Analyzing the AO operational behavior of non-sidereal tracking on the Thirty Meter Telescope using SysML

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ABSTRACT

We have modeled the functional and physical architecture, behavior, requirements, and parametric relationships through system-level simulation of observation workflows, using OMG's Systems Modeling Language (SysML), to validate use-case scenarios and verify timing requirements early in the life-cycle phase. This paper presents preliminary results for non-sidereal tracking scenarios, for LGS MCAO modes where the NFIRAOS pyramid wavefront sensor and the on-instrument wavefront sensors must hand off from one guide star to another. Operational modes and behavior are modeled using activity diagrams. Scenarios are captured primarily using sequence and activity diagrams. Verifiable requirements are formally captured using constraints on properties. This type of modeling can be particularly useful when investigating the effect of parallelizing or re-ordering sequence tasks.

Keywords: MBSE, SysML, Requirements, TMT

1. INTRODUCTION

In a previous paper [1] we introduced our SysML modelling effort to analyze TMT observation workflows, to help to understand operational scenarios and use cases, determine constraints on the system, verify timing requirements, and identify opportunities for optimization. The larger TMT modeling effort covers all observation workflow activities, depicted in Figure 1. In [1] we focused on the NFIRAOS LGS MCAO mode, while in this paper we explore how non-sidereal tracking interacts with NFIRAOS LGS MCAO observation workflow.

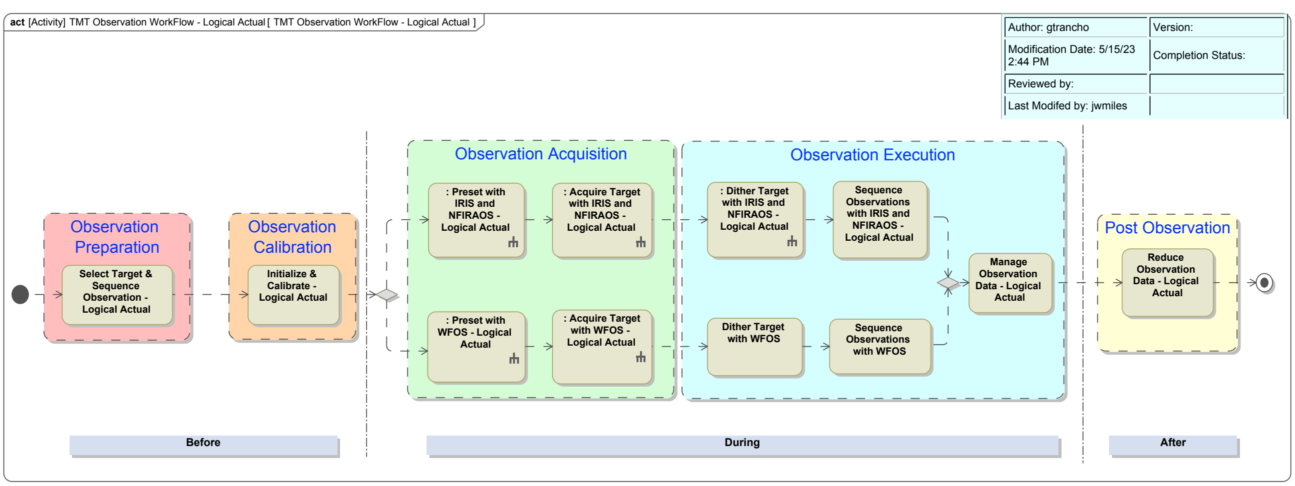

Figure 1: TMT observation workflow

1.1 NFIRAOS LGS MCAO mode

In NFIRAOS LGS MCAO mode, NFIRAOS 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, such as IRIS.

The PWFS is used as a Truth WFS (TWFS) running at low frame rate for correcting aberrations arising 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.

1.2 Guide star requirements

There are cases when a fast TTF OIWFS measurement cannot be used, for reasons like:

- vignetting science target,
- extended guide object that is comparable to seeing,
- lack of infrared guide stars,
- etc.

In such cases, 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.

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.

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Table 1: NFIRAOS guide star requirements

WFS	Observing mode	Number of guide stars	Magnitude limit
LGSWFS	NFIRAOS LGS MCAO	6	(20 W each Laser)
PWFS	NFIRAOS NGSAO	1	R=16
	NFIRAOS LGS MCAO (as TWFS)	1	R=20
	NFIRAOS LGS MCAO (as TTF)	1	R=18
	NFIRAOS Seeing-Limited	1	R=25
OIWFS	NFIRAOS LGS MCAO	1-3	J=22
	NFIRAOS NGSAO	0-1	J=22
	NFIRAOS Seeing-Limited	0-1	J=22
ODGW	NFIRAOS LGS MCAO	0-3	J=22
	NFIRAOS NGSAO	0-1	J=22
	NFIRAOS Seeing-Limited	0-1	J=22

1.3 Guide star catalogs and astrometry

The efficiency of the preset and acquisition sequences presented here depends on how well target/guide stars fields have been 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. For non-sidereal targets, the number of suitable natural guide stars may vary over the duration of the observation.

2. TOOLS

Operational modes and behavior are modeled using activity and state machine diagrams in the Systems Modeling Language (SysML) in Dassault Cameo Systems Modeler. Scenarios are captured primarily using sequence and activity diagrams with probabilistic flows. Verifiable requirements are formally captured using constraints on properties.

This type of modeling is particularly useful to investigate the effect of parallelizing or reordering sequence acquisition tasks. This is because diagrammatic language makes it easy to re-order or reconnect things quickly that result in complex changes in the underlying behavior.

3. NON-SIDEREAL TRACKING

TMT supports non-sidereal tracking rates of up to 1.5 arcsec/s relative to the fixed stars. Fast-moving near-Earth objects ($\gtrsim$ 0.08 arcsec/s) will typically be bright enough to guide on directly using just the NFIRAOS Pyramid WFS in either NGSAO mode or at least in tip/tilt/focus mode.

For slower-moving targets in LGS MCAO mode, the IRIS OIWFS probe arms perform a "crab walk" maneuver across the field, exchanging guide stars as they move out of the field, while maintaining lock on at least one guide star. AO performance will vary as the asterism geometry changes and stars drop in and out of the AO loop during the observation.

Figure 2 shows the non-sidereal tracking workflow model. It assumes that the observer has identified a train of potential guide stars along the observing track. Figure 3 and **Error! Reference source not found.** show guide star acquisition on the PWFS and OIWFS, respectively (ODWG not used). The workflows show the interaction between the executive software, AO sequencer, telescope control system, real-time control system, and the NFIRAOS and IRIS controllers.

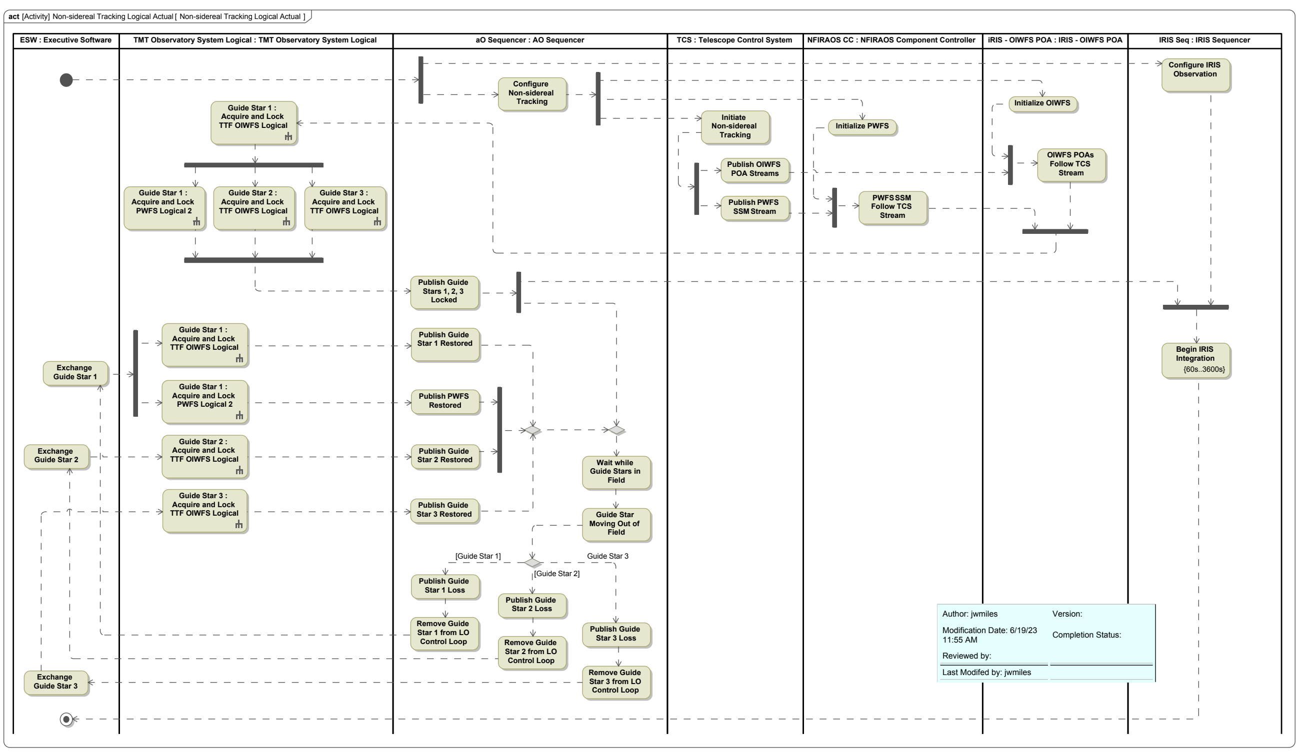

Figure 2: Non-sidereal tracking model

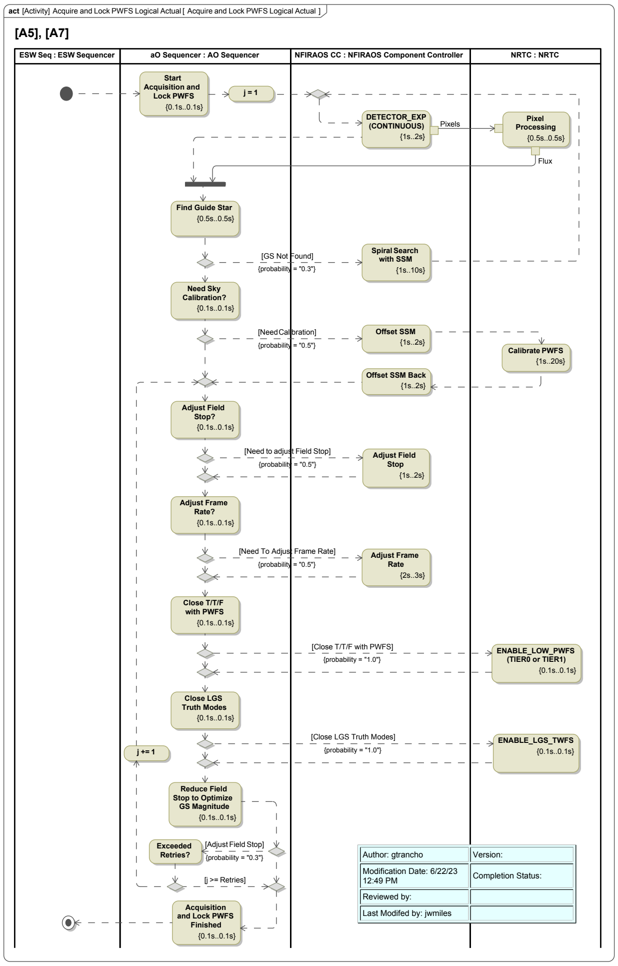

Figure 3: PWFS acquisition model

4. SIMULATION

The simulation allows up to three guide stars to be tracking on the OIWFS at one time, with up to one of those stars also tracking on the PWFS. This simulation assumes a specified probability that each attempted guide star is successfully acquired, and switches as needed to a new guide star, up to four stars per acquisition. It also assumes the same probability of achieving AO lock, once acquired, allowing for one additional guide star acquisition if the lock fails.

Monte Carlo simulation ($N = 1000$) results for the length of time a guide star drops out of the AO loop until another one is acquired are shown in Table 2. The probabilities give an indication of the impact that field star density has on the dropout time, i.e., low-density fields will have a lower probability that an acquisition is successful. For example, in high density fields, with a better selection of brighter guide stars, guide star exchanges take ~ 30 s, while in low density fields exchanges take ~ 2 minutes.

Table 2: Model results

Probability guide star acquired	Guide star dropout time (s)	
	OIWFS	OIWFS + PWFS
50%	100 ± 59	110 ± 60
70%	53 ± 42	63 ± 43
90%	21 ± 18	31 ± 20

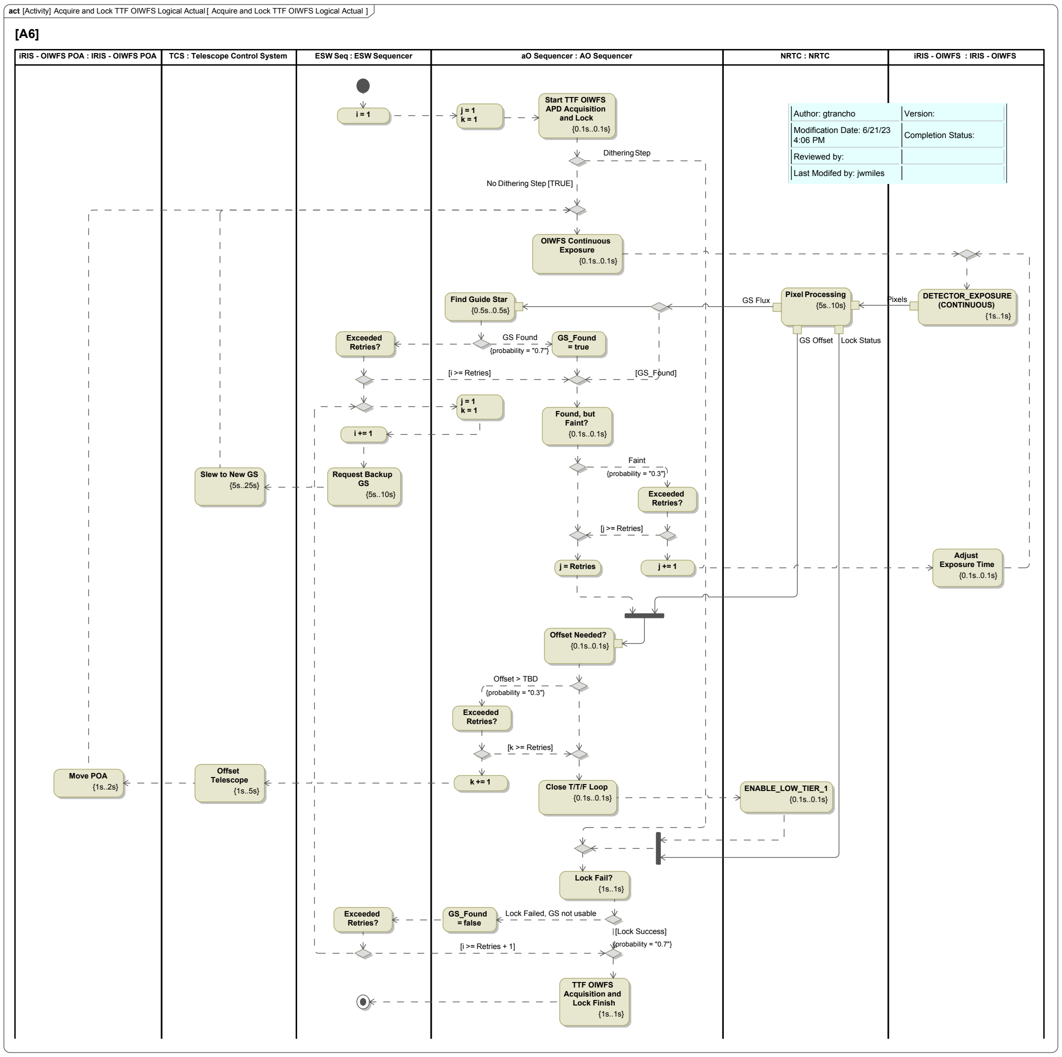

Figure 4: OIWFS acquisition model

Acknowledgments

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