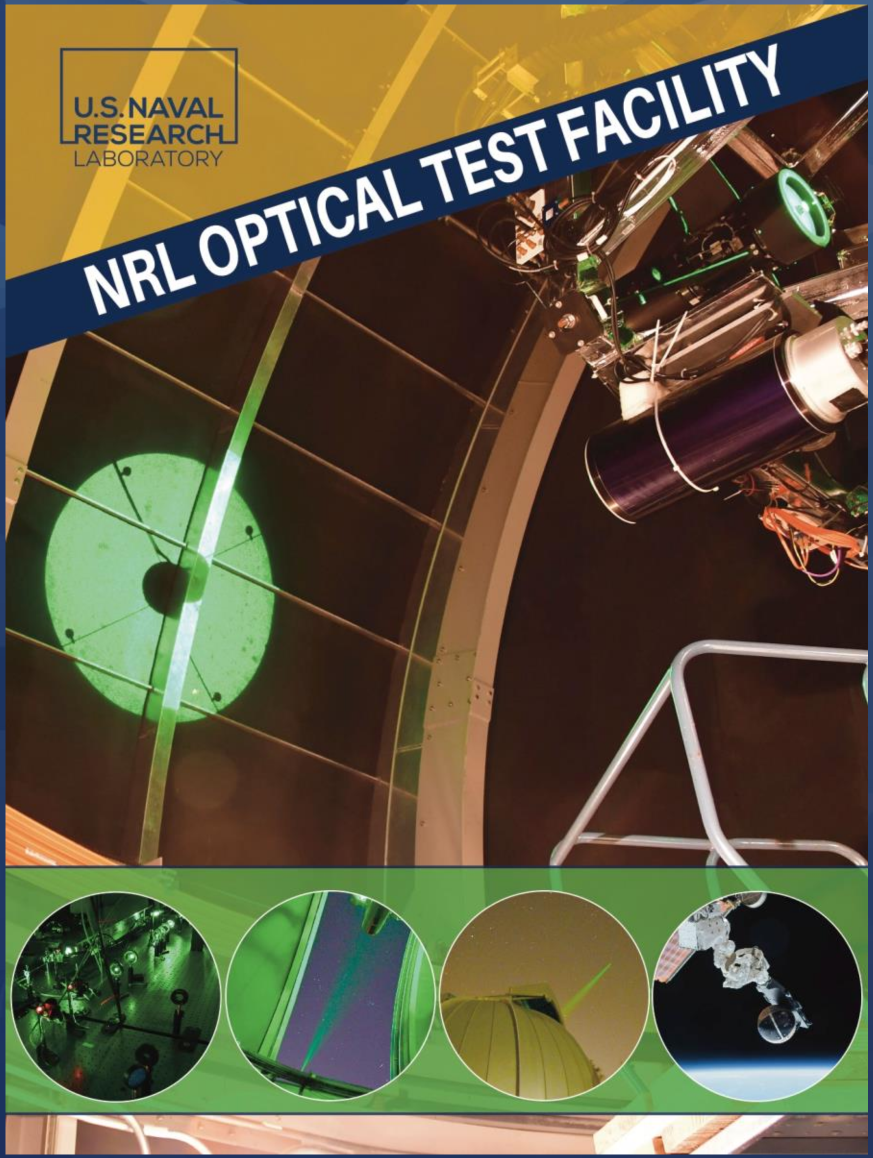
Status of Laser Time Transfer at Stafford, Virginia



J. Griffiths, ***C. Font, R. Smith, A. DeRieux, L. Willstatter, C.I. Moore, F. Santiago, J. Ghiorzi, L. Thomas***

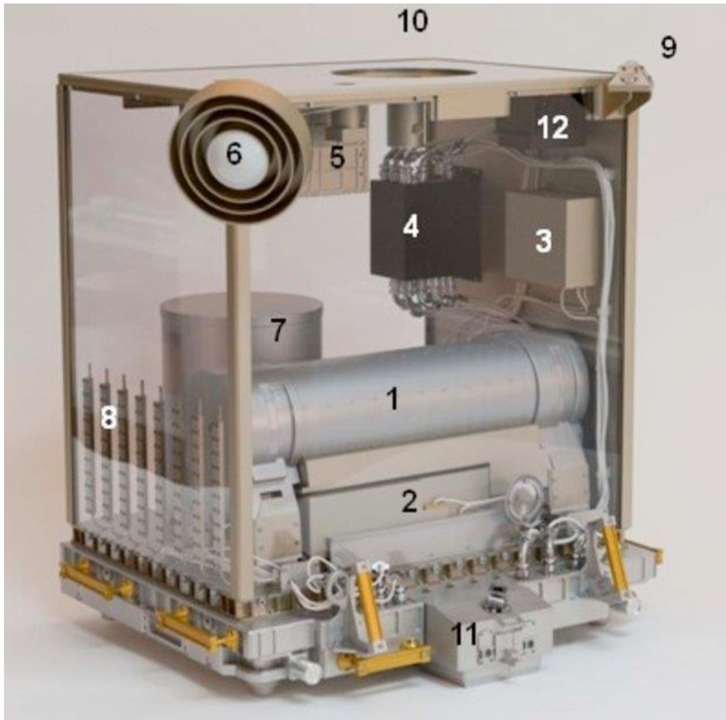
U.S. Naval Research Laboratory
Naval Center for Space Technology
Advanced Laser Technologies
Washington, DC USA

ILRS Technical Workshop – 21-25 October 2019 – Stuttgart, Germany

Objective & Motivation

- Enable NRL to participate in ILRS and other Laser Time Transfer (LTT) experiments, including CHOMPTT (NASA Ames/U. of FL) and ESA's ACES/ELT
  - leverage COTs equipment and technological advances from ILRS to date

- ACES/ELT
  - launch to ISS: expected in 2020
  - ultra-stable atomic (Cs fountain + H-maser) clock ensemble[1,2,3]
  - microwave link[10] for ACES primary time transfer mode
  - 532nm laser link[12] for optical timing experiments
    - gated detector: laser pulse on target within 100ns



Source: http://www.esa.int

- Objectives of optical link payload:
  - evaluate limits in comparing precision ground clocks via LTT utilizing ACES timescale
  - improve atmospheric propagation models by comparing refractive index to microwave propagation delay
  - optically derived precision orbits for ISS

Technical Plan

- Goals since 21st IWLR
  - Close link to LEO satellite
  - Demonstrate 1 mm ranging precision
  - Demonstrate 1 cm or better ranging accuracy to LEO satellite
  - Calibrate transmit delays to within 1mm
  - Begin developments to control laser fire time

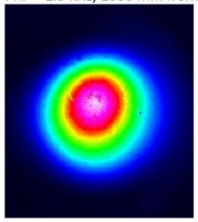
Calibration & Validation

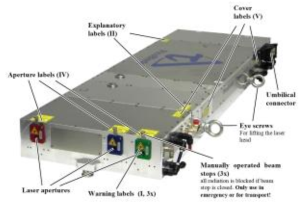
LTT Testbed: Hardware Setup

Telescope: NRL's Brashear 1m telescope
- All reflective design
- F89; Focal plane @12.640 m
- Slew rates:
  - El: 15 deg/s
  - Az: 25 deg/s
- Pointing accuracy: <2 arcsec RMS all sky

Laser: Lumentum PicoBlade
- Ultra-short pulses
  - ~34 ps (532 nm)
  - Single shot to 20 kHz
  - Approved for 5kHz ops
  - Operating @ 2kHz
    - 1.4 W avg power
  - 82 MHz oscillator syncs to high precision external clock
  - 1064nm capable

λ = 532 nm
PRF = 1.5 kHz, 1000 mm from exit window

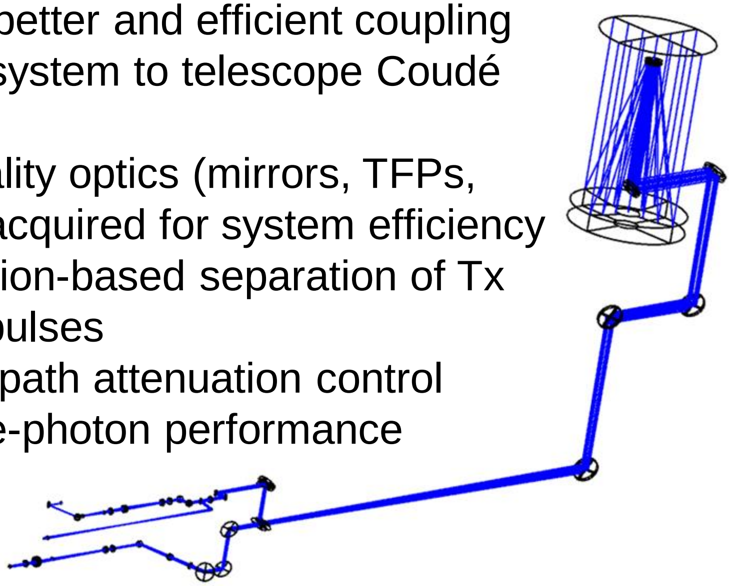




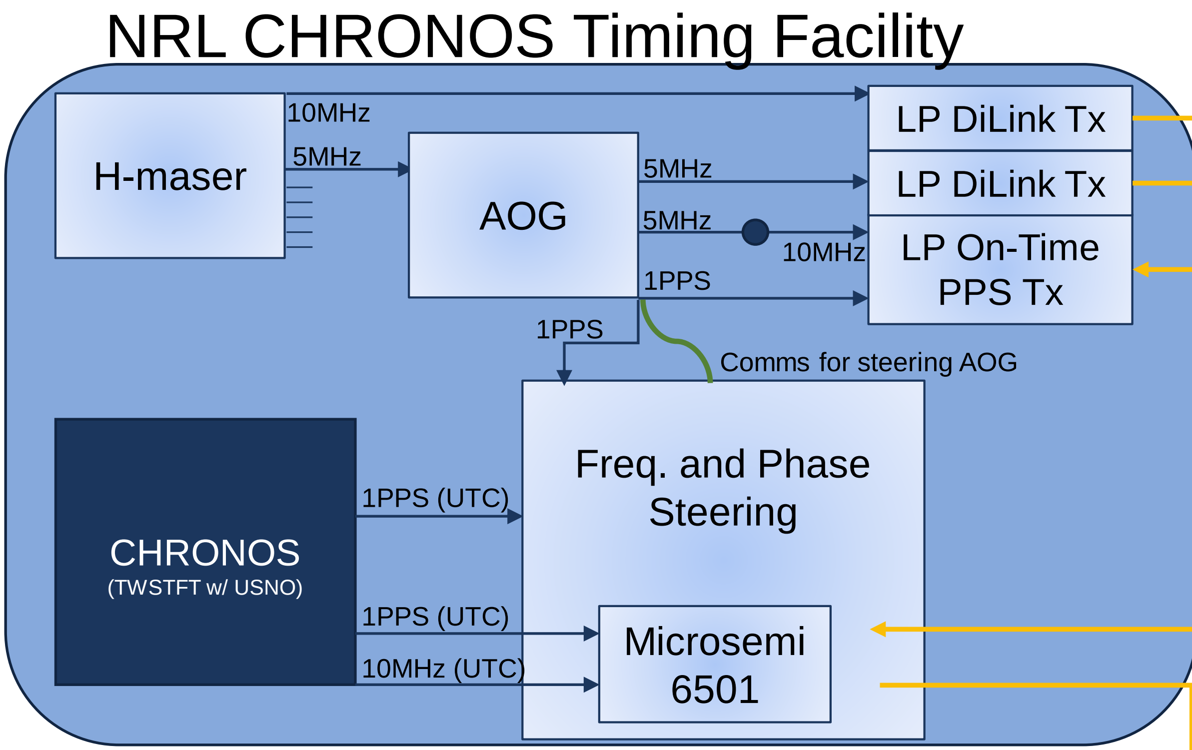
Detector: C-SPAD
- Si APD
- 200 μm active area
- Quantum Efficiency: 40%
- AR coated for 532nm
- Geiger-mode
- Time walk compensation <12ps

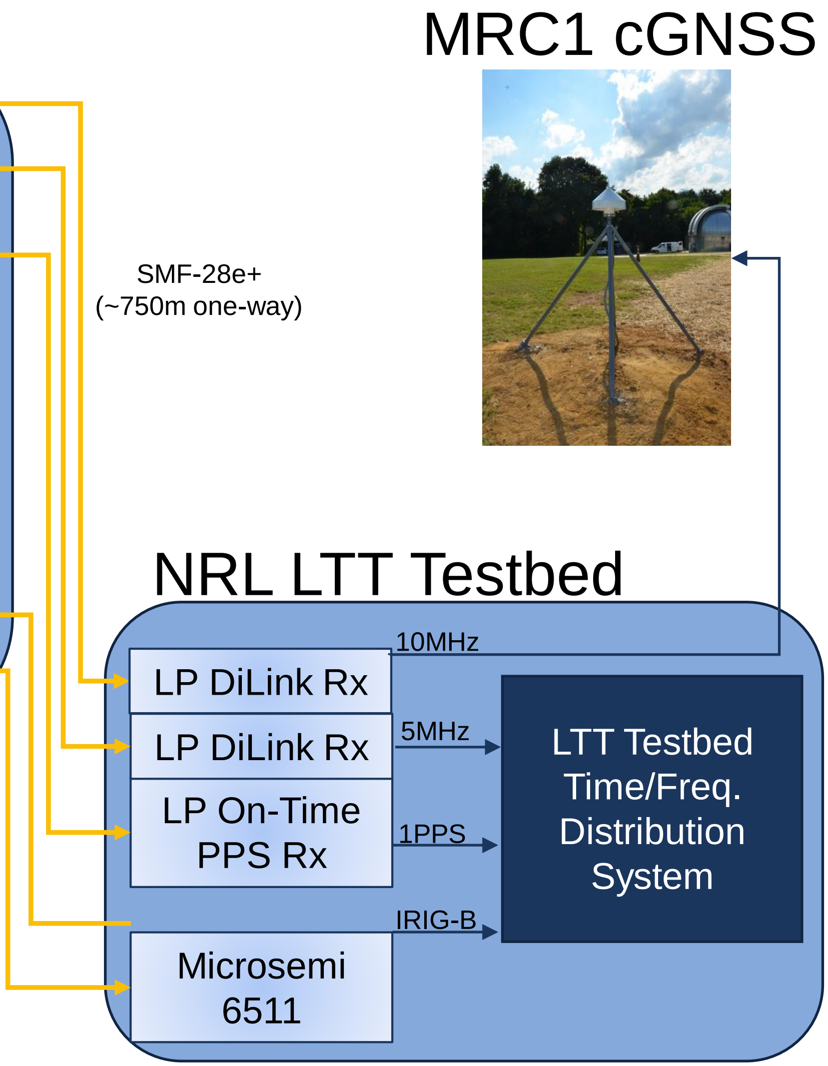
Event timers: NPET
- Supports 2+kHz epoch timestamping
- <0.9ps timing jitter per channel
- <0.5ps timing drift per Kelvin
- <0.1ps/hour timing stability
- Requires spectrally clean clock signal

Optics:
- Custom optical elements designed at NRL for better and efficient coupling of laser system to telescope Coudé path
- High quality optics (mirrors, TFPs, lenses) acquired for system efficiency
- Polarization-based separation of Tx and Rx pulses
- Tx & Rx path attenuation control for single-photon performance



LTT Testbed: Reference Clock and Timing





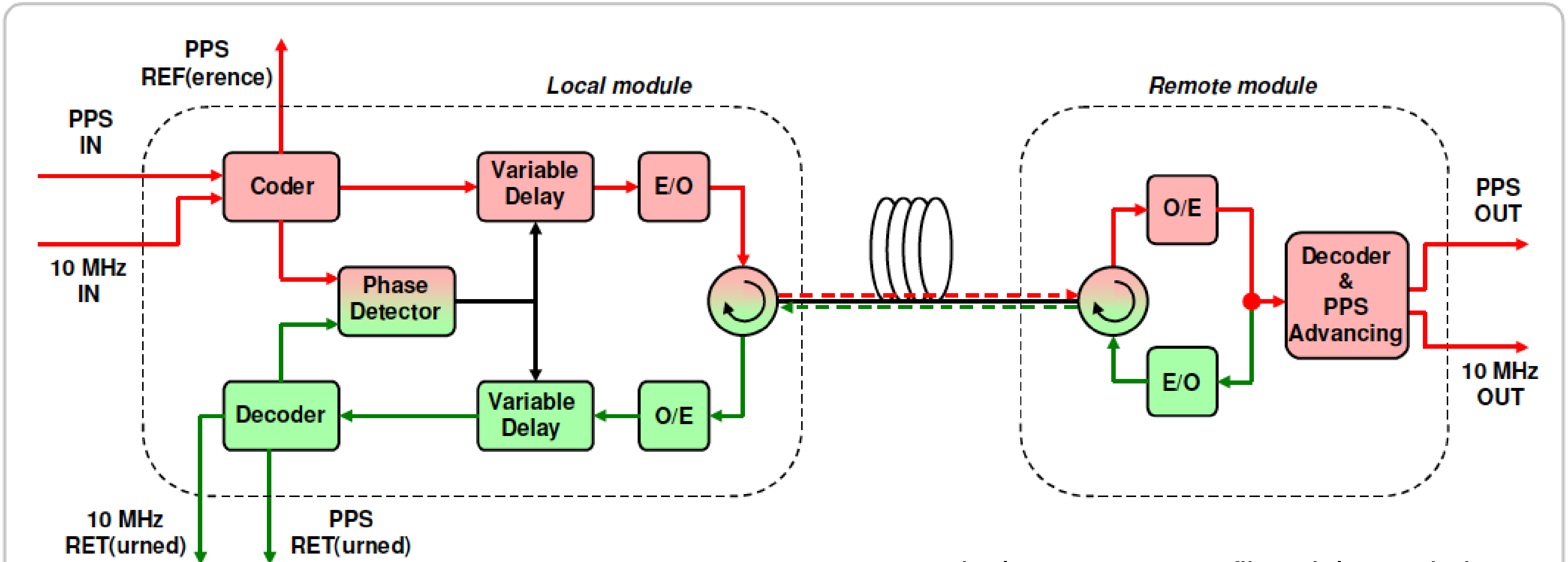
- 6511 IRIG used for time of day
- LP DiLink
  - uncompensated for dispersion effects and fiber path delay variations
- LP On-time PPS Tx – Rx offset: 276ps

Upgrading LP units with PikTime OSTT-3 to improve H-maser+AOG distribution

PikTime OSTT-3 Fiber Time & Freq. Transfer

At Reference Clock

At LTT Testbed



Actively compensates fiber delay variations

Time transfer stability: TDEV < 3 ps for 10 s averaging, < 1 ps for 10^5 s averaging

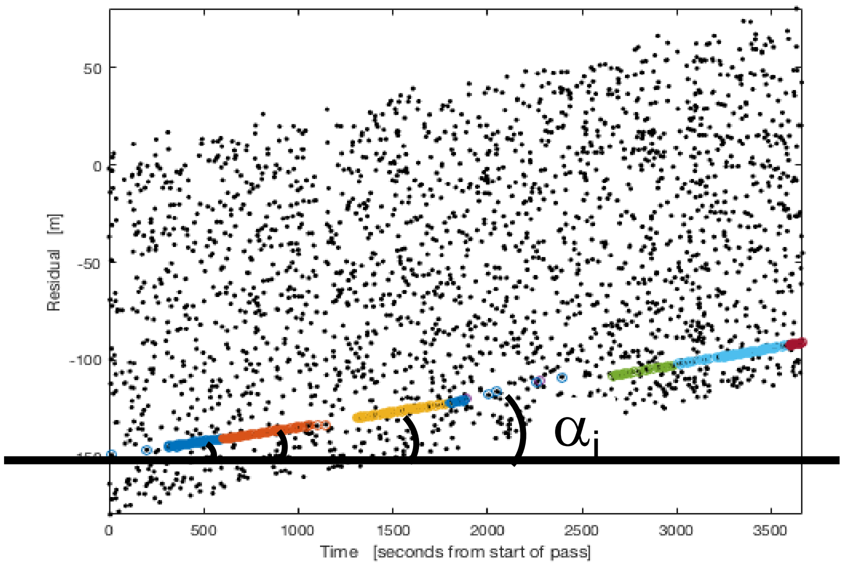
Frequency transfer stability: ADEV < 3×10^{-13} for 1 s averaging, < 3×10^{-17} for 10^5 s averaging

LTT Testbed: Analysis Toolkit Development

(see A. DeRieux poster for latest developments)

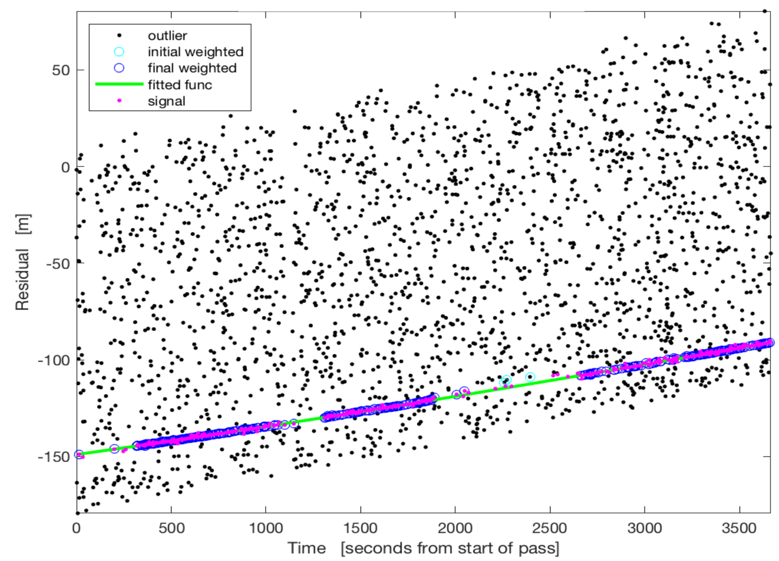
Step #1: *Initial search*

- Two-modes: ground calibration and satellite
- For each 10-sec interval, i,
  - determine direction, α_i, that minimizes width of a high-resolution histogram and contains bin with maximal number of data points
  - select SLR measurements for residuals that fall within narrow band along direction α_i
    - thickness of the band is a function of system jitter and target signature

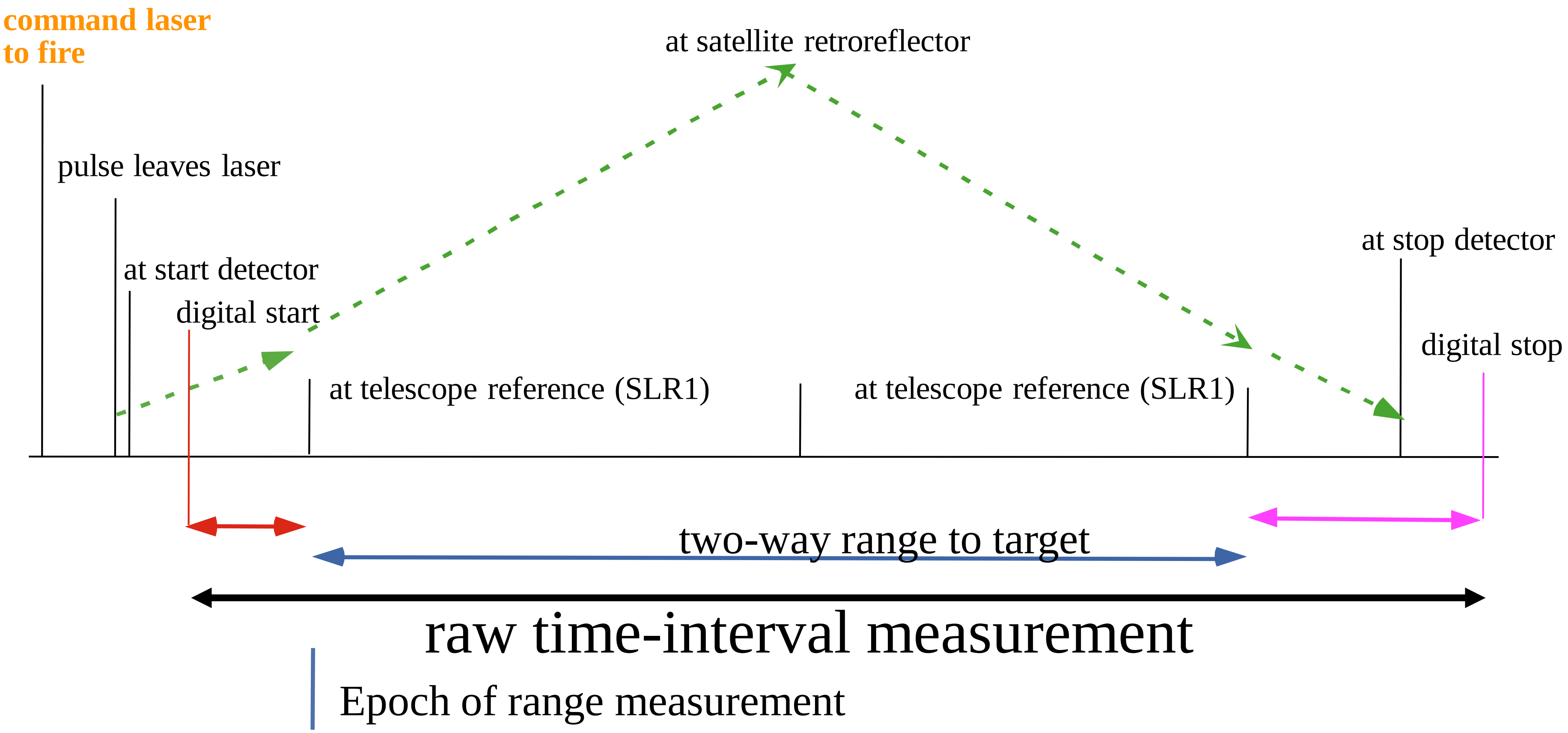


Step #2: *Outlier rejection*

- Iterative weighted least-squares of regression function to find signal photons
  - all data points are included
  - data found in Step 1 (cyan) used for initial weighting
  - subset of initial weighted data points remain (blue) after iterative fitting and outlier rejection
  - solution converges when no outliers remain
  - full-rate signal photons (magenta) are all remaining data points



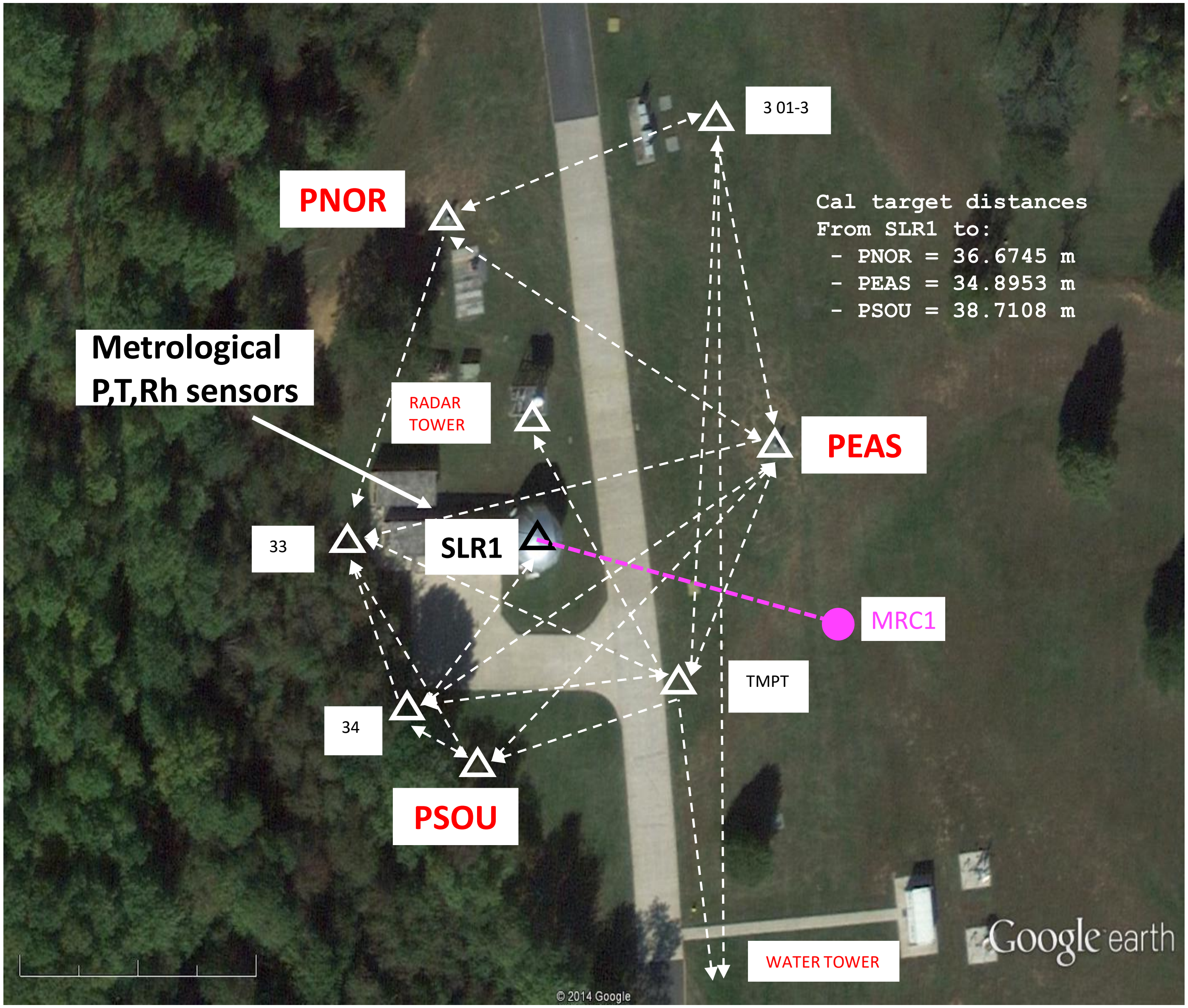
Calibration for LTT Experiments



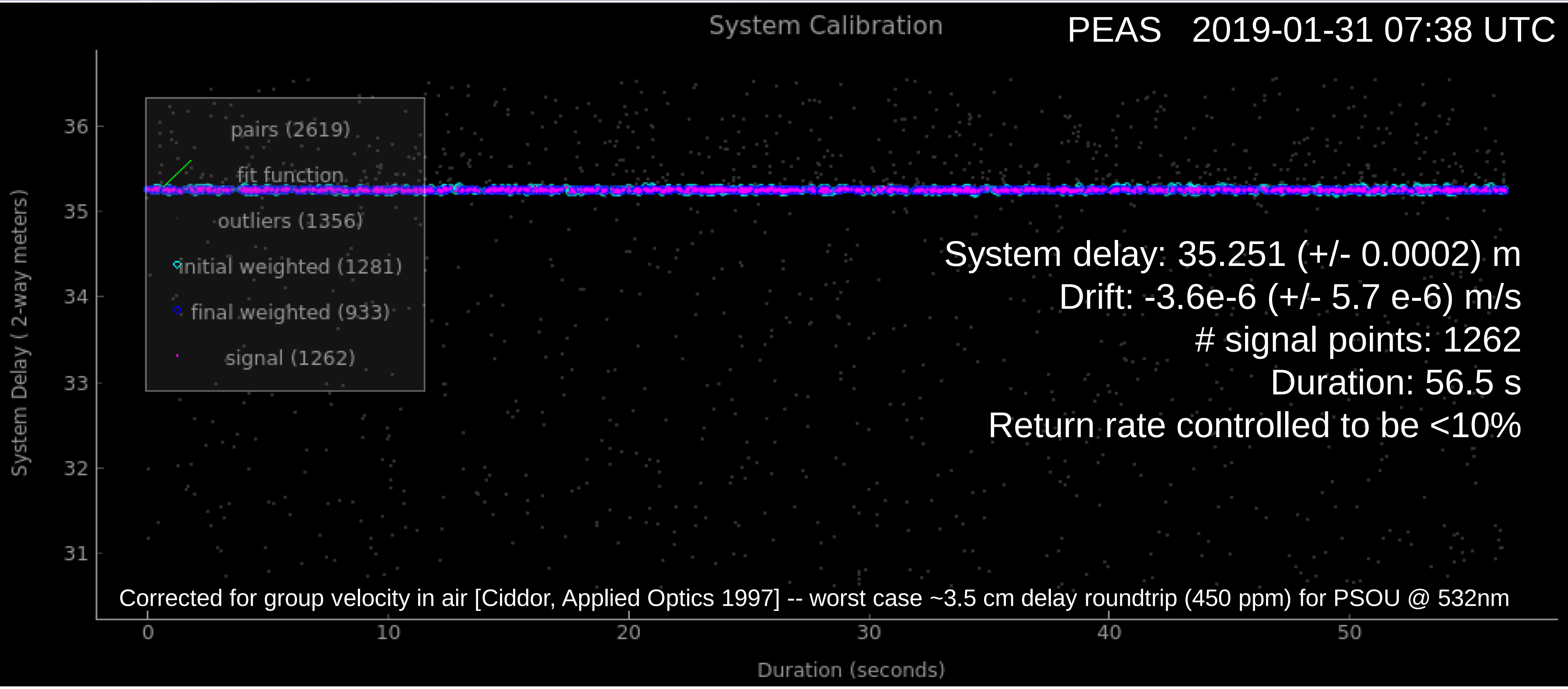
- Determination of SLR1 and satellite position (state-of-art: ~30 mm 1D RSS error)
- Combined ranging delays [red + magenta] (GGOS goal: ~1 mm accuracy or better)
- Pulse transmission delay [red] (LTT goal: ~1 mm accuracy or better)
- Control laser fire [orange] to put pulses at SLR1 on-time (NRL goal: ~1 ns of UTC)

Ground Ranging Targets and Local Ties

- Collaboration with NOAA National Geodetic Survey (NGS) Site Survey Team
- 2015-2016 Survey
  - developed techniques for realizing SLR1 and relative ground target distances
- July 2019 resurvey
  - new techniques for realizing SLR1
  - MRC1 – SLR1 tie
  - verified 2016 surveyed ranges to within ~0.5mm



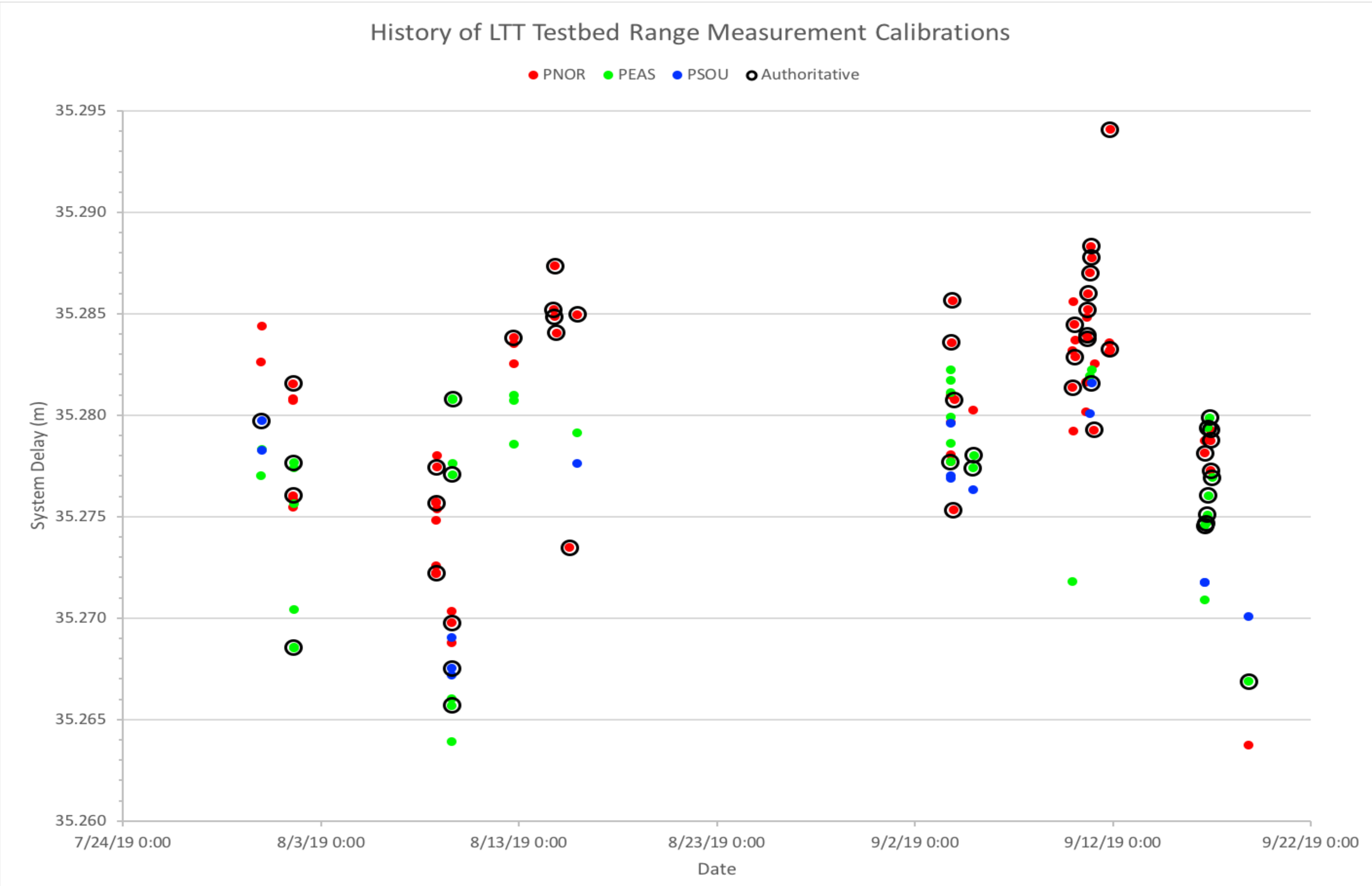
LTT Testbed Range Calibration Precision



- Repeated collects on a ground cal target varies +/- 0.5 mm
- Collect on PNOR (7 min later) diff from PEAS by 3 mm
- PSOU collect (18 mins later) diff from PEAS by 1 mm

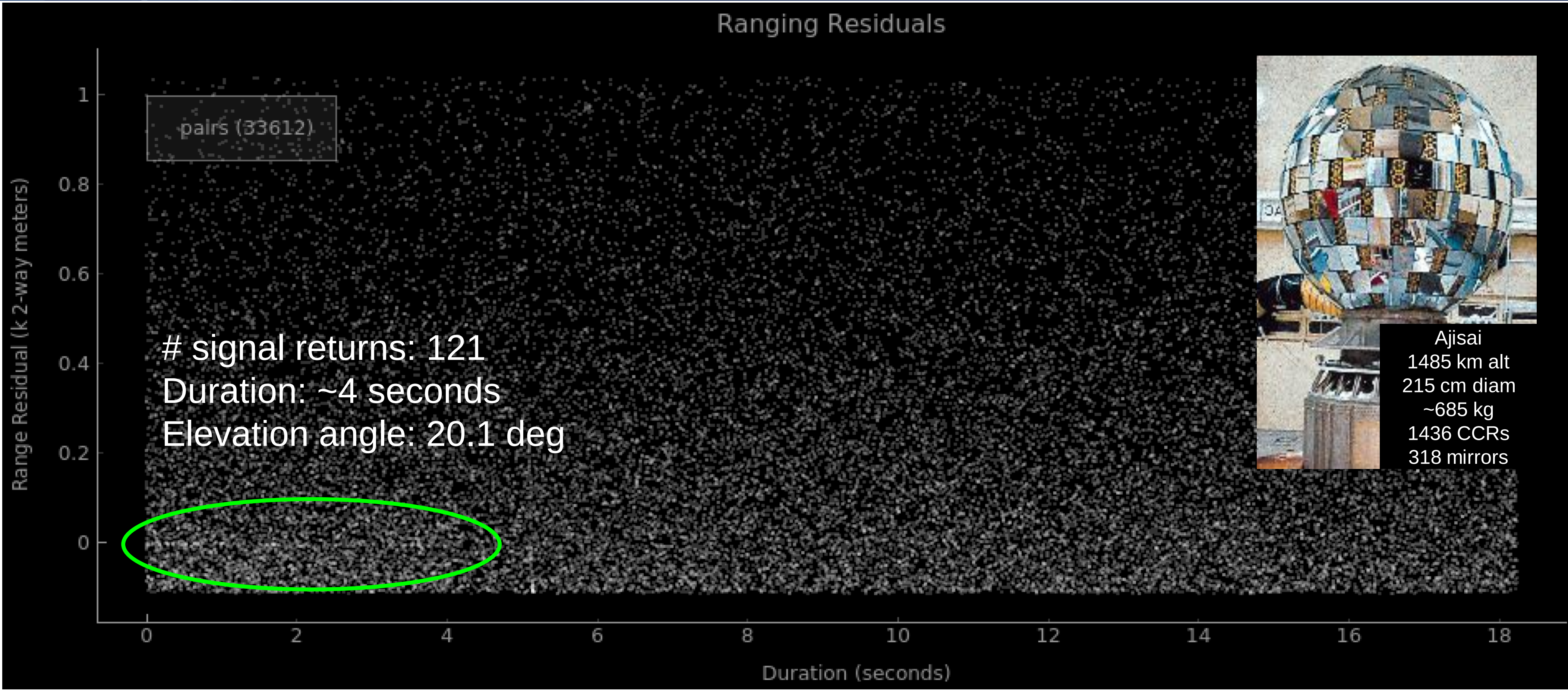
Possible issue with CCR mount

LTT Testbed Range Calibration Stability



Back-to-back cals repeatable at ~3 mm level; drifts require cal <60 mins

First light on 31 Jan 2019 (Ajisai)



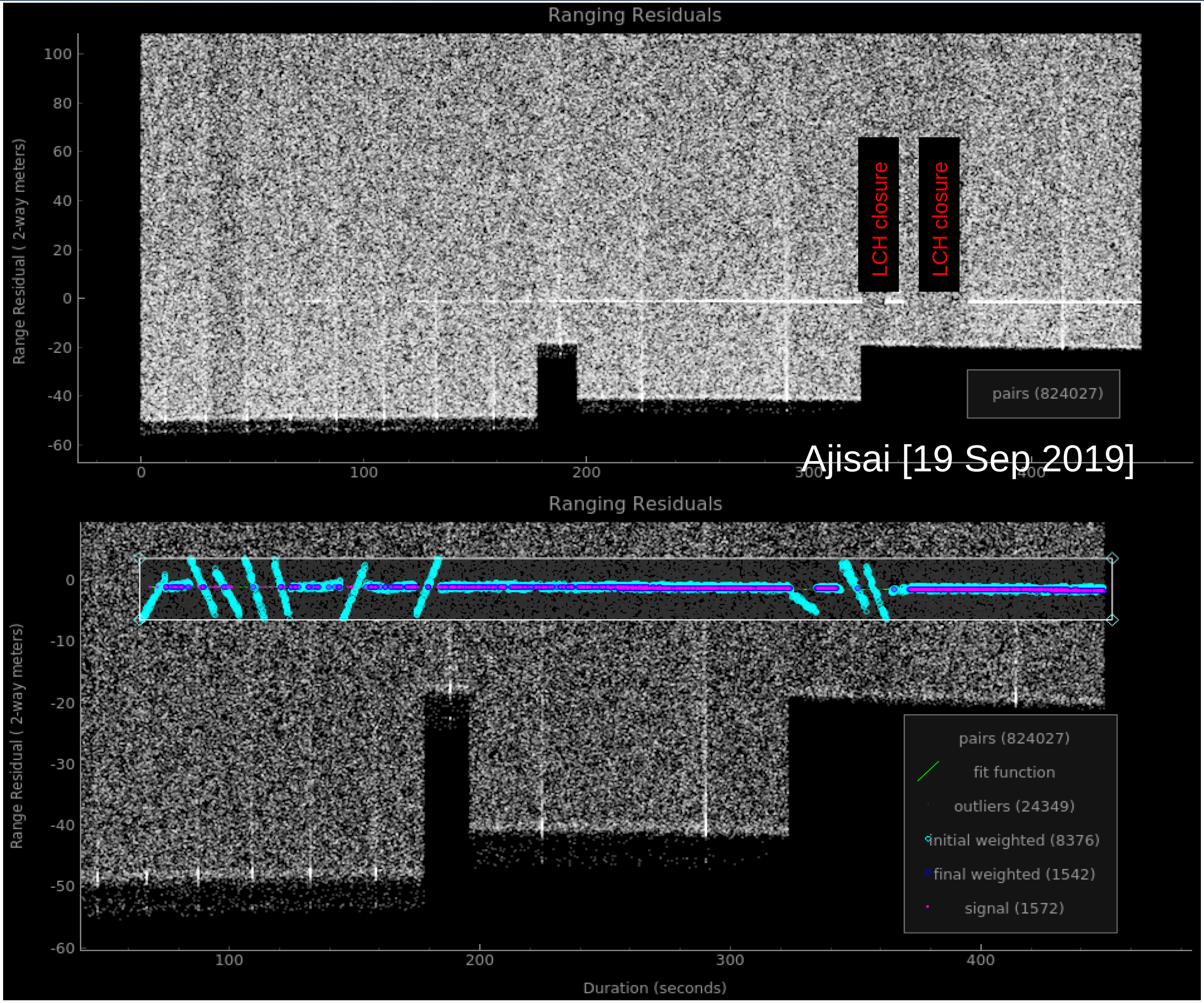
Residuals near zero after correcting a 1s bias in event timer timescale

Additional Ajisai and Lageos collects in Sep 2019 after significant efforts to refine and validate ground calibration performance

Analysis Filter for Extracting SLR Signal

- Generate all possible start/stop pairs for 2 kHz data

- Isolate and filter data
  - write signal data to Consolidated Ranging Data (CRD) product files used for precise OD



Validating LTT Testbed Range Accuracy

- Precision orbit determination (POD) using NRL and ILRS data for geodetic LEO satellites -- *Ajisai, Lageos, Starlette, Lares, Larets*

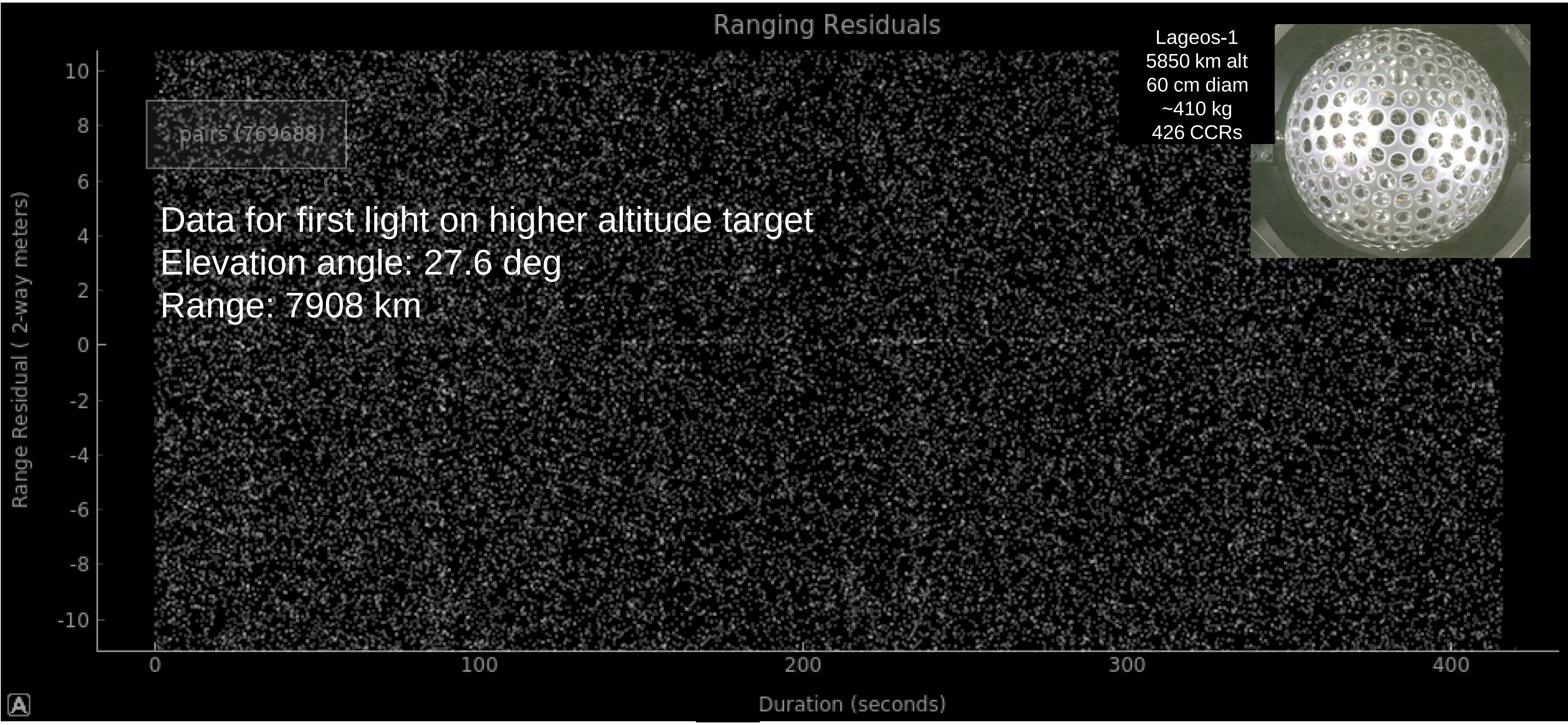
- New analysis tools used to extract NRL signal returns, then data used in precise orbit solutions
  - 7d arc solutions for Jan and Sep 2019 data sets
  - NASA's GEODYN POD s/w with latest models and methods consistent with IERS 2010 Conventions (Petit and Luzum, 2010)
  - Station positions not adjusted
  - Solved for station range biases per 7d orbit arc in addition to orbit initial state
  - Ajisai is dense spherical satellite above atmosphere—highly dynamical orbit
  - SLR-derived orbits using full ILRS network consistently ~2 cm 1D RSS accuracy

Ajisai POD Results

[31 Jan 2019] 1s time bias removed, 70 cm range bias, 5 cm RMS of post-fit residuals

[10-11 Sep 2019] ~0 s time bias, 2 cm range bias, 5 cm post-fit RMS

Lageos-1



Preliminary result based on in-house GEODYN POD analysis

[19 Sep 2019] ~0 s time bias, 1 mm range bias, 8 mm post-fit RMS

More recent L1 & L2 collections with much stronger signal returns

Summary

- Goals since 21st IWLR
  - Close link to LEO satellite
  - Demonstrate 1 mm ranging precision
  - Demonstrate 1 cm or better ranging accuracy to LEO satellite
  - Calibrate transmit delays to within 1mm
  - Begin developments to control laser fire time

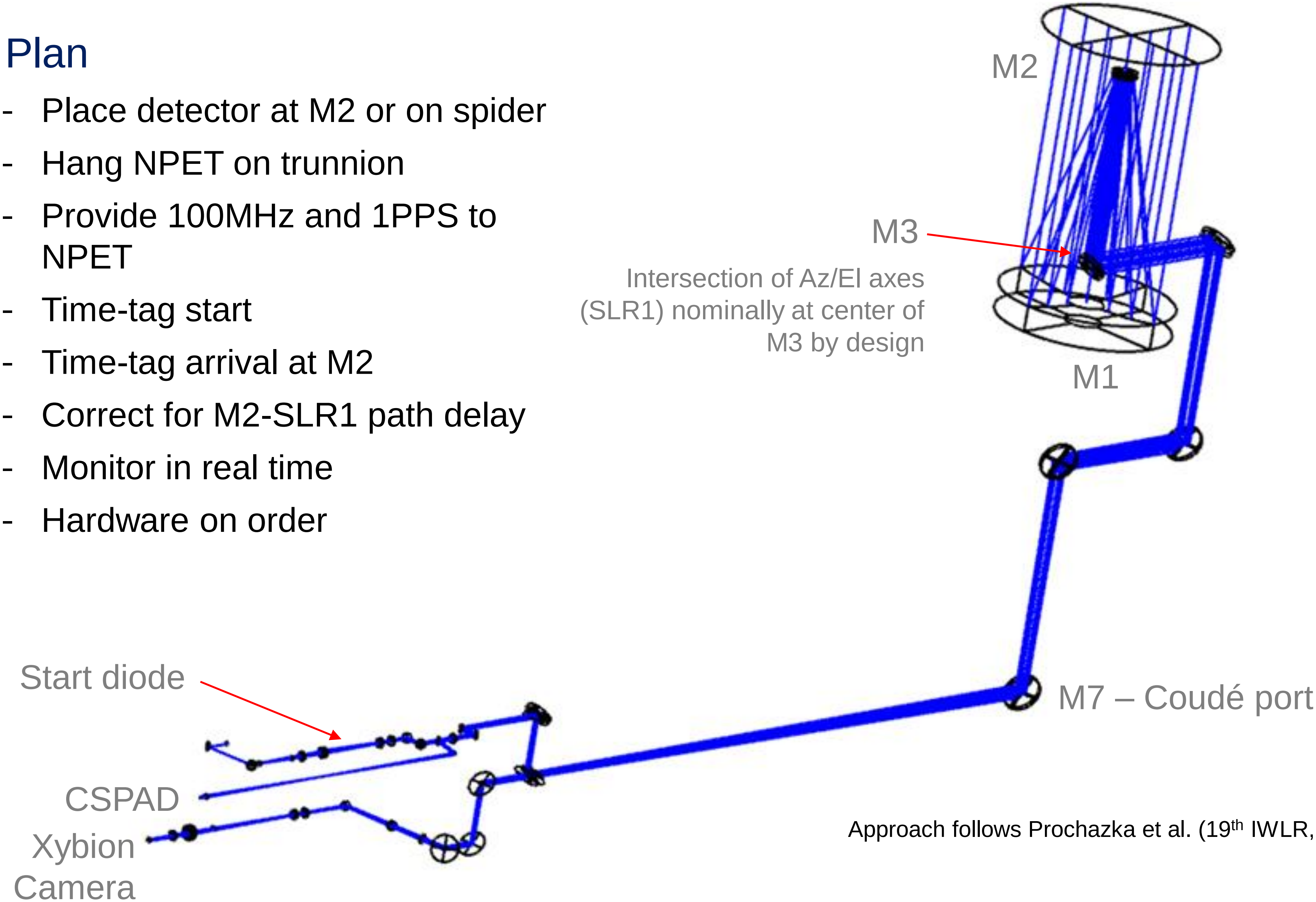
Calibration & Validation

- Current Status
  - Ground ranging repeatable to within 1 mm at each target, but up to 3 mm difference between targets (probably misalignment of target reflectors)
  - First light to Ajisai (1485 km) 31 Jan 2019
  - 2 cm ranging accuracy to Ajisai in Sep 2019, but results limited by satellite structure
  - Potential <1 cm ranging accuracy (Lageos), but need more data
  - Plan developed for calibrating transmit leg, waiting on hardware delivery
  - Plan for controlling laser fire time, waiting on hardware delivery
  - Currently working with NASA SLROC to submit quarantine data for ASC feedback

Questions?

Transmit Delay Calibration

- Plan
  - Place detector at M2 or on spider
  - Hang NPET on trunnion
  - Provide 100MHz and 1PPS to NPET
  - Time-tag start
  - Time-tag arrival at M2
  - Correct for M2-SLR1 path delay
  - Monitor in real time
  - Hardware on order



Approach follows Prochazka et al. (19th IWLR, 2014)

Control Laser Fire