the guide star, ask the OIWFS POA to do a spiral search.
 - If the ODGW has not captured the guide star, ask the OIWFS DC or the IRIS DC to step back to full window readout mode.
 - If there is still no flux, restart this process with a backup guide star.
 - Determine start position using CoG (or brightest pixel with median filter, based on information in the acquisition table). If the average spot position is away from the desired location (e.g., center of FoV) by more than TBD amount (> 20 mas, this is possible if the guide star is used for the first time due to catalogue errors), report the error to ESW, which asks TCS to correct the POA position. The TMT guide star catalogue is updated based on this information.
 - Check to make sure the guide star is a point source. Request a backup star if this is not the case. Update target sub-window size if the S/N is different than expected.
2. Close T/T/F and plate scale mode loops with all available OIWFS/ODGW measurements.
3. Ask the RTC to switch the gradient computation algorithm of all OIWFS/ODGW from CoG to matched filter.

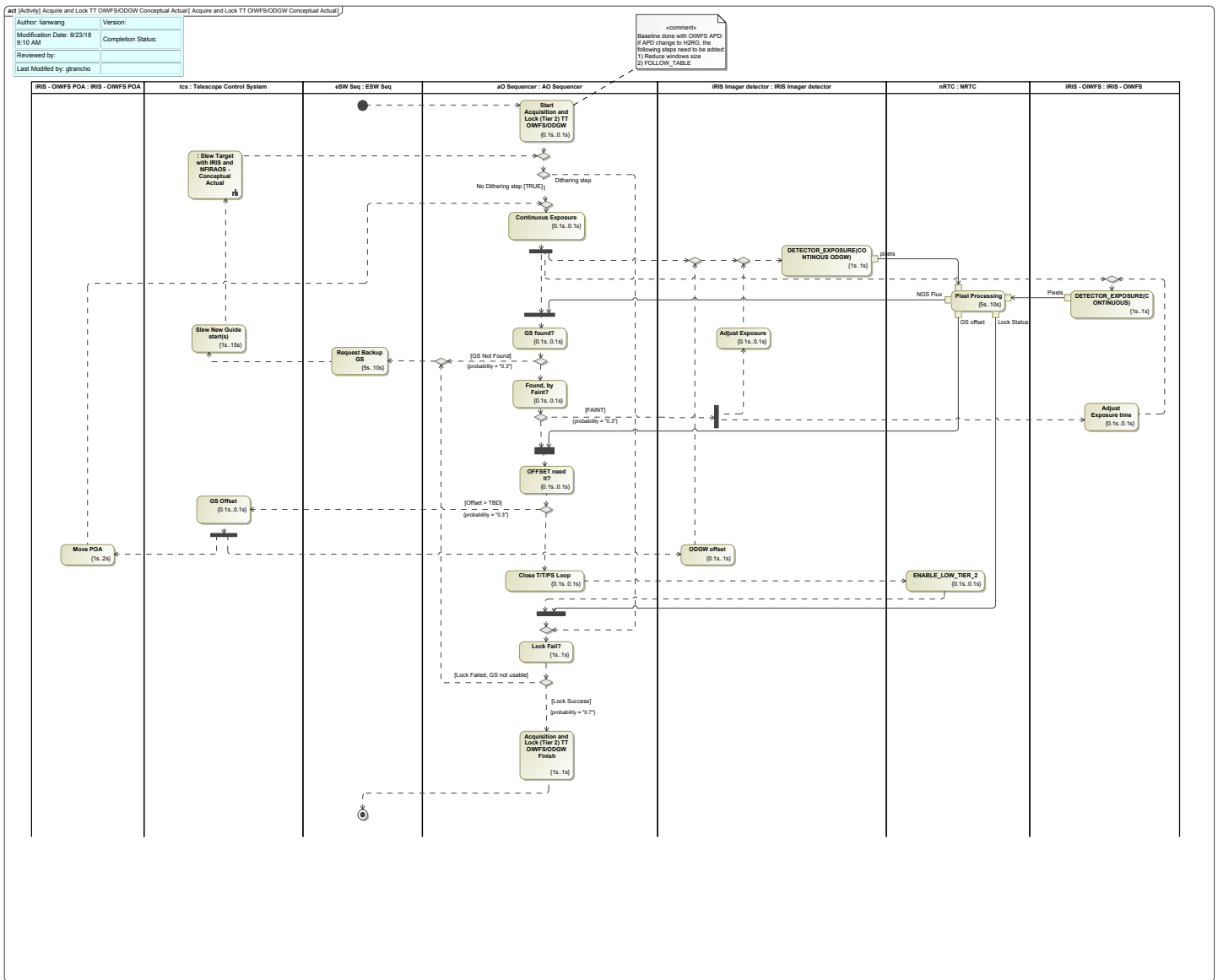


Figure 16. Acquire and Lock TT OIWFS/ODGW Conceptual Actual

Figure 3-10: Task A8-Acquire and Lock TT OIWFS/ODGW

3.1.2.7 Task A9: Acquire and Lock TT Truth OIWFS/ODGW

Task A9: Acquire and Lock TTF and TT Truth OIWFS/ODGW

Acquire low order truth WFS if used (Figure 3-11).

The OIWFS/ODGW functioning as the low order truth WFS is either running at a lower frame rate than the OIWFS/ODGW guide stars acquired in step A8, or reusing them at a slower rate by binning the measurements. The process is essentially the same, although stepping down the ODGW sub-window size can be done in one step.

Finally, wait for loops to stabilize and the Guide Star Acquisition sequence is done.

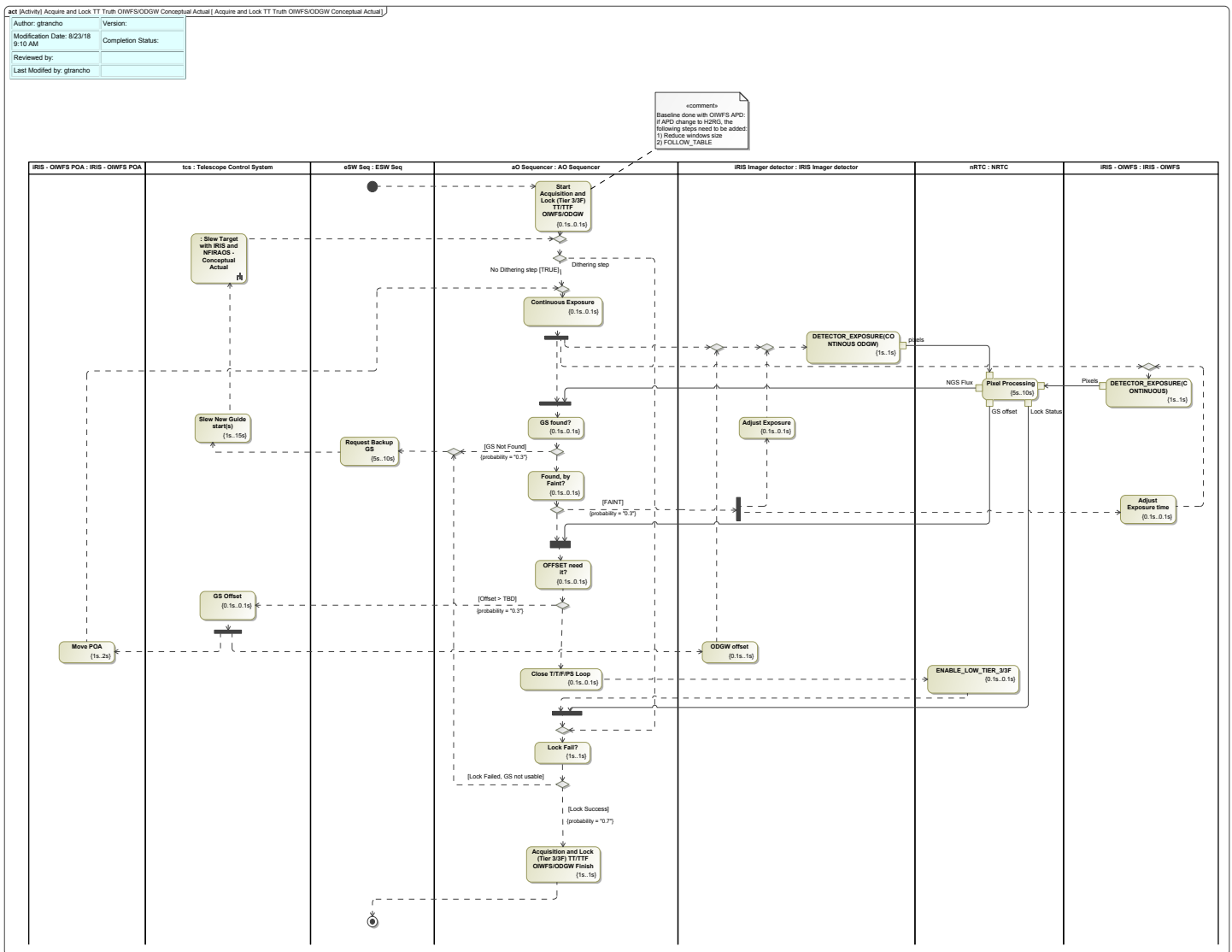


Figure 17. Acquire and Lock TT Truth OIWFS/ODGW Conceptual Actual

Figure 3-11: Task A9-Acquire and Lock TTF and TT Truth OIWFS/ODGW

3.1.2.8 NFIRAOS MCAO LGS Acquisition Timing

The expected acquisition time for each group is listed in Table 3-1, assuming average preset (60 seconds). The expected acquisition time ranges from 119 to 195 seconds.

Time(s) avg±stddev	REQ compliance	Groups	HO Truth	Tier1	Tier2	Tier3/3f
181±47	✓	Group1	PWFS	PWFS	X	X
119±22	✓	Group2	PWFS	PWFS		X
153±30	✓	Group3	PWFS	OIWFS		X
195±48	✗	Group4	PWFS	OIWFS	X	X
141±35	✓	Group5		OIWFS		X
164±32	✓	Group6		OIWFS	X	X

Figure 18. Table 3-1: NFIRAOS LGS MCAO Acquisition Timing

3.1.3 Guide Star Acquisition Sequences for IRIS/IRMS and NFIRAOS Seeing-Limited Observations

It is expected that some science can be obtained with IRIS or IRMS even when AO is not available (for example, when the presence of clouds prevents the use of LGS, or no sufficiently bright NGS is available). This mode is referred to as the NFIRAOS Seeing-Limited mode.

This mode is implemented as a degraded NGS AO, where the DM is still driven by the RTC while simultaneously offloading to the telescope. Therefore, the NGS AO acquisition sequences apply, with the following differences:

1. PWFS is used in binned mode.
2. The frame rate is lower and therefore sky brightness calibration may be required.
3. IRMS OIWFS is used in Seeing-Limited mode if such mode is implemented.
4. The number of telescope modes offloaded to the TCS is less.

The degradation of NGS AO into seeing-limited AO may be a gradual process that allows a range of guide stars to be used with PWFS in various binned modes.

3.2 WFOS Preset and Guide Star Acquisition Sequences

3.2.1 Preset Sequence for WFOS

For WFOS the Preset Sequence of an acquisition consists of having the two TMT main sequencers performing the following actions almost in parallel (Figure 3-12) (TCS and WFOS seq).

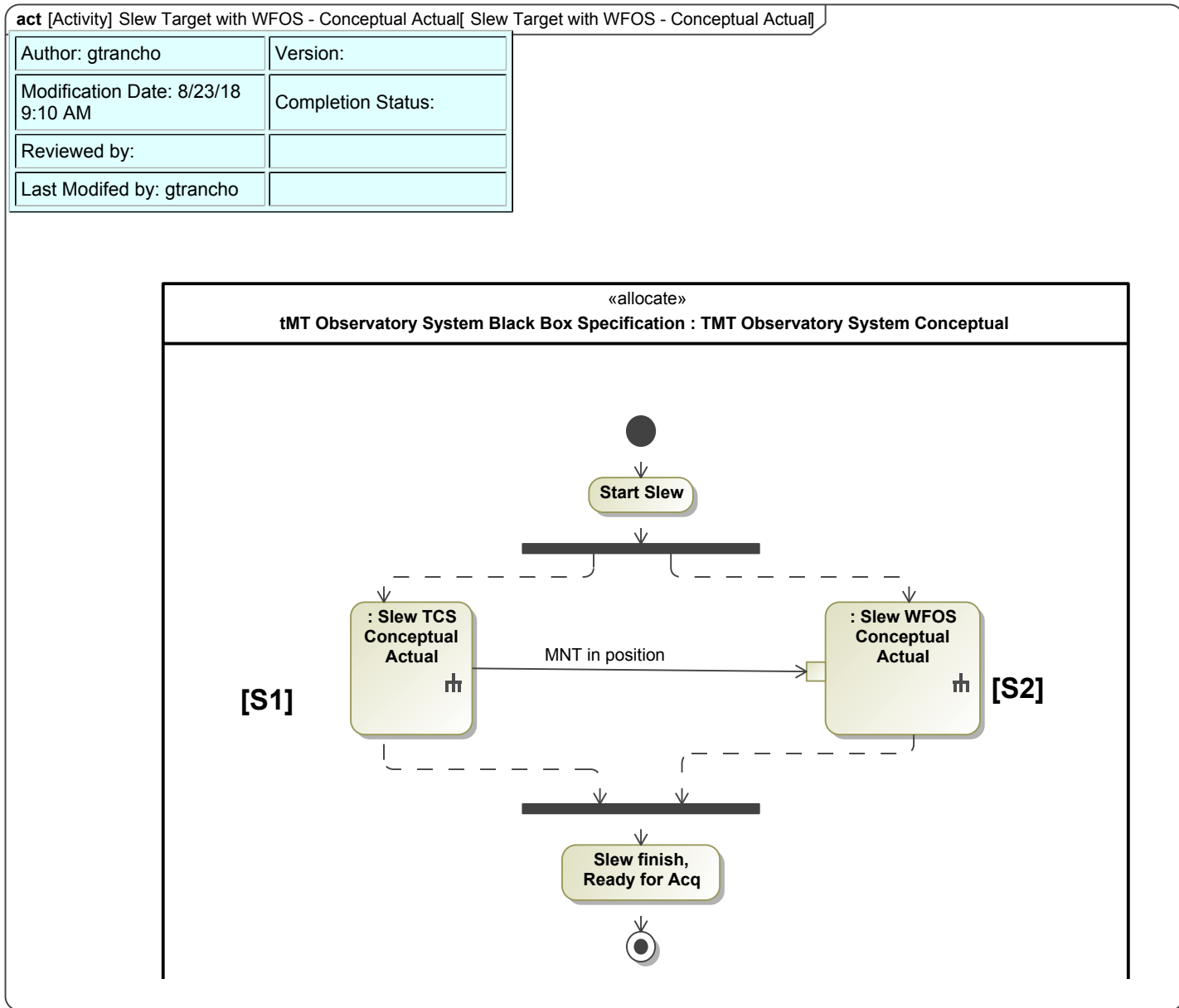


Figure 19. Slew Target with WFOS - Conceptual Actual

Figure 3-12: Task S1-Preset Sequence for WFOS

3.2.2 Guide Star Acquisition Sequences for WFOS observations

The WFOS Guide Star Acquisition sequence is described here and shown in Figure 3-13.

act [Activity] Acquire a target with WFOS - Conceptual Actual[Acquire a target with WFOS - Conceptual Actual]

Author: gtranco	Version:
Modification Date: 8/23/18 9:10 AM	Completion Status:
Reviewed by:	
Last Modified by: gtranco	

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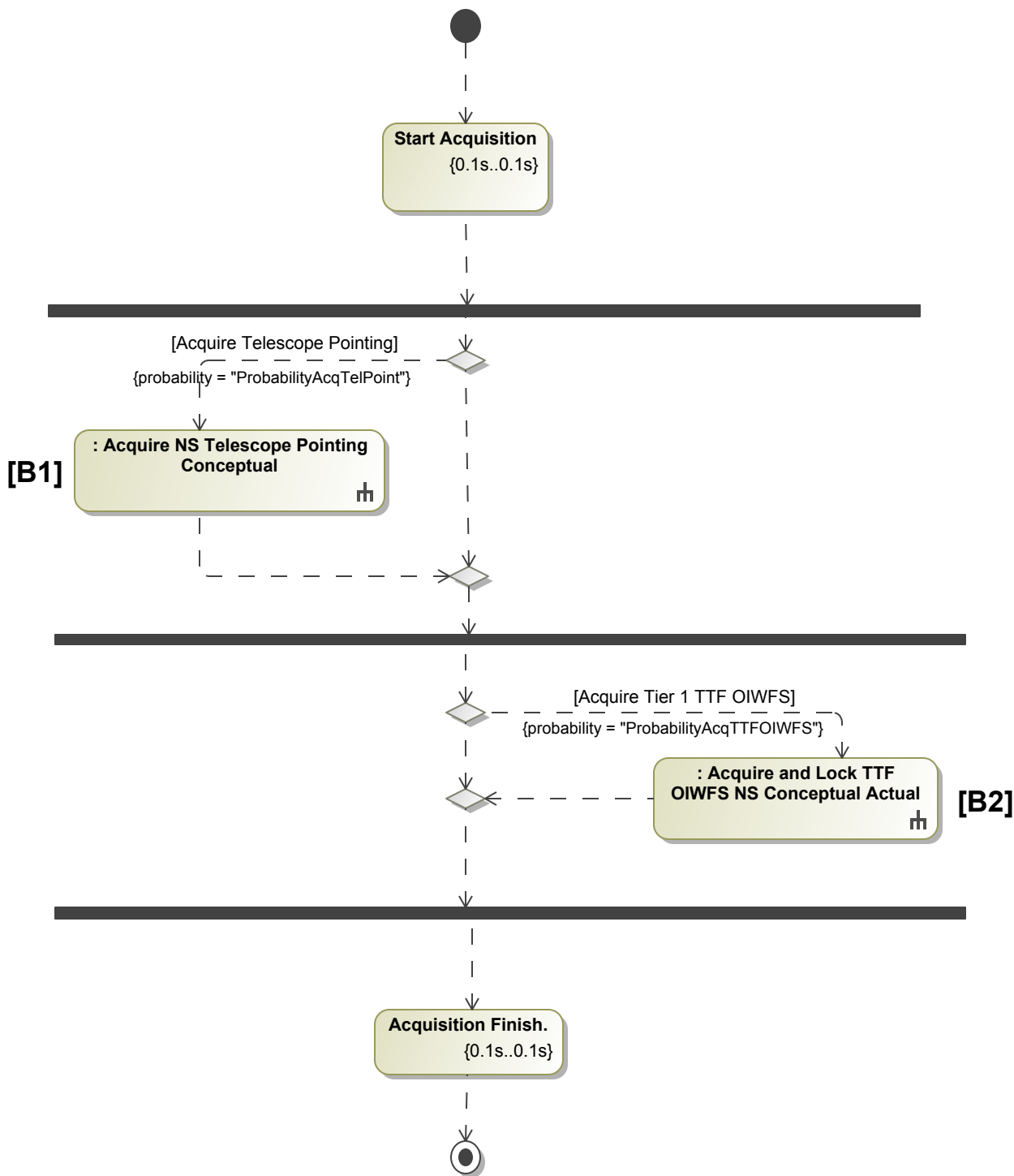


Figure 20. Acquire a target with WFOS - Conceptual Actual**Figure 3-13: Guide Star Acquisition Sequence for WFOS**

Tasks B1 and B2 are described in the following sections.

3.2.2.1 Task B1: Acquire Telescope Pointing

See Figure 3-14.

act [Activity] Acquire Telescope Pointing w/WFOS Conceptual Actual	
Author: gtranco	Version:
Modification Date: 8/23/18 9:10 AM	Completion Status:
Reviewed by:	
Last Modified by: gtranco	

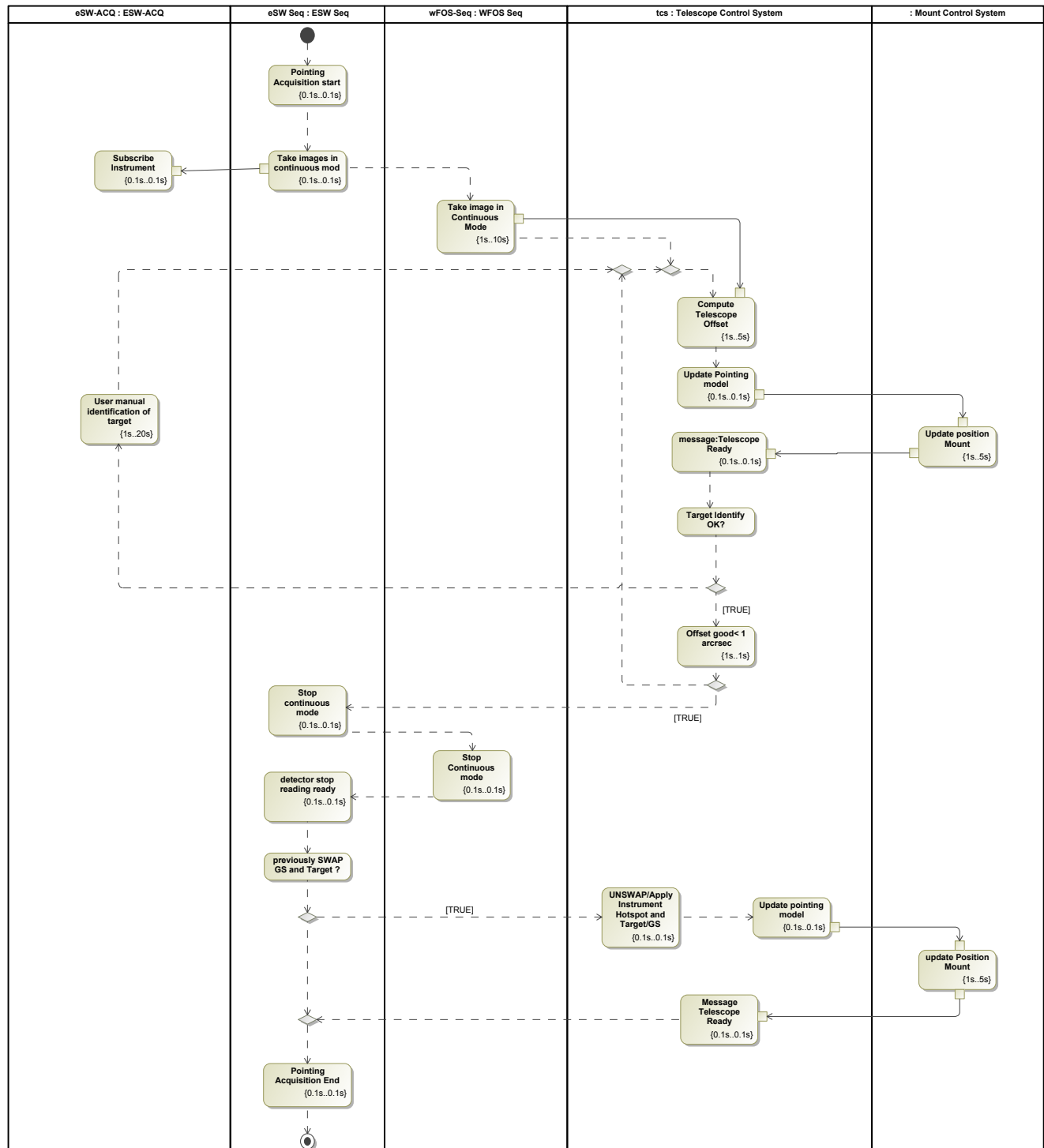


Figure 21. Acquire Telescope Pointing w/WFOS Conceptual Actual

Figure 3-14: Pointing Sequence for WFOS

3.2.2.2 Task B2: Guide Star Acquisition Sequence for WFOS

See figure 3-15

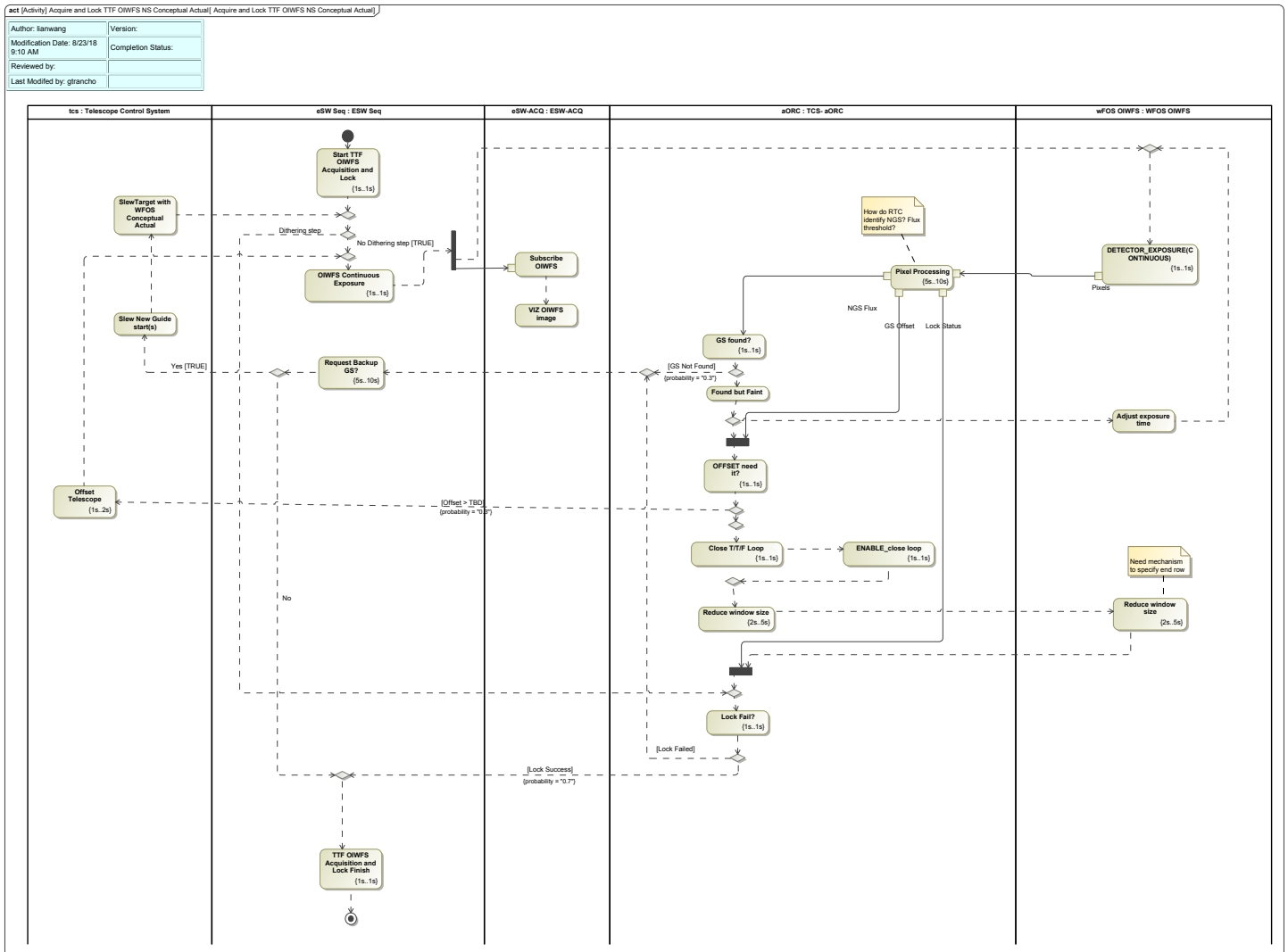


Figure 22. Acquire and Lock TTF OIWFS NS Conceptual Actual

Figure 3-15: Guide Star Acquisition Sequence for WFOS

4 Observation Science Target Acquisition

4.1 Science Target Acquisition for IRIS/IRMS and NFIRAOS

In the NGS AO mode, if the NGS and science object are the same, science observations can start without further verification. However, if the NGS and science object are different, or if NFIRAOS is in LGS MCAO mode, additional checks are needed before the science observation can start. It falls into three categories:

- 1) The science object is very faint and cannot be seen in a < 5 minute white light image. In this case, it takes too long to check the IRIS science data before starting the science observation. As a consequence, the science observation relies on very precise guide star and science target coordinates, and very good performance of the telescope, NFIRAOS, and the instrument (telescope pointing, WFS positioning accuracy, instrument rotator positioning accuracy, ADC positioning accuracy). Detector non-destructive reads can be used to perform the check if available, otherwise no additional checks are performed.
- 2) In IRIS IFU or IRMS Slit Spectrograph mode. First acquire a white light image, compute the position of the IFU or slit openings on the sky, and determine if the target is well aligned on the IFU or slit openings (provided that a bright enough object is in the FOV). If there is an alignment problem, re-center the telescope by simultaneously applying an offset to the telescope, NGS SSM (in NGS mode), OIWFS POAs (if used), ODGW window location (if used), while the AO loops are closed. It is not defined yet how to compute the telescope offset from the white light image (this process may require user intervention). For IRMS slit mode, a spiral search may be needed to maximum the light on the slits. For IRIS IFU mode, the IRIS imager may be concurrently used on a reference target (if available) to determine the alignment. This is described further in the Instrument OCDD.
- 3) In IRIS or IRMS imaging mode. Start the science observation and check the science image with non-destructive reads to verify that the telescope is aligned on the correct science field. If there is an alignment problem, abort the science observation, and re-center the telescope in the same way as in case 2). It is not yet defined how to compute the telescope offset from the science image (this process requires user intervention).

4.2 Science Target Acquisition for WFOS

Once step WFOS-B2 is completed, appropriate slit masks are inserted, and the ESW asks the WFOS Sequencer to take a short image with WFOS. The ESW checks the alignment of the alignment stars. If the alignment stars are not well centered^[2], the WFOS sequencer adjusts the mask location for each field, provided that the required adjustments are within the range of motion of the masks. If the required adjustments are beyond the range of motion of the masks, the telescope position is adjusted by moving the OIWFS while the loops are closed, and the WFOS rotator position is adjusted while

[1] Focus: Average focus is sent to telescope, what about differential focus?

[2] This step does not require user intervention.

5 Observation Execution

5.1 IRIS/IRMS And NFIRAOS Observation Execution

5.1.1 IRIS/IRMS and NFIRAOS Dithering Target

5.1.1.1 General Considerations

During observation, the TCS publishes position demands for all AO sub-system mechanisms that depend on telescope pointing. The ESW instructs the TCS to start the dithering/nodding process, and tells the AOSQ whether the the NGS WFS should expect to follow or freeze a TCS dither demand. The TCS provides smoothly varying position demands for the PWFS SSM, OIWFS POA, and ODGW position. The AOSQ instructs the RTC to open the NGS dependent loops if they cannot remain closed, or to switch pixel processing to CoG and slightly enlarge the ODGW read out windows to obtain better dynamic range and then to switch back after dithering is completed.

Dithering with (IRIS) ODGW as T/T WFS can only be handled with on-chip dithering due to the lack of a pick off arm mechanism. The IRIS imager has a field of view of $34^\circ \times 34^\circ$, but each ODGW can only use a quadrant of the discontinuous focal plane and therefore has a limited FoV of $17^\circ \times 17^\circ$.

Each OIWFS POA can patrol over a one-third sector of the 2° diameter FoV, which gives an averaged dithering distance of $\sim 30^\circ$.

During dithering the following apply to all cases:

1. The OIWFS reconstruction parameters are updated at a rate of up to 20 Hz by the RPG and therefore should be able to respond to OIWFS pupil angle or probe arm position changes due to dithering.
2. Higher order loops remain closed. Some background may remain active if information is available.
3. The offload to telescope, except tip/tilt, is paused while dithering and resumed after settling in the new position.

5.1.1.1.1 Non-sidereal Tracking

The system is required to track solar system targets using fixed natural guide stars as the guiding reference. There is a maximum of 1.5 arcsec/s differential motion on the sky. For the closest trans-Neptunian objects (TNOs), non-sidereal tracking rates above 0.1 arcsec per minute are necessary.

5.1.1.1.1.1 On-chip Non-sidereal Tracking in LGS/NGSAO Mode (OIWFS/ODGW)

For short exposures or slow non-sidereal rates it may be possible to place the guide star in one corner of the FOV in the OIWFS or ODGW at the beginning of the observation and let it move on chip to the opposite end during the integration. The POA is held still during this process. This has the best tracking performance since the POA is not moving. The procedure is the same as on-chip dithering.

5.1.1.1.1.2 POA Assisted Non-sidereal Tracking

For longer exposures or faster non-sidereal tracking rates, simple on-chip OIWFS tracking may prove insufficient. The tracking is accomplished with continuous movement of the POA (if OIWFS is used), ODGW (if used) and SSM. When guide stars move in/out of the patrol FoV of certain POAs, either OIWFS switching or re-closing OIWFS loops with new OIWFS asterisms are needed. The science exposure is paused during OIWFS reconfiguration.

Figure 4-1 Shows IRIS/IRMS and NFIRAOS Dithering Sequence.

5.1.1.2 Types of Dithering

Figure 3-16 shows a dithering sequence for IRIS and NFIRAOS using the different types of dithering: Follow and Freeze, as explained in the following sections.

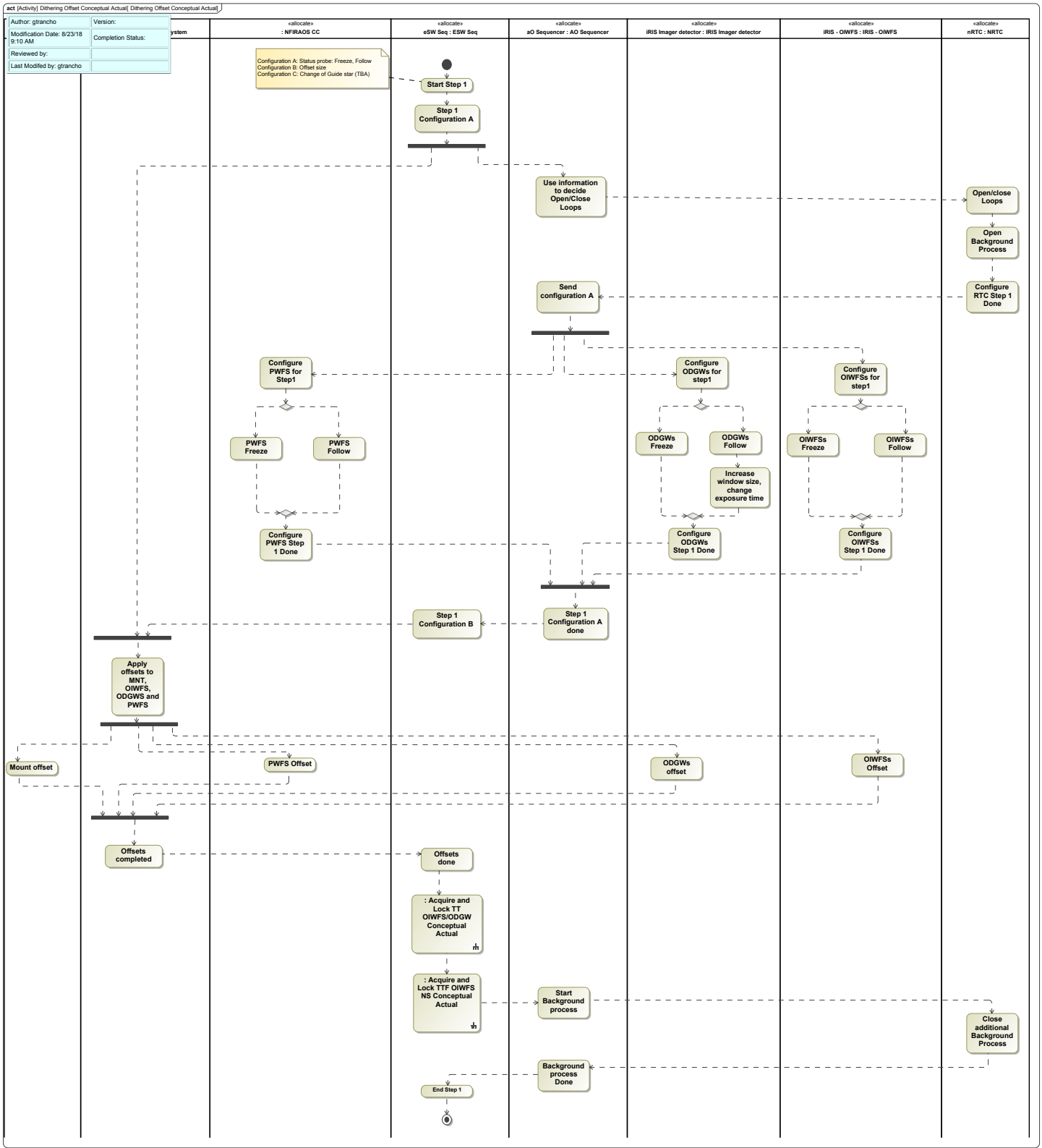


Figure 23. Dithering Offset Conceptual Actual

Figure 3-16: Dithering Sequence for IRIS and NFIRAOS

5.1.1.2.1 Follow

Follow means that the OIWFS/PWFS/ODGW follows offsets sent to it by the TCS. The decision to OPEN or CLOSE loops associated with them is decided by the AOSEQ.

5.1.1.2.1.1 On-chip Dithering with OIWFS or ODGW

Dither with ODGW is always on-chip, as it has no patrolling mechanisms. Each ODGW window has a maximum FoV of $\sim 16''$, which limits the possible dithering range. The on-chip dithering with OIWFS is limited to the available FoV ($1.5''$ for the current detector choice, possibly increase to $3''$ in the future).

This works in both LGS MCAO and NGS AO mode with ODGW.

5.1.1.2.1.2 POA Assisted Dithering

During the process, the guide stars must remain within the patrol FoV of OIWFS POA, and the ODGW if they are also used.

Therefore, careful planning is needed to make sure the guide stars can be reached by the same POA or ODGW in all dithering locations. If (IRIS) ODGW is used to provide T/T correction, the possible dithering distance may be less than $17''$.

5.1.1.2.2 Freeze

Freeze means the loops associated with the WFS/probes/ODGW do not use information about them. The WFS/probes/ODGW do not follow an offset, so the guidestar(s) are not available at that dither position.

5.1.1.2.3 Switching

It is anticipated that we may need to switch guide stars for OIWFS when the dithering/nodding distance is too large, or for fast-moving non-sidereal tracking. The science exposure is stopped before switching OIWFS, and restarted after OIWFS switch is finished. The OIWFS mode control requires that there is at least one TTF OIWFS to control the defocus. In order to simplify the process, we can either require that all the OIWFS be in TTF mode when the OIWFS switch is anticipated, or rely on focus measurement by PWFS when we lose the TTF OIWFS. The following describes the processes in various scenarios:

1. A guide star falls off the patrol field of view of its OIWFS POA:
 - a. Instruct the RTC to ignore the measurement from the OIWFS and switch reconstructor accordingly.
 - b. Stop the OIWFS gradient processing for this OIWFS. Stop the corresponding OIWFS readout mode.
 - c. Stop the OIWFS POA and ADC follow mode.
2. A guide star enters (based on catalog) into the patrol field of view of an idle OIWFS POA:
 - a. Place the POA on the new guide star. Ask the ESW (TCS) to provide POA and ADC demands for the new source. Start the corresponding OIWFS readout mode in full window mode and reduced frame rate. Reduce the window size following Steps LGS.4.6-8.
 - b. Instruct the RTC to include the measurement from this OIWFS and switch reconstructor accordingly.
3. Switch a guide star from one OIWFS to another:
 - a. Instruct the RTC to ignore the measurement from both affected OIWFS.
 - b. Switch the POA, start the corresponding OIWFS readout mode in median window size mode and reduce frame rate iteratively. Follow Steps LGS.4.6-8.

- c. Instruct the RTC to include the measurement from the OIWFS that just acquired the star and switch reconstructor accordingly.

Similar sequences apply when ODGW guide stars move out of or into the IRIS imager FOV or move from one H4RG detector array to another.

5.1.1.3 End of an Observation

The stopping process in all cases is very short (less than 5 seconds) and does not require sub-tasks to be completed before executing the next one.

The ESW asks the instrument sequencer to stop observation and then asks AOSQ to stop all AO loops. The AOSQ asks the RTC to stop all loops, background processes, and offloading processes automatically. There may be additional steps depending on the mode of operations, as listed in the following sections.

5.1.1.3.1 LGS to LGS Observation

The LGSF is put in a standby mode.

5.1.1.3.2 LGS to NGS Observation

The LGSF is put in shuttered mode.

5.1.1.3.3 NGS to NGS or LGS Observation

No additional steps are needed.

5.1.1.3.4 Seeing Limited Observation to NGS/LGS/Seeing Limited Observation

No additional steps are needed.

5.1.1.3.5 Stopping Sequence when Switching to another Instrument

- ? Switching from IRIS or IRMS to WFOS: Put NFIRAOS in standby mode, with the entrance shutter closed, and the DM high voltage amplifiers turned off.
- ? Switching from WFOS to IRIS or IRMS: Put WFOS in parked mode (corresponds to closing the entrance shutter).
- ? Switching from IRIS to IRMS does not add an extra step in the stopping process.

5.1.1.3.6 WFOS to WFOS Observation

When the current observation and associated calibrations are completed:

- ? Task WFOS B1: the AGWFS loops are turned OFF
- ? Task WFOS B2: the AGWFS follow mode is stopped.

5.1.2 IRIS/IRMS and NFIRAOS Sequencing

See instrument OCDD for more details.

5.1.3 IRIS/IRMS and NFIRAOS Data Management

5.1.3.1 AO PSF Reconstruction

The PSF reconstruction related statistics data are continuously recorded by the RTC telemetry storage during AO operation. The PSFR subscribes to the science observation start/end timing information, retrieves corresponding PSFR telemetry items from the RTC storage, processes them, and then stores them in the TMT scientific data storage system.

5.1.3.2 Data Management

See Instrument OCDD for more details

5.2 WFOS Observing Execution

TBA

6 Post Observation

6.1 NFIRAOS and IRIS/IRMS Post Observation Activities

6.1.1 Processing Data Obtained with NFIRAOS

The operational considerations for NFIRAOS extend past the mechanics of data acquisition. As with all facility instruments, NFIRAOS must log information while it is operating that is used by the astronomer during data reduction. A NFIRAOS user requires the following information when they are reducing their science data:

- 1) Basic information about the configuration of NFIRAOS while the data is recorded. For example, a list of any neutral density or color filters that were in the light path, and/or the gain of the control loop. It is anticipated that information of this nature is saved in the header of all data recorded using NFIRAOS.
- 2) WFS signals. The signals from the WFS are logged. While this information may not be of interest to the typical astronomer, it is useful for long term statistical studies of atmospheric characteristics, which in turn is of use for developing future AO systems and improving the performance of NFIRAOS.
- 3) Environmental Information. To make full use of the scientific capabilities of the TMT, it is anticipated that atmospheric properties are monitored during the night. Any information of this nature, such as the C_N^2 profile, should be made available to NFIRAOS users.

6.1.2 PSF Reconstruction

Some of the basic operational modes of instruments that are used with NFIRAOS (e.g. NIREs, and the IFU in IRIS) have a small field of view, and there is only a slight chance that reference stars that are bright enough to be used to empirically measure the PSF are sampled. And for instrument modes with larger fields of view, the PSF varies across the field significantly due to various anisoplanatic effects. Therefore, it is crucial that NFIRAOS provide PSF reconstruction obtained from the WFS signals.

The NFIRAOS RTC records statistics for PSF reconstruction to RTC telemetry storage continuously during AO operation. The PSFR subscribes to the science observation start/end timing information, retrieves corresponding PSFR telemetry items from the RTC storage, carries out PSF reconstruction, and then stores the results in the TMT scientific data storage system. It is anticipated that one set of PSFs is reconstructed for observations of short to medium integration. For observations of long integration ($> 1/2$ hr), multiple sets of PSFs may be reconstructed (TBC). Processed telemetry data are also stored in the scientific DMS in order to revise PSF reconstruction using different parameters at the astronomer's request and/or enable future algorithm updates.

As a goal, a quick-look PSF is reconstructed right after each observation for examination by the astronomer.

The PSF reconstruction algorithm is specified in a separate document (RD2).

6.1.3 Data Reduction Pipeline

See Instrument OCDD for more details

6.1.4 Data Archiving

TBD

6.2 WFOS Post Observation Activities

TBA

7 Observation Interruption

7.1 Laser Safety Event

7.1.1 Interrupting Observation

During LGS observations, it is anticipated that the propagation of the laser may be shuttered for aircraft or some other safety events.

When the TBAD detects airplanes very close to the beam, the fast safety shutter is closed first. Then the ESW asks the Instrument Sequencer to stop the science observation and AOSQ to open all AO loops. In this case, all loops in the BTO are open except the LUT based loops. Resuming the observation includes reclosing the BTO loops and AO loops.

7.1.2 Resuming Observation

The ESW asks the AOSQ to resume the observation after the safety event is cleared and the laser can resume propagation. The sequence is similar to the LGS Acquisition Sequence except that:

1. The Acquisition camera is no longer required as the telescope open loop tracking should be able to maintain position on the OIWFS (The specification on telescope open loop tracking error is 70 mas after 10 minutes).
2. No need to check flux on OIWFS or PWFS. The OIWFS starts with medium size window (100 mas, TBC) and iteratively closes down to the desired size.
3. No need to verify the science object in the instrument.

7.2 Fault

The AO systems should handle fault conditions gracefully without posing safety threats to personnel, damaging components of the AO system or telescope, or threatening the integrity of the science data. The AOESW is not involved in safety critical procedures, however, it may be notified when safety related events happen.

7.2.1 Loss of Signal on One OIWFS/ODGW

During observation the RTC may lose signal to one of the OIWFS or ODGW. This may happen due to failed POA, or poor S/N. If it is not the TTF OIWFS in LGS MCAO mode (it is ok to lose the TTF OIWFS in NGSAO mode), the RTC notifies the AOSQ and automatically continues without the failed WFS by switching the reconstructor. The science performance degrades slightly, but can still continue.

7.2.2 Loss of Lock in Low Order Control

During observation, the RTC may detect loss of signal in TTF OIWFS in LGS MCAO mode or all OIWFS/ODGW. The latter may happen due to sudden strong telescope windshake that even the guard windows lose signal.

The AOSQ gets this notification from the RTC and notifies ESW to suspend the science observation and proceed to low order WFS acquisition.

7.2.3 AO Loop Open

During observation the RTC may detect the following error conditions and open the AO loops:

1. LGS WFS signal loss (e.g., due to failure of laser or actuators in BTO).
2. PWFS signal loss.

3. Excessive number of subapertures fall below threshold (e.g., due to pupil misalignment).
4. Too many actuators have reached the full actuator or inter-actuator stroke limit.
5. Tip/Tilt stage commands have reached the limit.
6. DME reports that the DM command from RTC is not valid, or actuators do not respond (open-circuit) or respond too quickly (short-circuit).
7. Faults from the safety system.
8. User requests to terminate the observation based upon warnings published by the RTC (e.g., large wavefront error).

The RTC notifies the AOSQ immediately when this happens. The AOSQ notifies the ESW to stop the science observation and then proceeds with the end of observation sequences described in [Section 5.1.2](#).

7.2.4 Telescope Fault

The ESW asks the AOSQ to stop the observation. The AOSQ executes the end of observation sequences described in [Section 5.1.2](#).

7.2.5 Instrument Fault

The ESW asks the AOSQ to stop the observation. The AOSQ executes the end of observation sequences described in [Section 5.1.2](#).