On-orbit pointing performance of the Modular Agile Scalable Optical Terminal (MAScOT) for the ILLUMA-T mission

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[j]NASA Goddard Space Flight Center, Greenbelt, MD, USA

This material is based upon work supported by the National Aeronautics and Space Administration under Air Force Contract No. FA8702-15-D-0001. Any opinions, findings, conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Aeronautics and Space Administration.

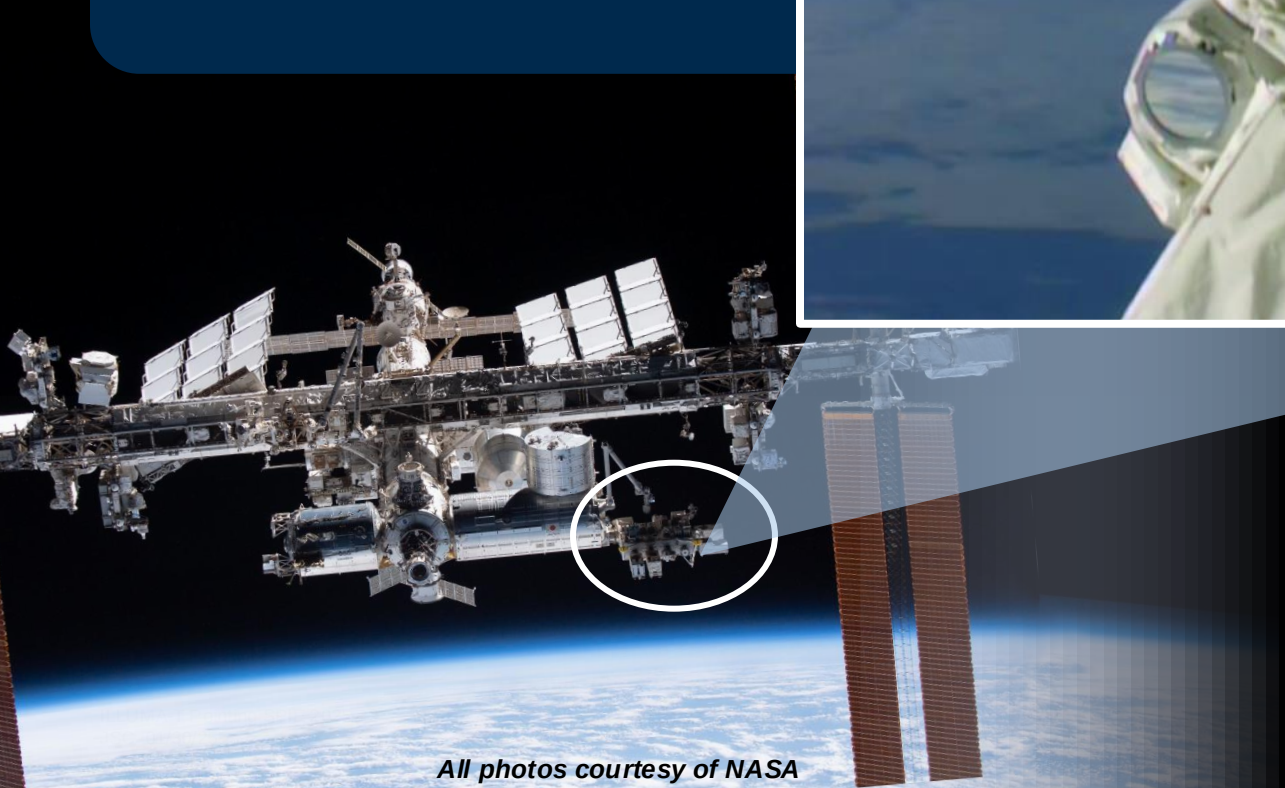
ILLUMA-T: First lasercom user terminal for human exploration

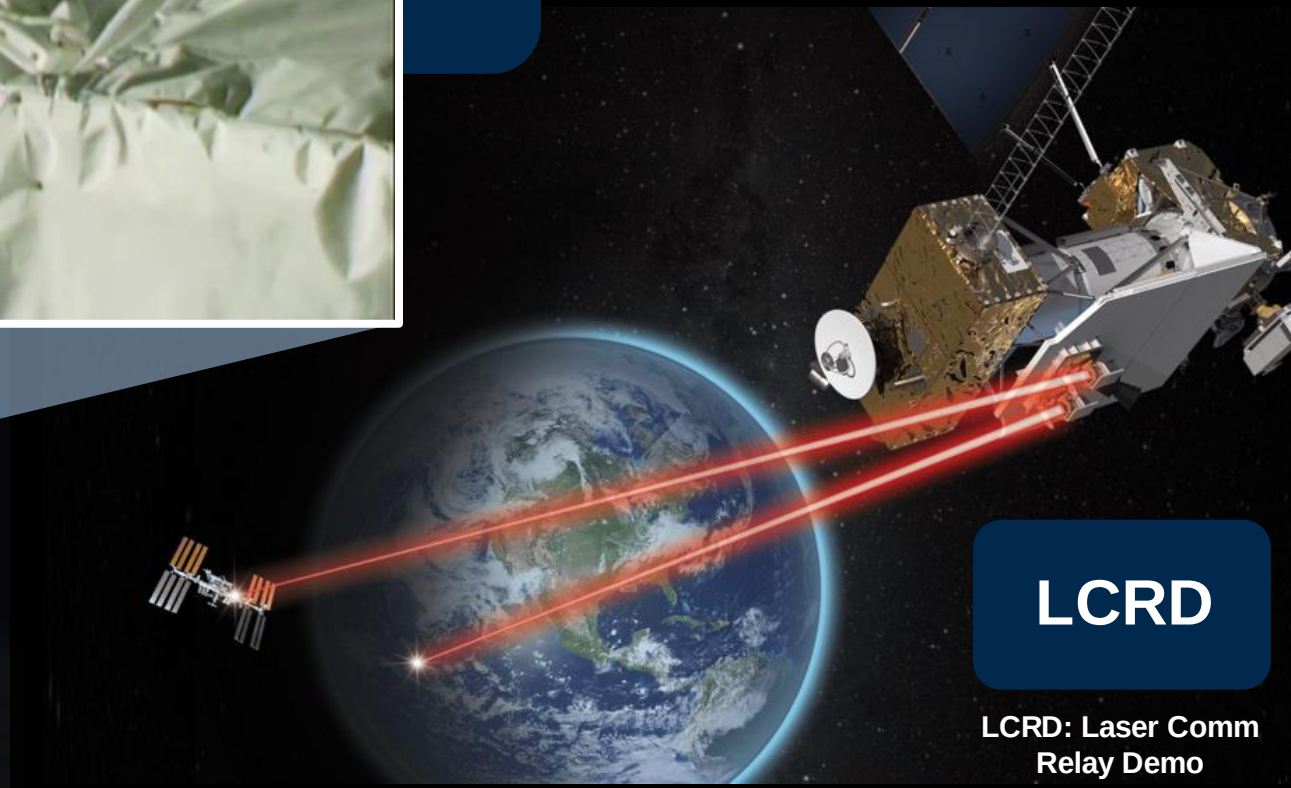
ILLUMA-T: Integrated LCRD LEO User Modem and Amplifier Terminal

Launched November 2023
Successful Operation
Duration: 8 months

Precision Pointing Acquisition and Tracking Required For Laser Communications

On-orbit Pointing Performance Successful





LCRD

LCRD: Laser Comm Relay Demo

All photos courtesy of NASA

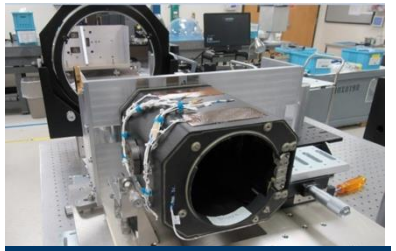
Outline

- **ILLUMA-T and the Modular Agile Scalable Optical Terminal (MAScOT)**
- **ILLUMA-T and LCRD Pointing Acquisition and Tracking Overview**
- **Open-Loop Pointing Parameters**
- **Open-Loop Pointing Analysis**
- **Impact**

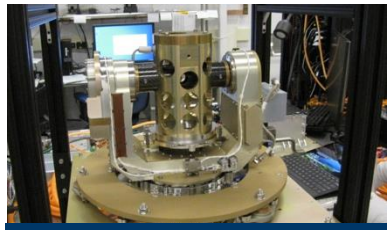
ILLUMA-T: ISS Space Terminal

ILLUMA-T Space Terminal

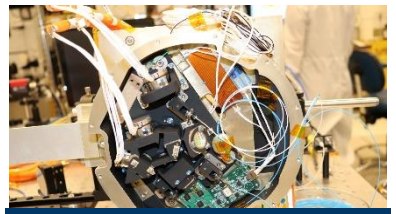
Modular, Agile, Scalable Optical Terminal (MAScOT)



Telescope and Relay



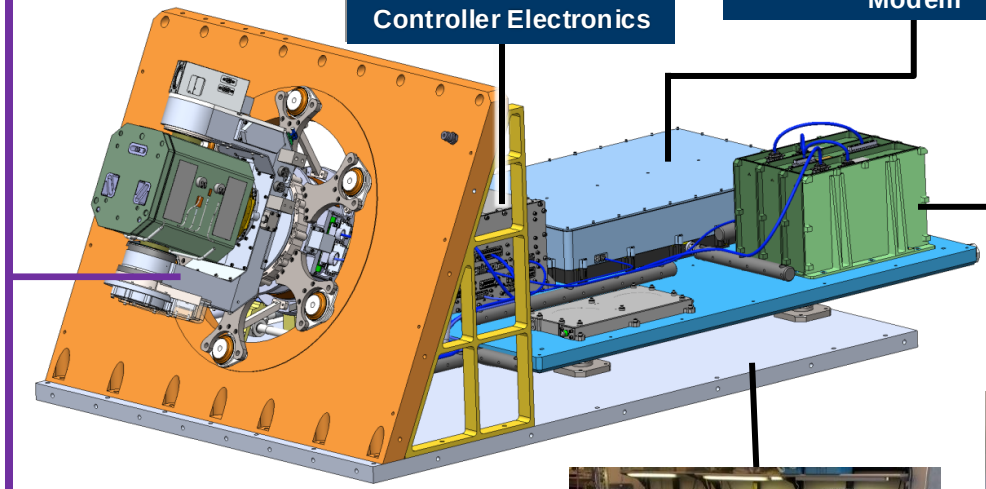
Latch and Gimbal



Backend Optics

Controller Electronics

Modem

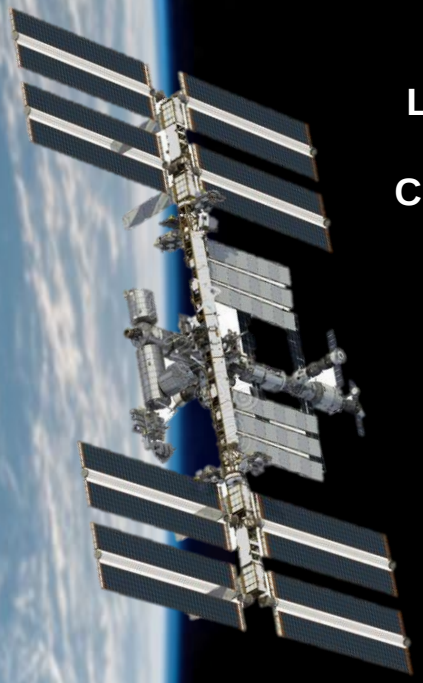


Sled

Power Converter

Modular Agile Scalable Optical Terminal (MAScOT) Missions

ILLUMA-T
(Integrated LCRD LEO User Modem and Amplifier Terminal)



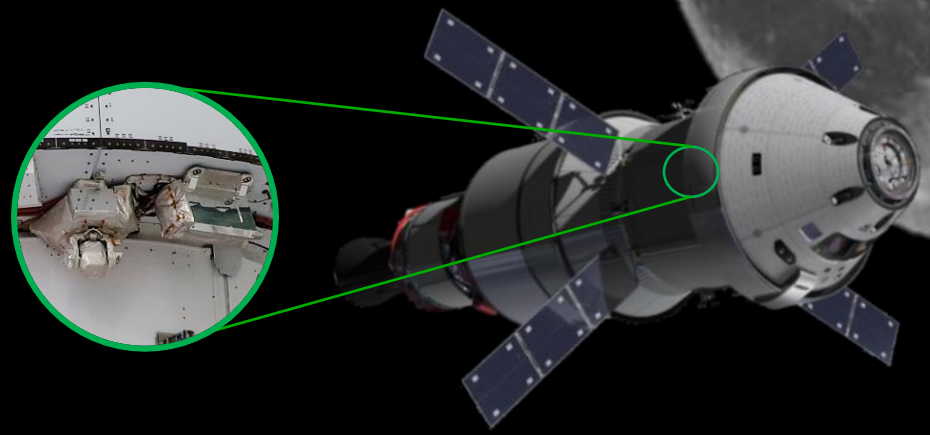
Launched to ISS* on SpaceX Dragon:
Nov. 2023
Comm demonstrated with LCRD* relay
Mission completed: June 2024

*** Internal Space Station and Laser Communications Relay Demonstration,**

NASA Goddard | NASA Johnson Space Center | JAXA 宇宙航空研究開発機構 Japan Aerospace Exploration Agency

O2O
(Orion AM-2 Optical Comm)

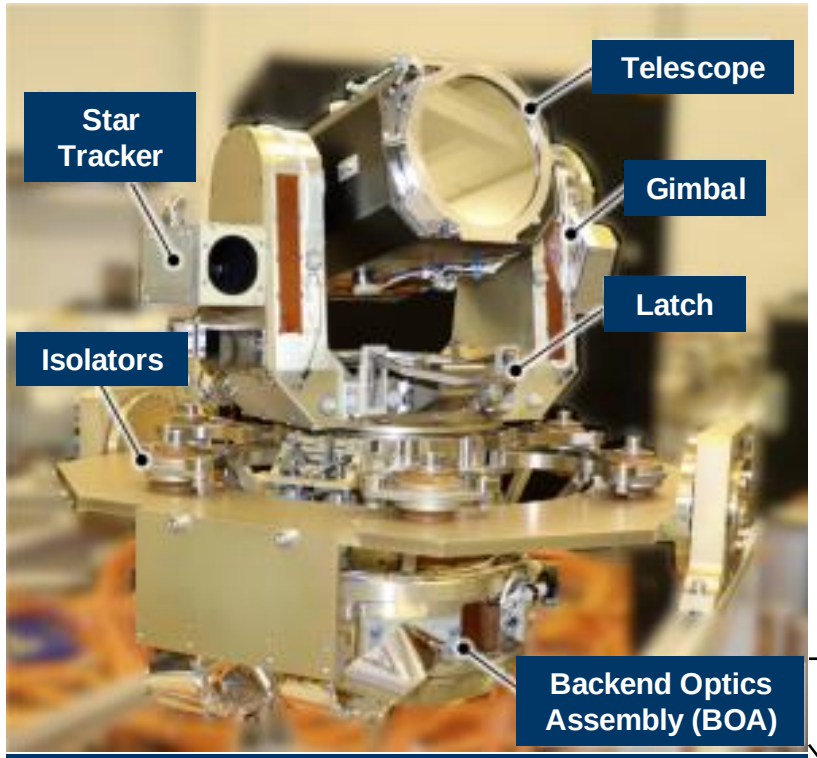
Direct to ground (WSC, TMF)**
Launch on Orion/SLS: April 2026
10 day mission



*** White Sands Complex & Table Mountain Facility**

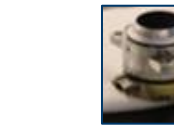
NASA Goddard | LOCKHEED MARTIN | NASA Johnson Space Center | JPL | NASA Marshall Space Flight Center

MAScOT Design



MAScOT: a multi-mission optical head design

- Modular design
  - Telescope and Relay, Backend Optics, Latch and Gimbal
- 43.25x Magnification from Telescope to BOA
- Customizable BOA
- Near-hemispherical field of regard
  - ±120° elevation and ±175° azimuth
- Gimbal used for open-loop, coarse closed-loop pointing
- BOA FSM used for high-frequency disturbance rejection and fine pointing
- On-board star tracker



Fast Steering Mirror

Quadrant Photodetector

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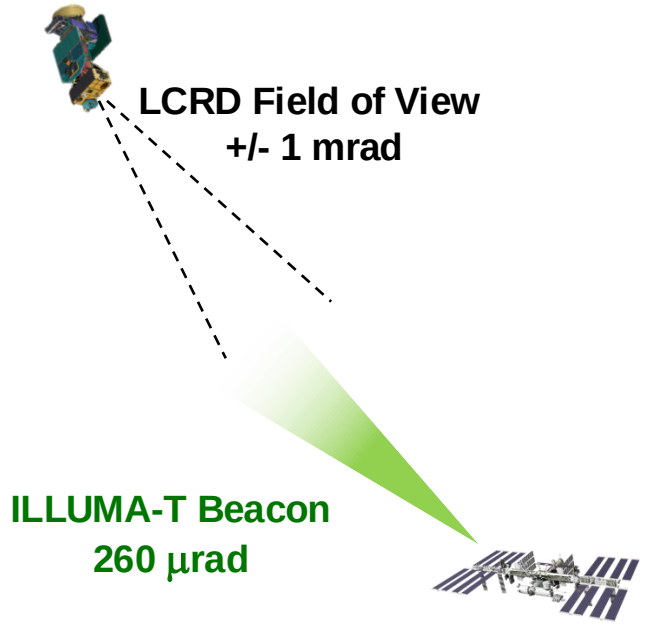
ILLUMA-T Pointing, Acquisition and Tracking (PAT)

- **ILLUMA-T uses a cooperative PAT process with LCRD employing a dedicated beacon**
- **Pointing:**
  - **LCRD and ILLUMA-T point at each other based on ephemerides and local attitude**
  - **ILLUMA-T transmits modulated, wide beacon signal toward LCRD's wide acquisition sensor**
  - **ILLUMA-T scans beacon slow enough so that LCRD has time to pull in and track**
- **Acquisition:**
  - **LCRD sees beacon light from ILLUMA-T, pulls it in and tracks on it**
  - **LCRD improves its pointing and transmits communications beam to ILLUMA-T**
  - **ILLUMA-T sees "cw" light on its wide acquisition sensor and pulls in on**
  - **ILLUMA-T improves its pointing and begins to transmit comm signal**
- **Tracking:**
  - **Both terminals can transition from "coarse" to "fine" track**
  - **ILLUMA-T uses acquisition sensor to do both coarse and fine tracking**
  - **LCRD uses fiber nutation / power in modem for fine tracking**
- **Communications:**
  - **Both terminals receive power in modem fibers lock clock and frames and communications link starts**

ILLUMA-T and LCRD Pointing Acquisition and Tracking Overview

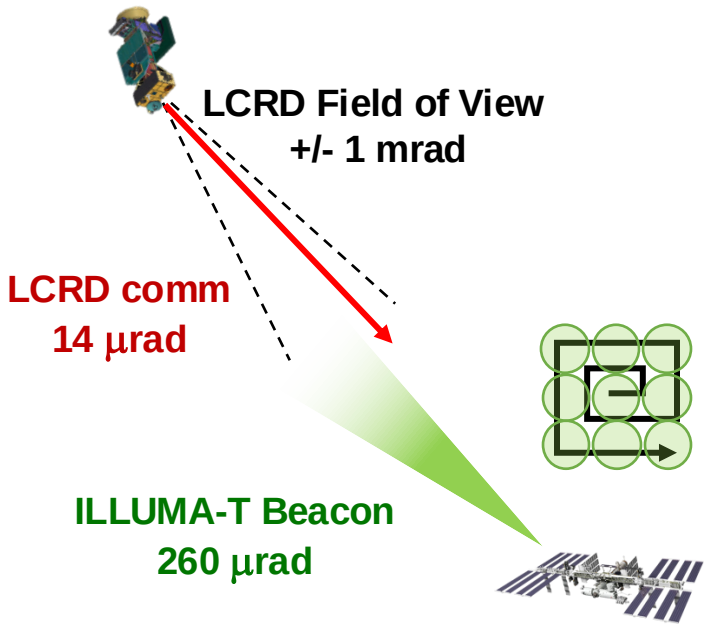
Pointing → Acquisition → Tracking → Communications



- **Receive initial knowledge of ephemeris of LCRD and ISS**
  - **This tells the lasercom systems where to initialize pointing**
- **ILLUMA-T orientation calibrated to ISS**
- **Appropriate configurations on all segments for selected experiments**

ILLUMA-T and LCRD Pointing Acquisition and Tracking Overview

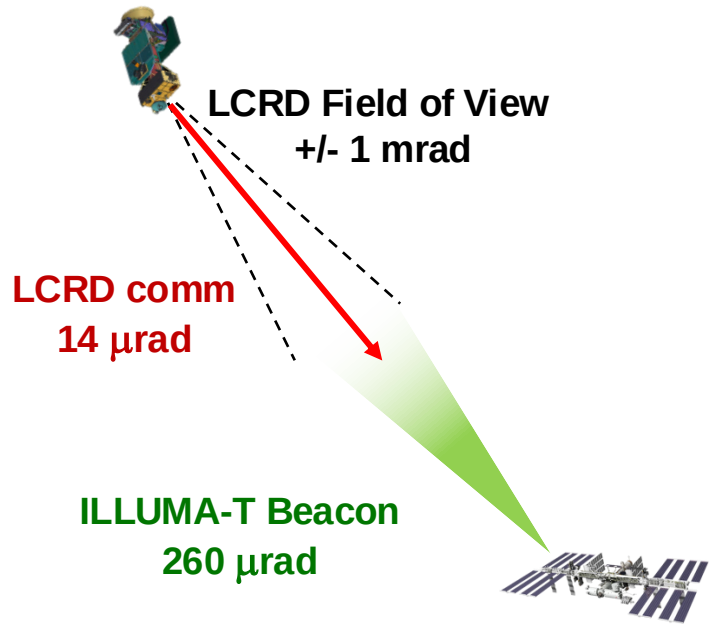
Pointing | **Acquisition** | Tracking | Communications



- **ILLUMA-T beacon** scans in a spiral pattern
- LCRD stares at expected location while transmitting **forward comm beam**

ILLUMA-T and LCRD Pointing Acquisition and Tracking Overview

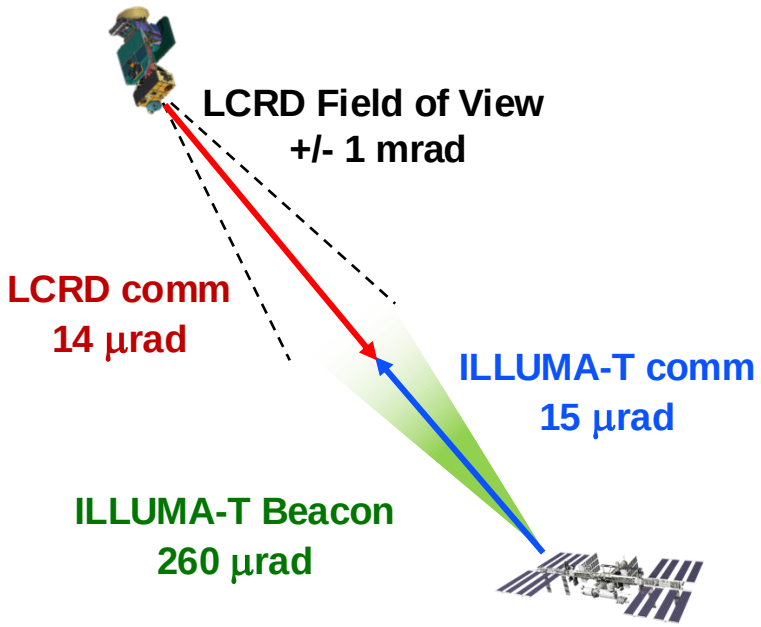
Pointing → Acquisition → **Tracking** → Communications



- ILLUMA-T beacon scans in a spiral pattern
- LCRD stares at expected location while transmitting forward comm beam
- **Once LCRD detects ILLUMA-T beacon, it can track on the beacon and maintain the forward comm beam in the correct direction**

ILLUMA-T and LCRD Pointing Acquisition and Tracking Overview

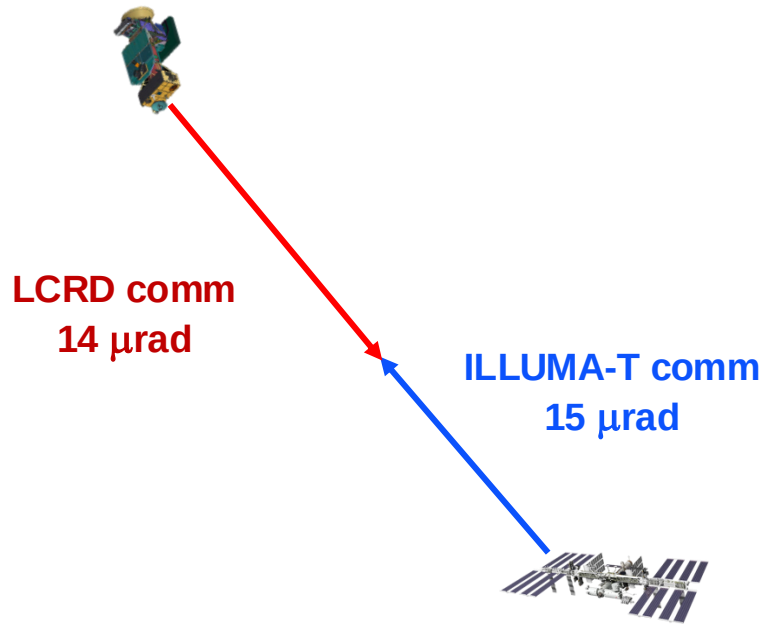
Pointing → Acquisition → **Tracking** → Communications



- ILLUMA-T beacon scans in a spiral pattern
- LCRD stares at expected location while transmitting forward comm beam
- Once LCRD detects ILLUMA-T beacon, it can track on the beacon and maintain the forward comm beam in the correct direction
- **Once ILLUMA-T sees the forward comm beam, it can track on it and maintain the return comm beam back to LCRD**
- **LCRD can then use the return comm beam to refine its tracking**

ILLUMA-T and LCRD Pointing Acquisition and Tracking Overview

Pointing → Acquisition → Tracking → Communications



- **LCRD & ILLUMA-T can maintain tracking using comm beams**
- **Multiple comm modes available**
  - **Return: 155 Mbps, 311 Mbps, 622 Mbps, 1.244 Gbps**
  - **Forward: 51 Mbps, 155 Mbps**
- **Each LEO-GEO pass lasts 20-40 min**

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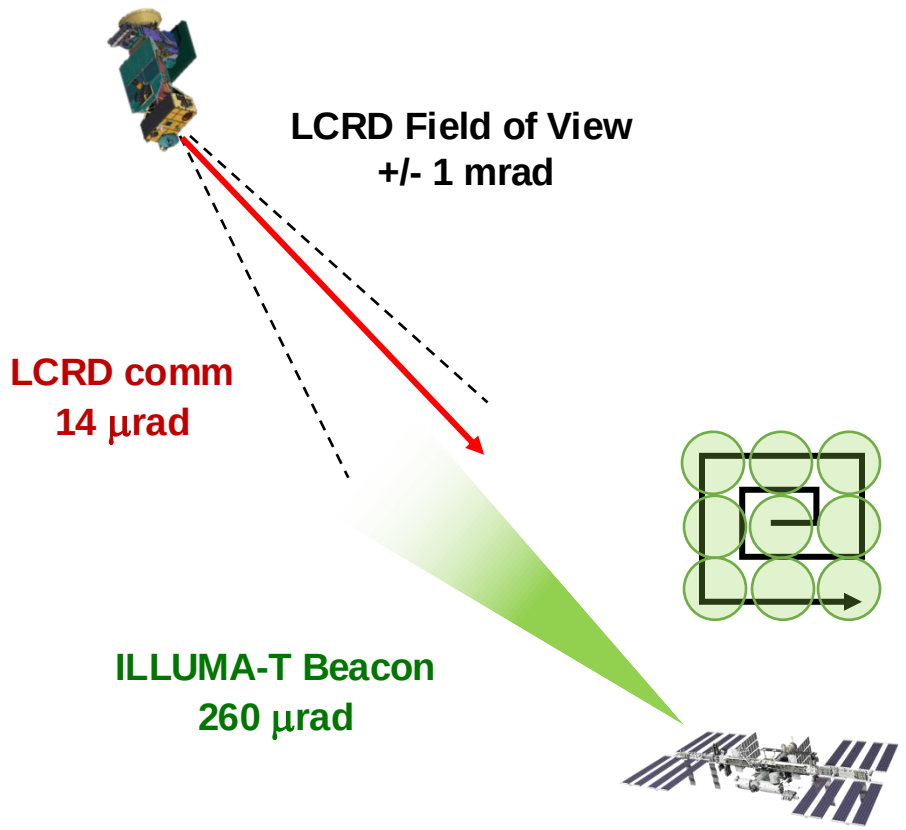
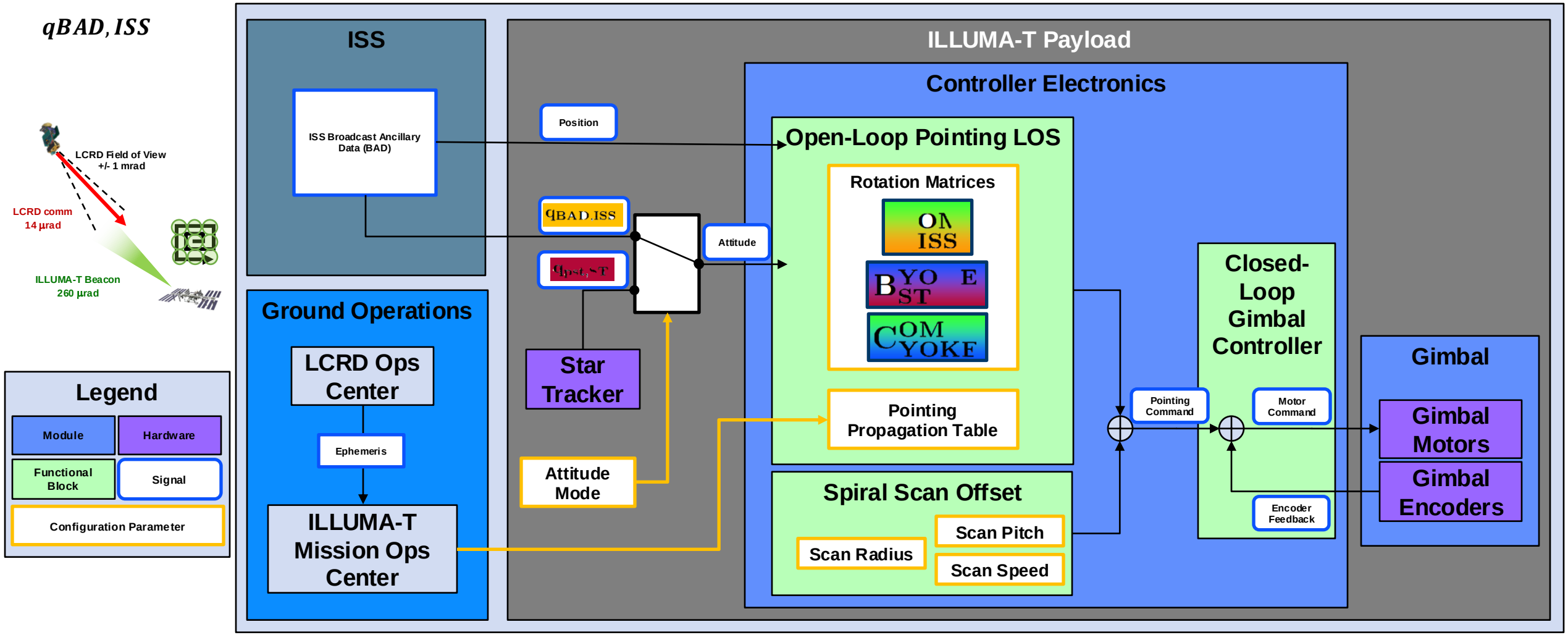
Open-Loop Pointing

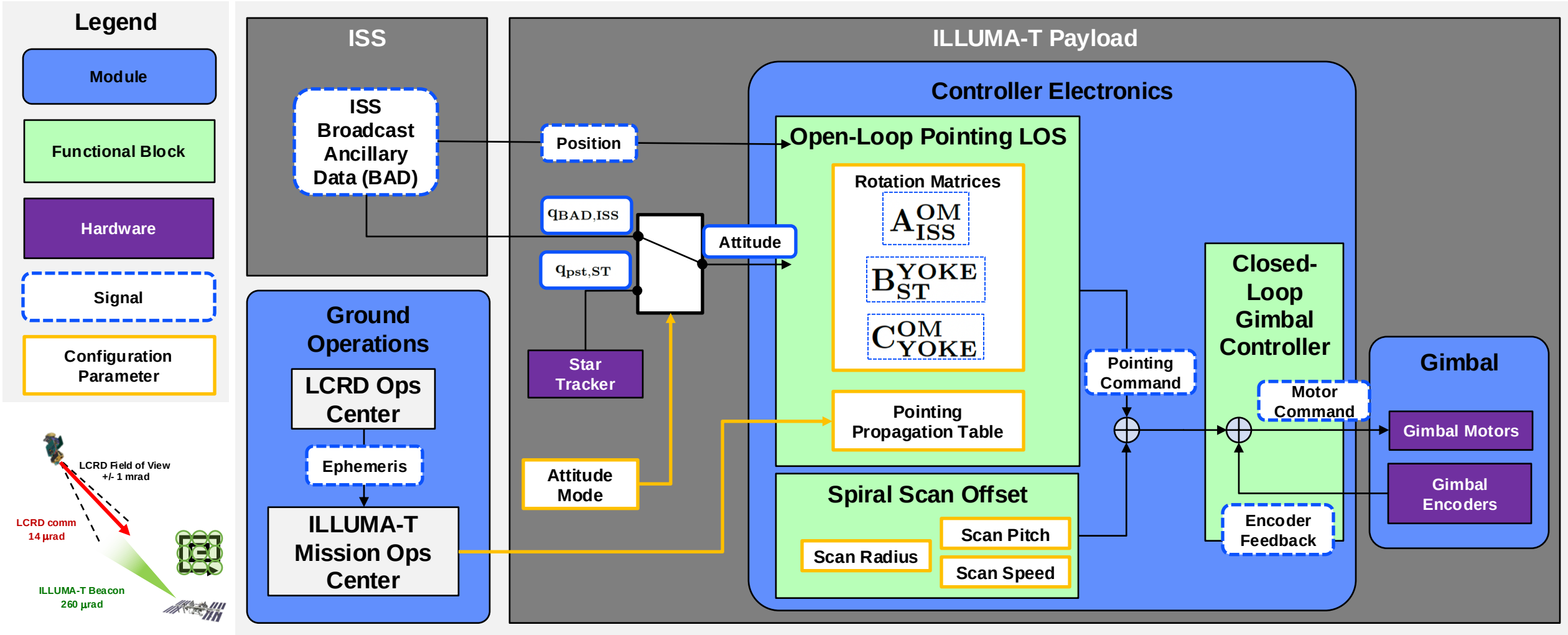


Open-Loop Pointing

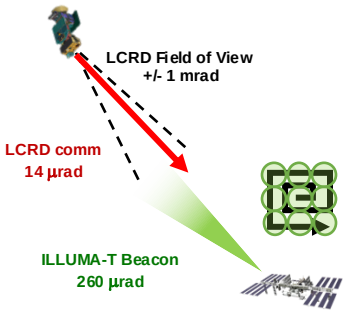
original



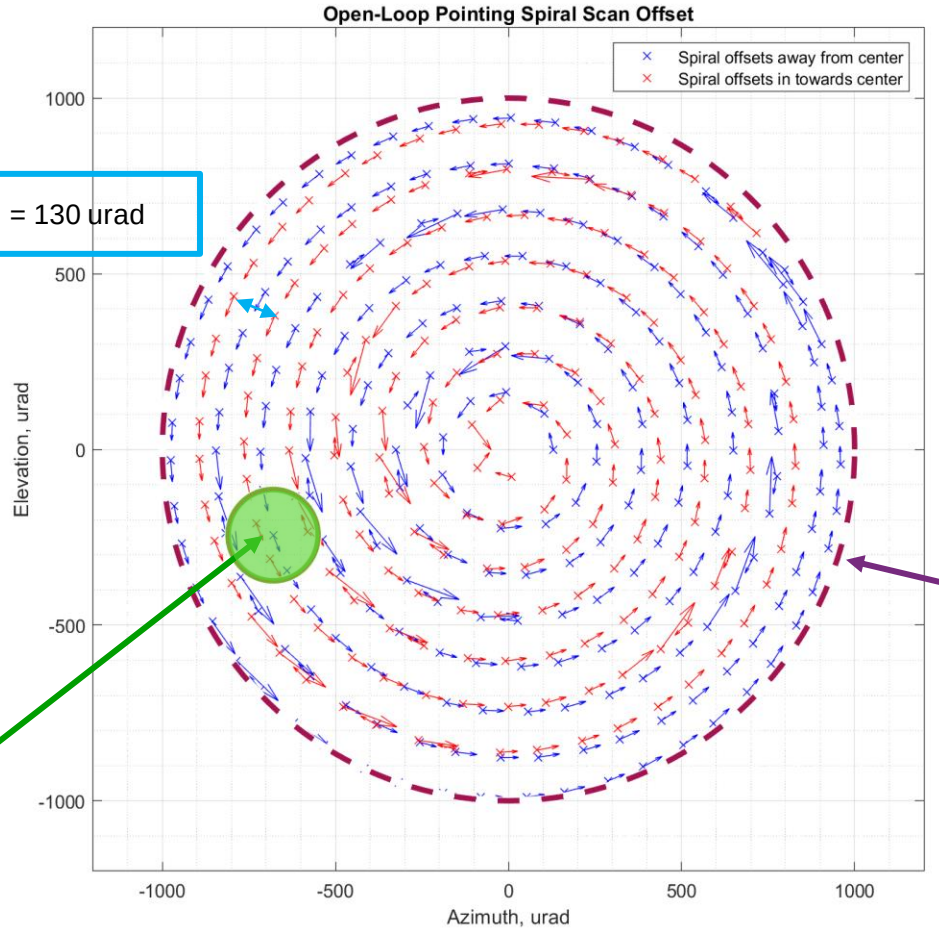
Open-Loop Pointing



Spiral Scan Parameters



Spiral Pitch = 130 urad



Size of ILLUMA-T Beacon as seen at LCRD (~260 urad)

Max Spiral Radius = 1 mrad

Parameter Trade-Offs
Fixed LCRD FOV, ILLUMA-T Beacon Diameter

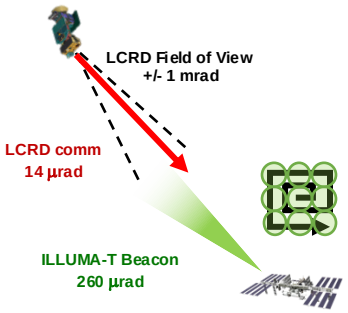
Radius ↑, Time ↑
Radius↓, Pointing-error tolerance ↓

Pitch↑, Acquisition probability ↓
Pitch ↓, Time ↑

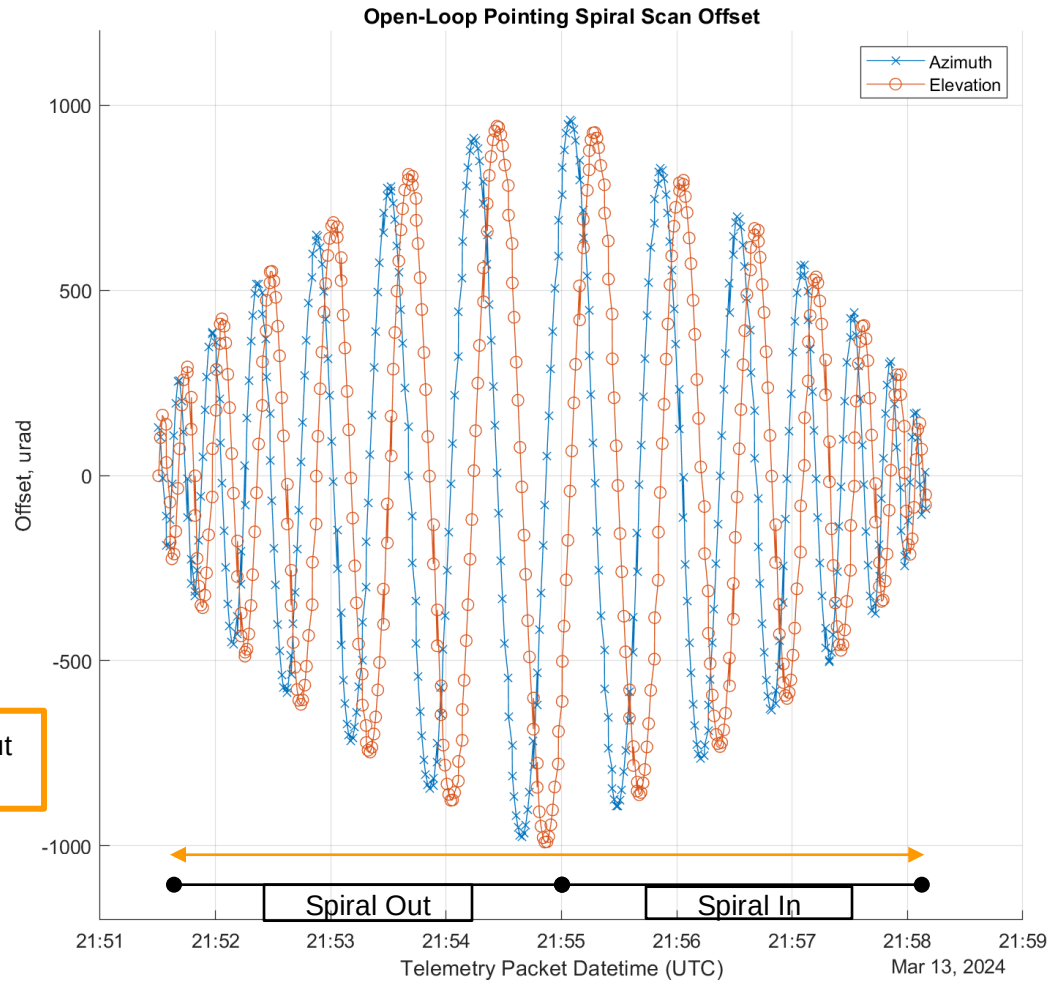
Speed ↑, Acquisition probability ↓
Speed ↓, Time ↑

Spiral Scan Example, March 13 2024	
Max Scan Radius	1 mrad
Scan Pitch	130 urad
Scan Time (time to complete spiral out and in)	~7 minutes

Spiral Scan Parameters



Time to complete spiral out and in ~ 7 minutes



Parameter Trade-Offs
Fixed LCRD FOV, ILLUMA-T Beacon Diameter

Radius ↑, Time ↑
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Pitch↑, Acquisition probability ↓
Pitch ↓, Time ↑

Speed ↑, Acquisition probability ↓
Speed ↓, Time ↑

Spiral Scan Example, March 13 2024	
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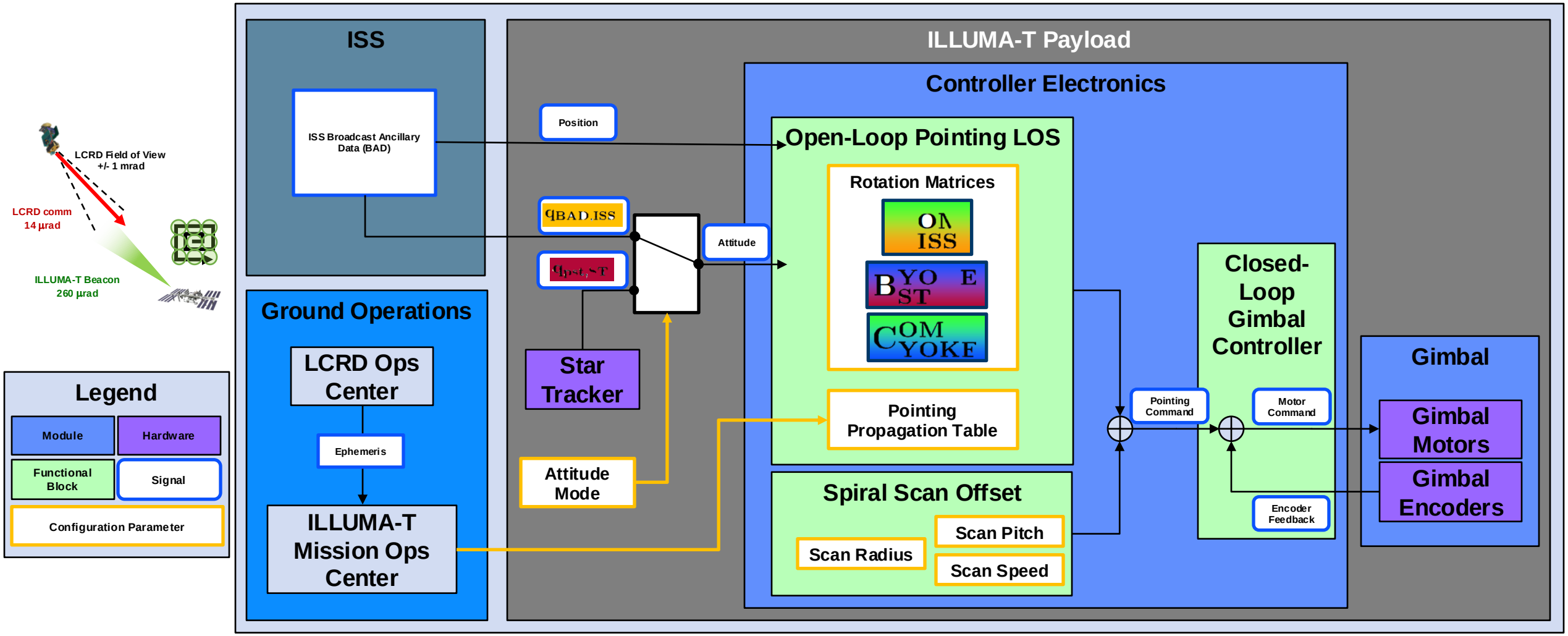
Open-Loop Pointing

original



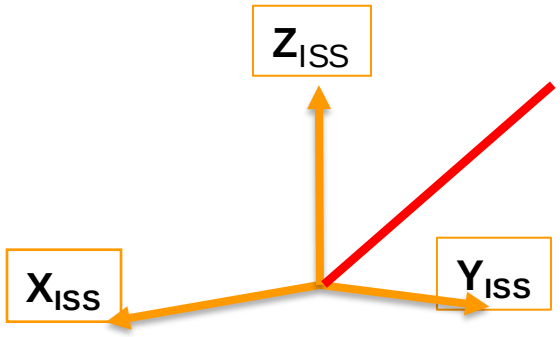
Rotation Matrices

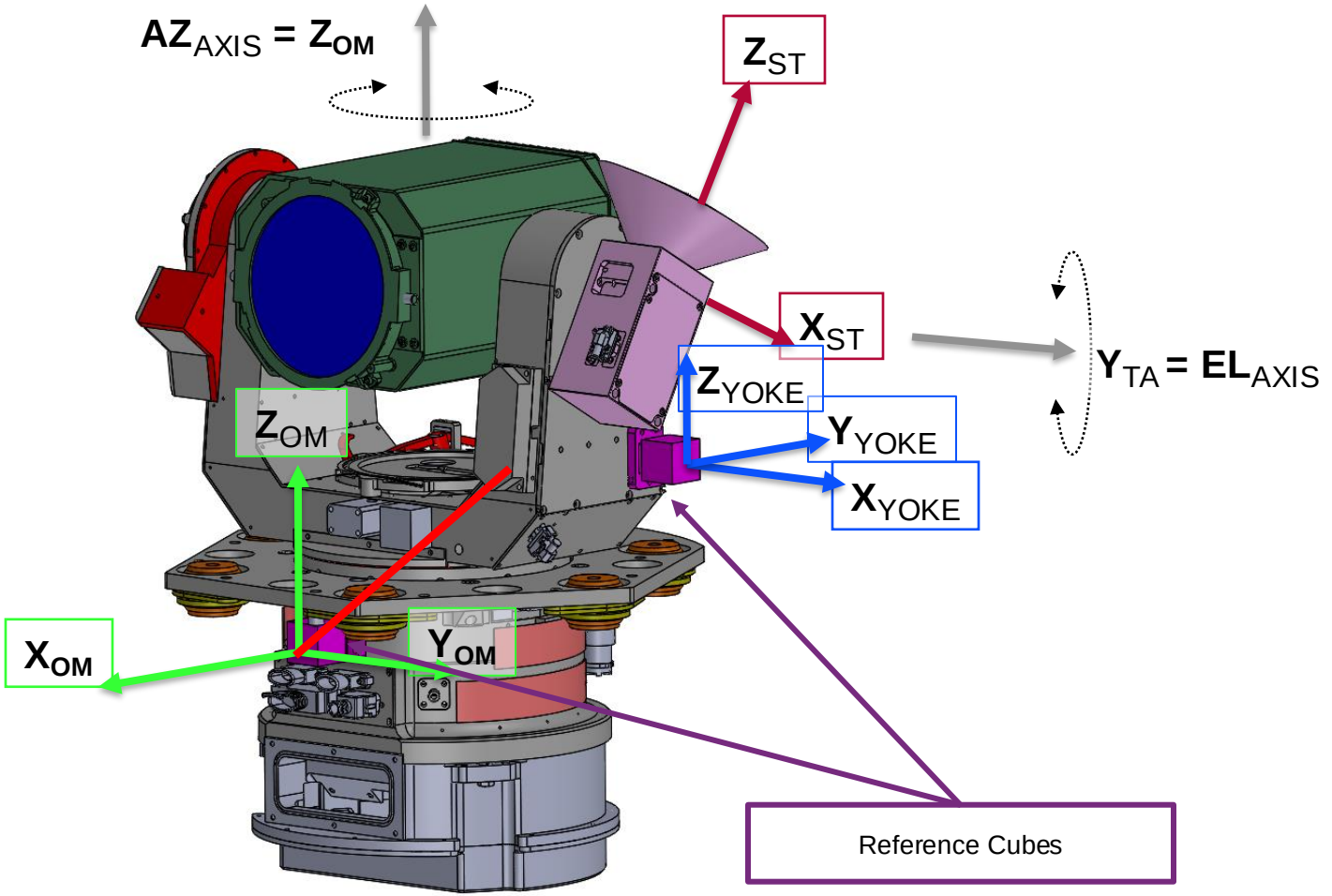
Coordinate Frames

- OM
- ISS
- Yoke
- Star Tracker

Rotation Matrices

- R_{ISS}^{OM}
- R_{YOKE}^{ST}
- R_{YOKE}^{OM}





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Analysis of Spacecraft to ILLUMA-T OM Rotation Change

Attitude Telemetry (quaternions)

$q_{BAD,ISS}$ $q_{pst,ST}$

As-Built Parameters (3x3 Rotation Matrices)

A^{OM}_{ISS} $B^{YO\ E}_{ST}$ C^{OM}_{YOKE}

Gimbal Azimuth Encoder Angle

θ_{azenc}

$q_{BAD,ISS}$ A^{OM}_{ISS} $q_{pst,ST}$ $B^{YO\ E}_{ST}$ C^{OM}_{YOKE} θ_{azenc}

$q_{BAD,OM} \stackrel{?}{=} q_{pst,OM}$

$\bar{q}^{OM}_{ISS} = q_{BAD,ISS} q_{pst,OM}$

$\bar{q}^{OM}_{ISS}$ is the "derived rotation between the coordinate frames of the two sources of attitude information"

$\bar{q}^{OM}_{ISS}$ can also be considered the ideal quaternion representation of -- A^{OM}_{ISS}

Analysis of Spacecraft to ILLUMA-T OM Rotation Change

Attitude Telemetry (quaternions)

$q_{BAD,ISS}$ $q_{pst,ST}$

As-Built Parameters (3x3 Rotation Matrices)

A^{OM}_{ISS} B^{YOKE}_{ST} C^{OM}_{YOKE}

Gimbal Azimuth Encoder Angle

θ_{azenc}

$$\bar{q}^{OM}_{ISS} = q^{*}_{BAD,ISS}\, q_{pst,OM}$$

$$\bar{q}^{OM}_{ISS} \longleftrightarrow A^{OM}_{ISS}$$

$$z = \bar{q}^{OM}_{ISS} * q^{OM*}_{ISS}$$

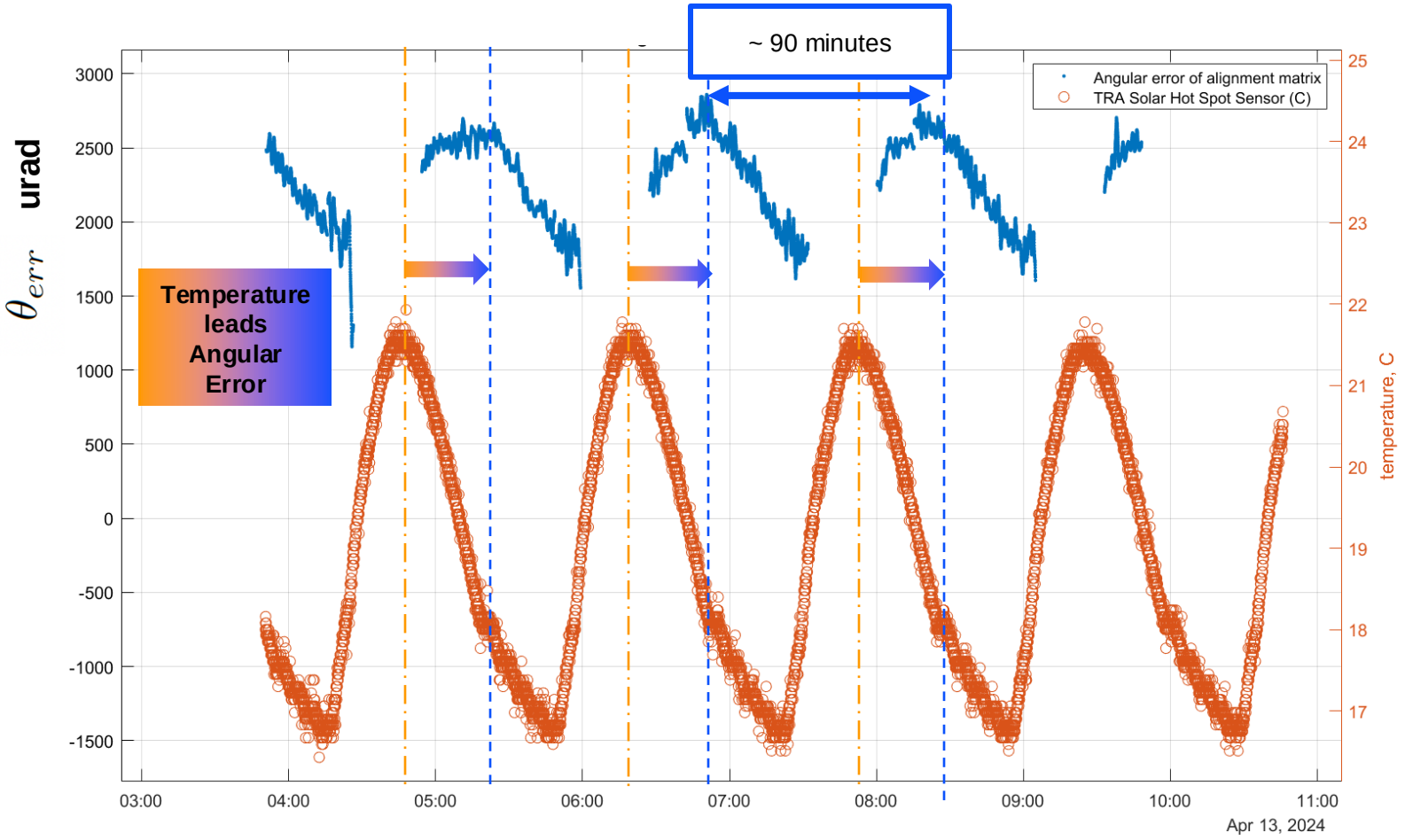
$$\theta_{err} = 2cos^{-1}(\Re(z))$$

θ_{err} is the angular distance between $\bar{q}^{OM}_{ISS}$ and $\bar{q}^{OM}_{ISS}$,

the derived and ideal rotation between the coordinate frames of the two

Spacecraft to ILLUMA-T OM Rotation change

Correlation of Angular Error and Temperature



Duration shown: ~ 7 Hours

Angular error shows periodicity consistent with ISS orbit

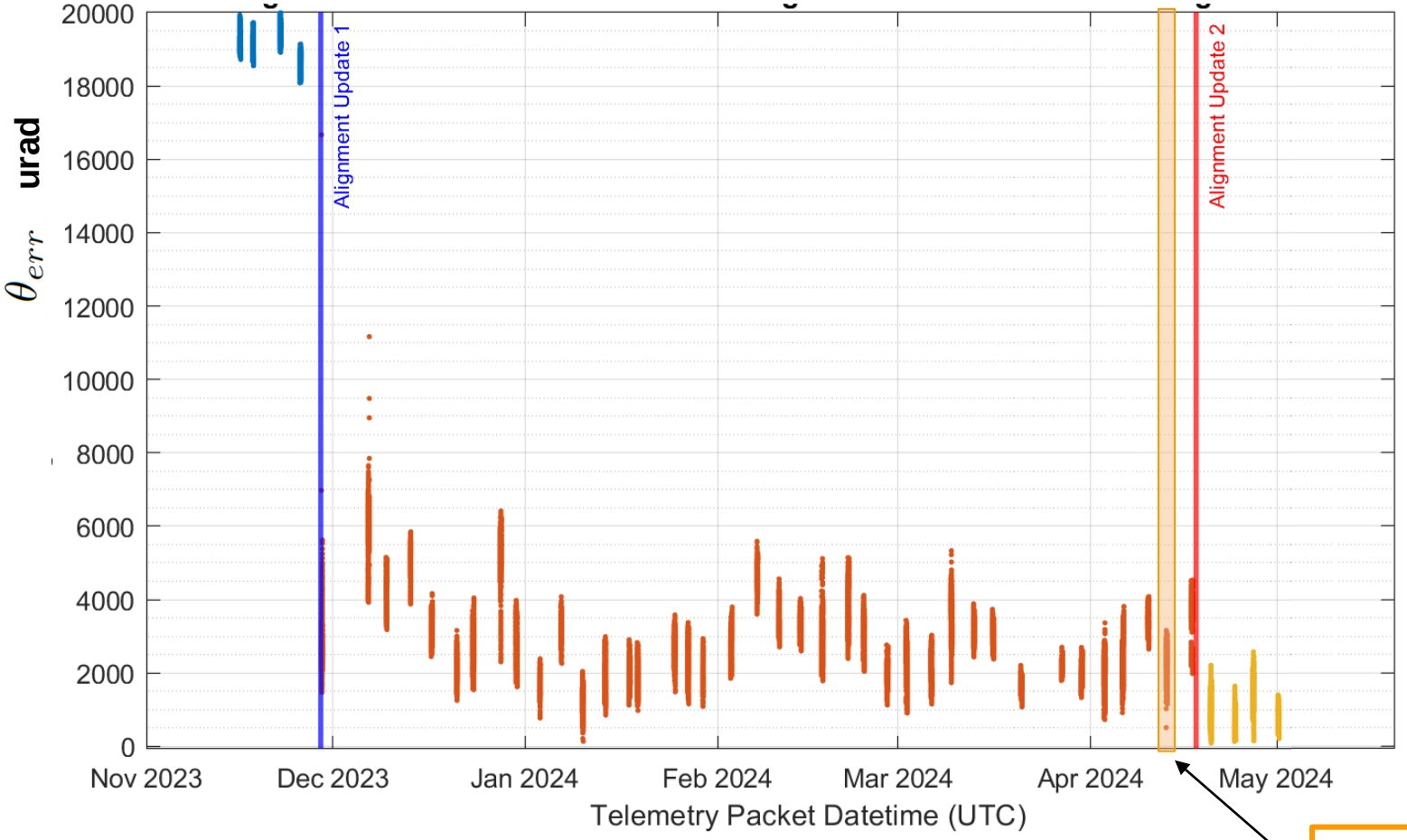
Temperature sensor on OM away from thermal drivers shows same periodicity

Temperature appears to lead angular error

Angular error changes ~1 mrad over orbital period

Spacecraft to ILLUMA-T OM Rotation change

Angular Error between On-Board Alignment Matrix and Derived Rotation between coordinate frames



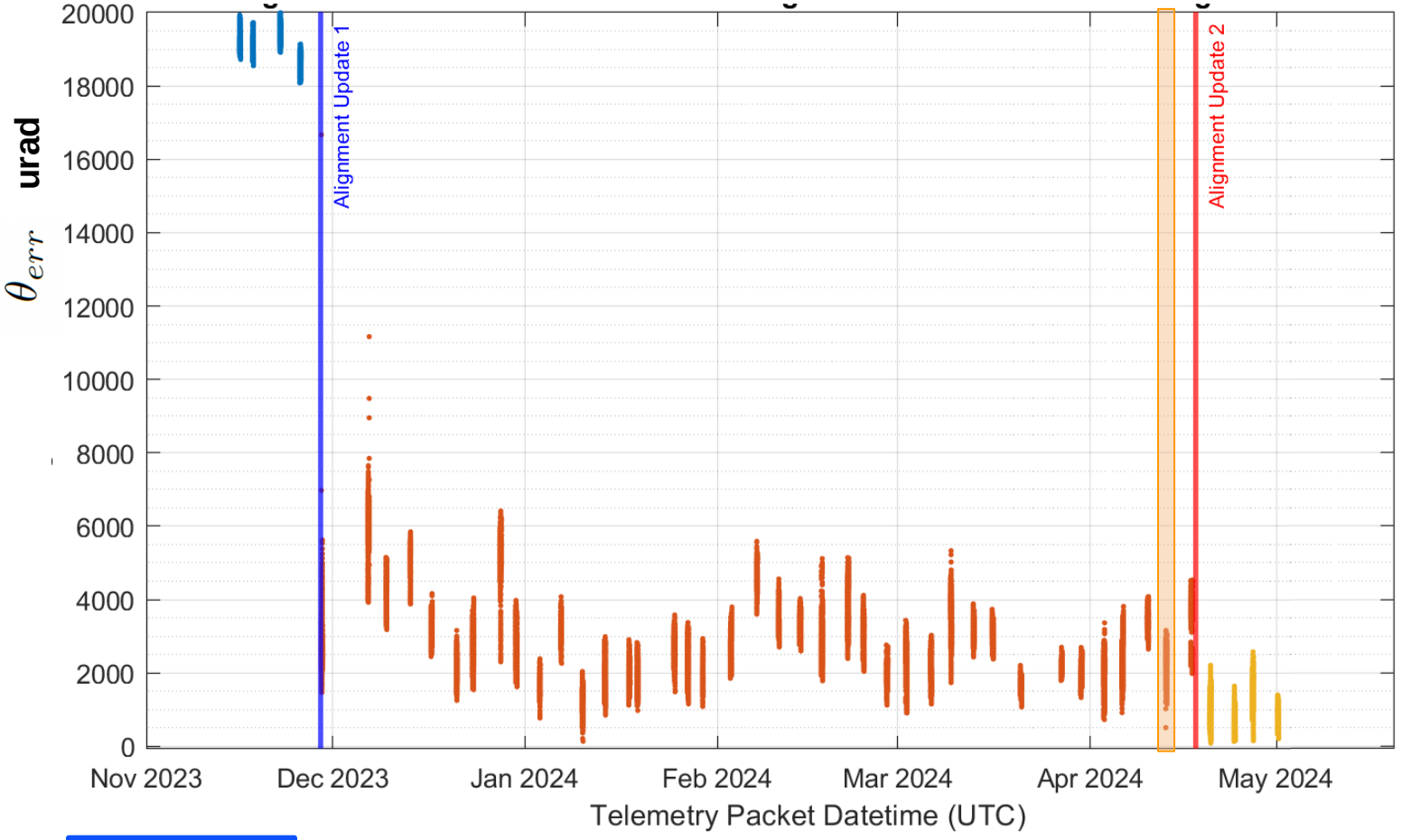
Duration shown: ~ 7 Months

Selected data processed; approx 4-6 hours of data taken twice per week shown.

Data from previous slide

Spacecraft to ILLUMA-T OM Rotation change

Angular Error between On-Board Alignment Matrix and Derived Rotation between coordinate frames

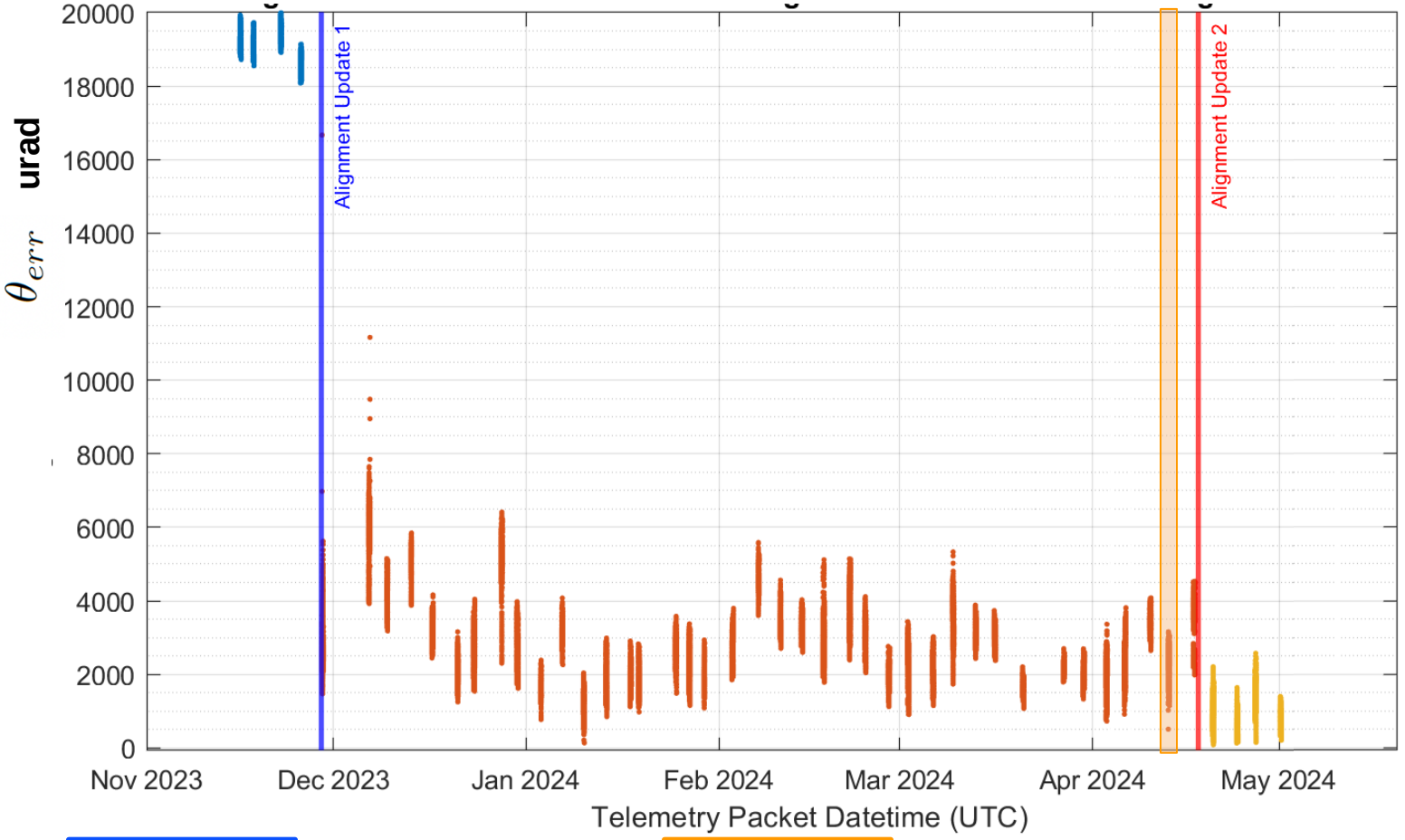


Initial Alignment Matrix (v0) was generated from model, no as-built measurement possible

AOM ISS v0

Spacecraft to ILLUMA-T OM Rotation change

Angular Error between On-Board Alignment Matrix and Derived Rotation between coordinate frames



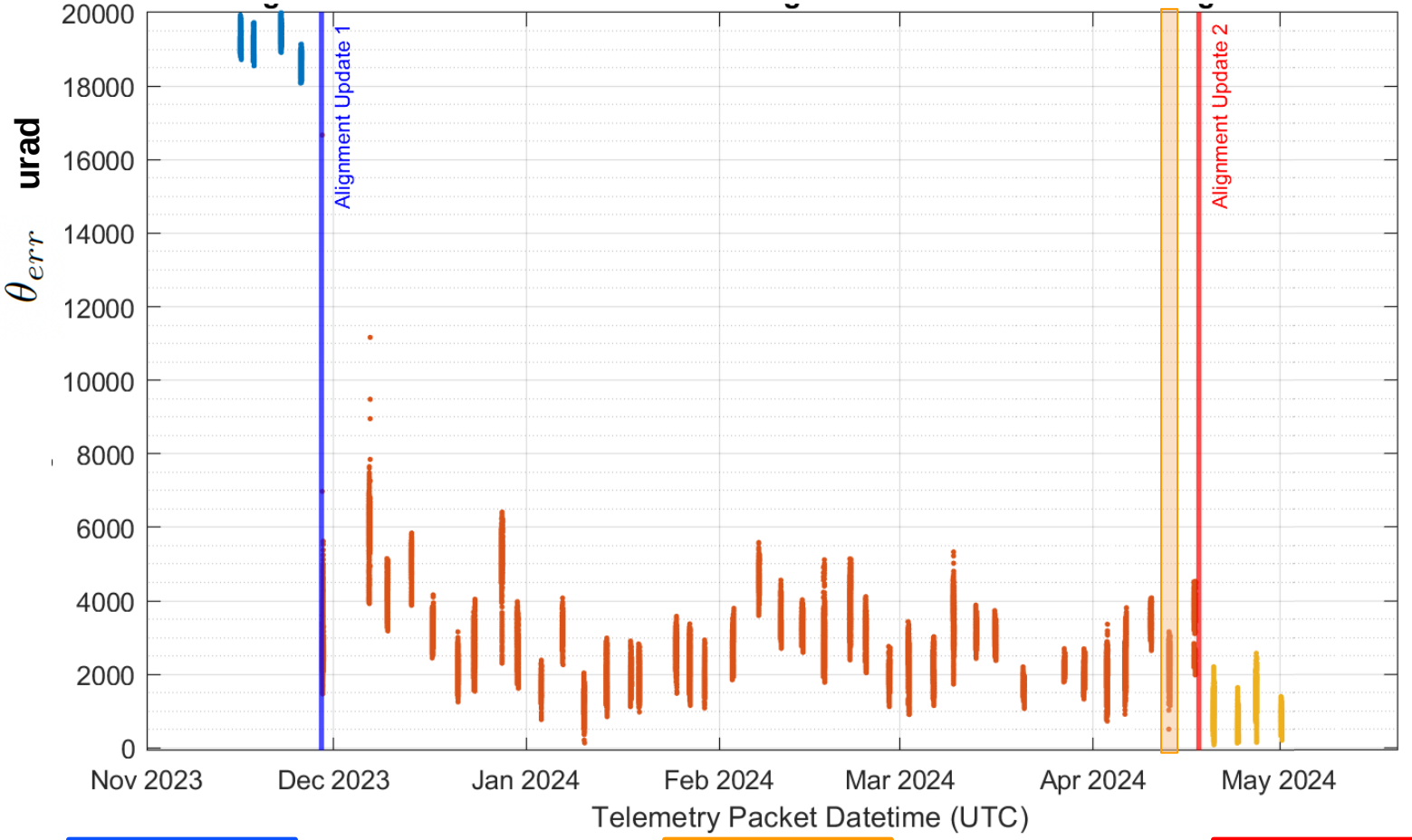
Alignment Matrix v1 reduced the angular error significantly - effectively the first as-built measurement

AOM ISS v0

AOM ISS v1

Spacecraft to ILLUMA-T OM Rotation change

Angular Error between On-Board Alignment Matrix and Derived Rotation between coordinate frames



Alignment matrix v2 again reduced the angular error

Long term shift observed, mission duration too short for conclusive analysis

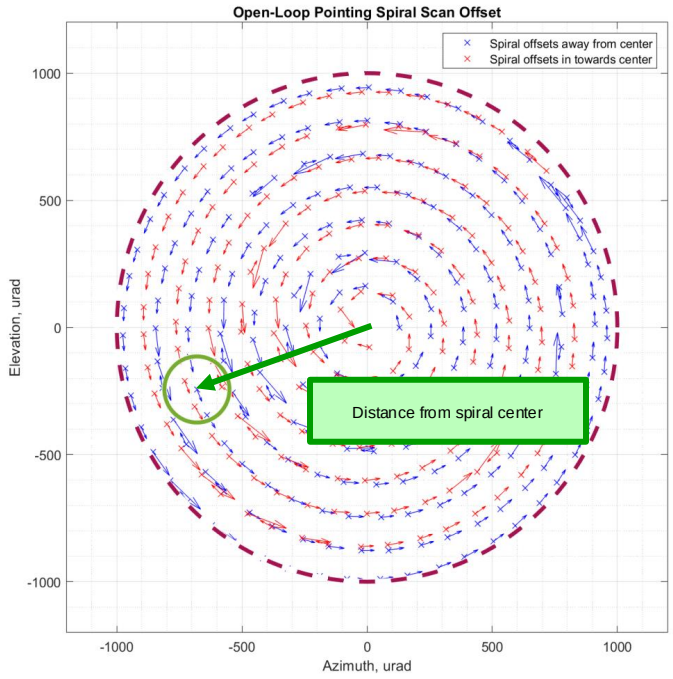
AOM ISS v0

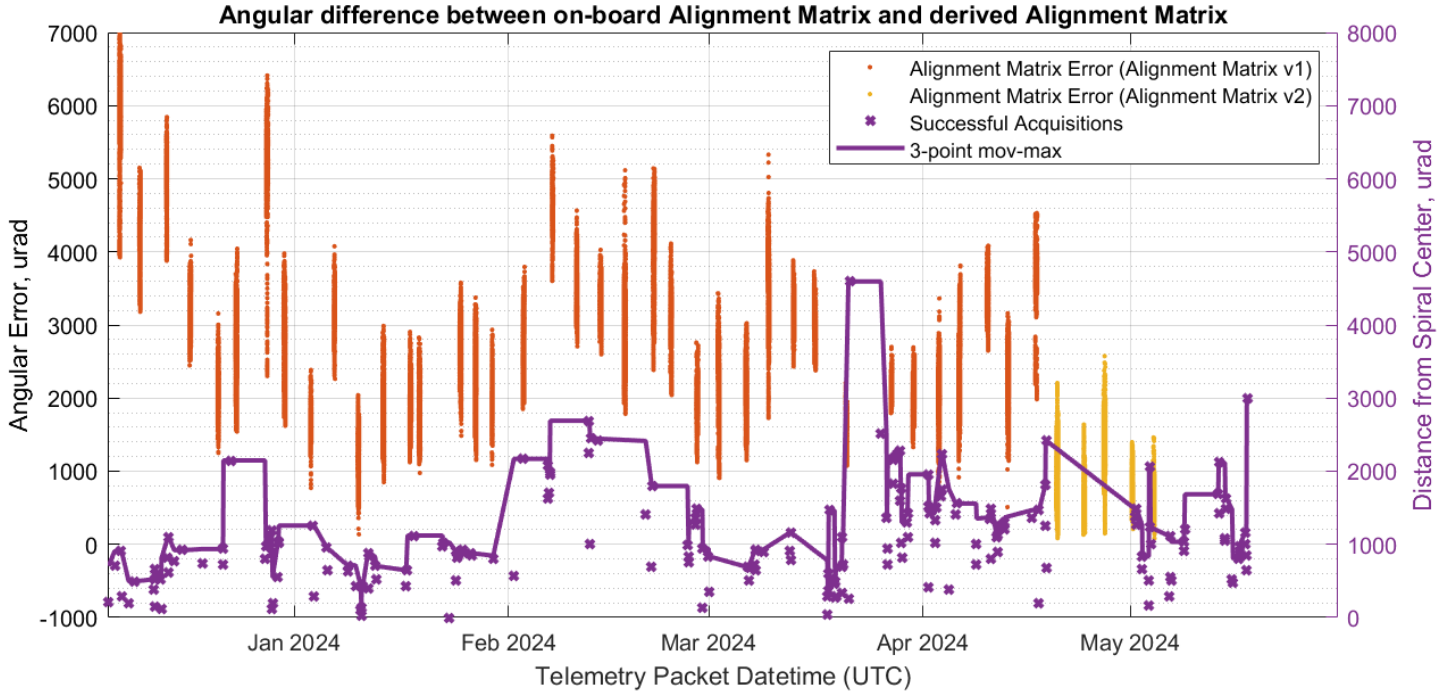
AOM ISS v1

AOM ISS v2

Quantifying Open-Loop Pointing Performance

- **Distance from spiral at moment of acquisition captures open-loop pointing error**
- **As angular error increases, distance from spiral also increases**





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Impact

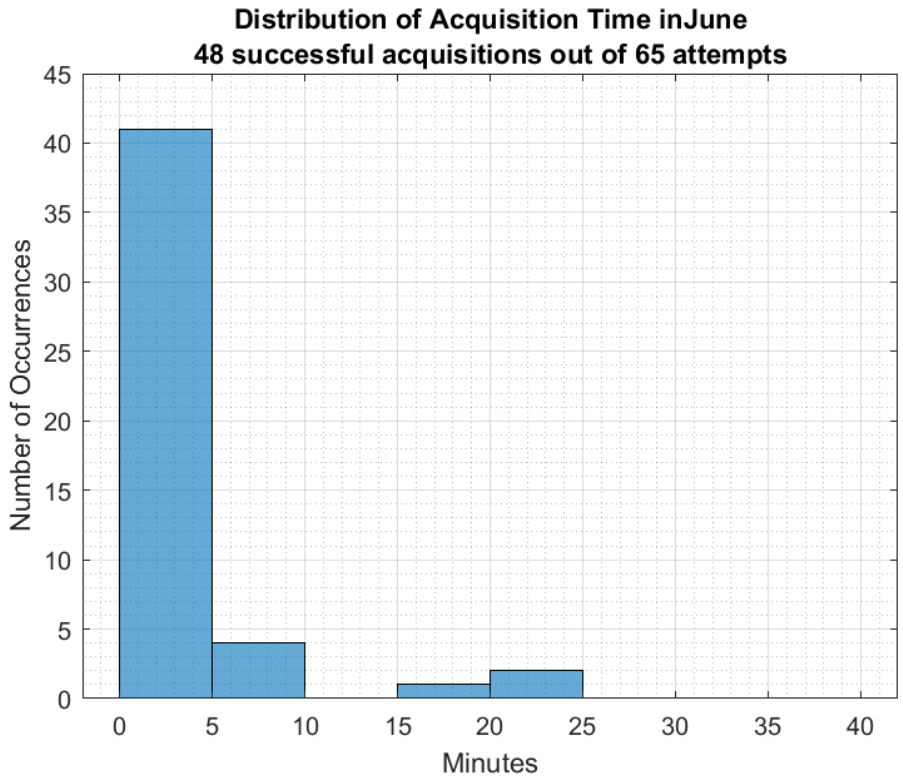
Open-loop pointing performance critical to mission success

307

Links established

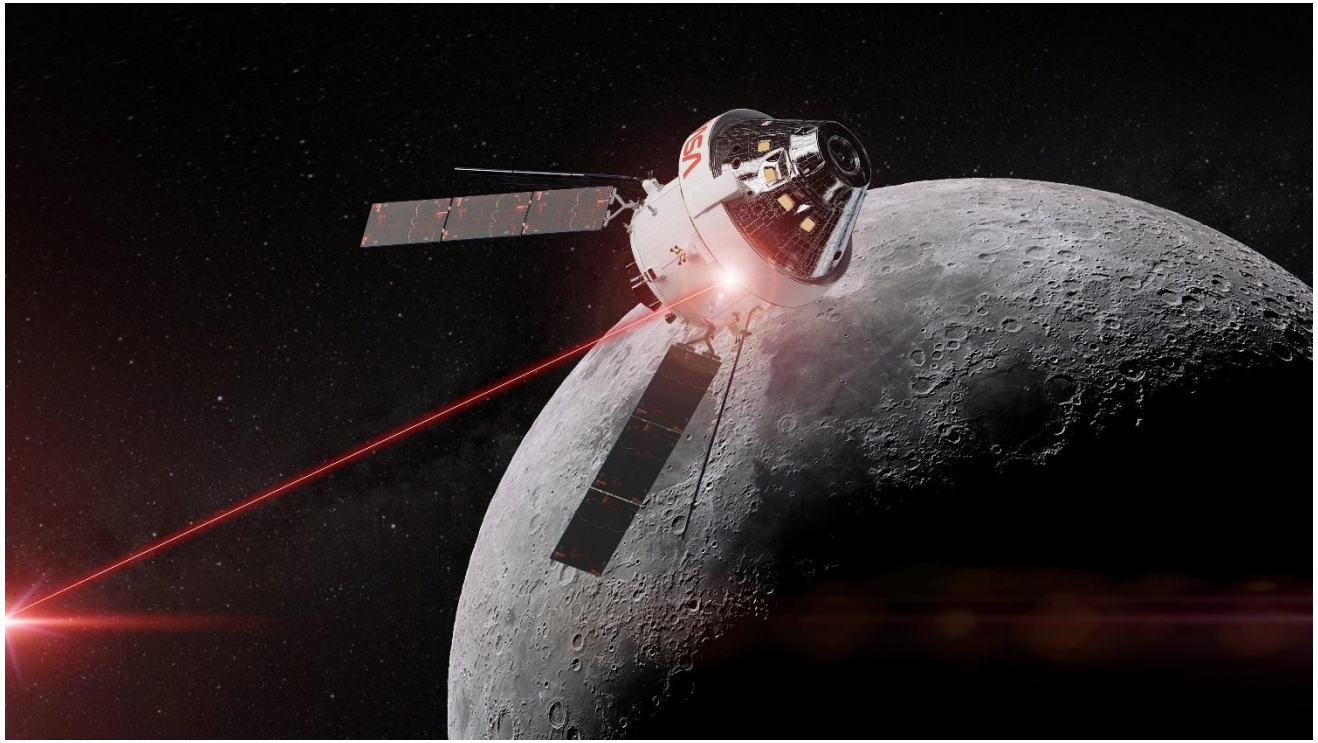
~5000 minutes

Active communications



In June 2024, 85% of all acquisitions were within 5 minutes

What's Next?



- Next MAScOT demonstration - O2O launches on Artemis II in April 2026
- Direct-to-Earth link from Lunar distances
- Adapt analysis tools and approaches to be used for this mission