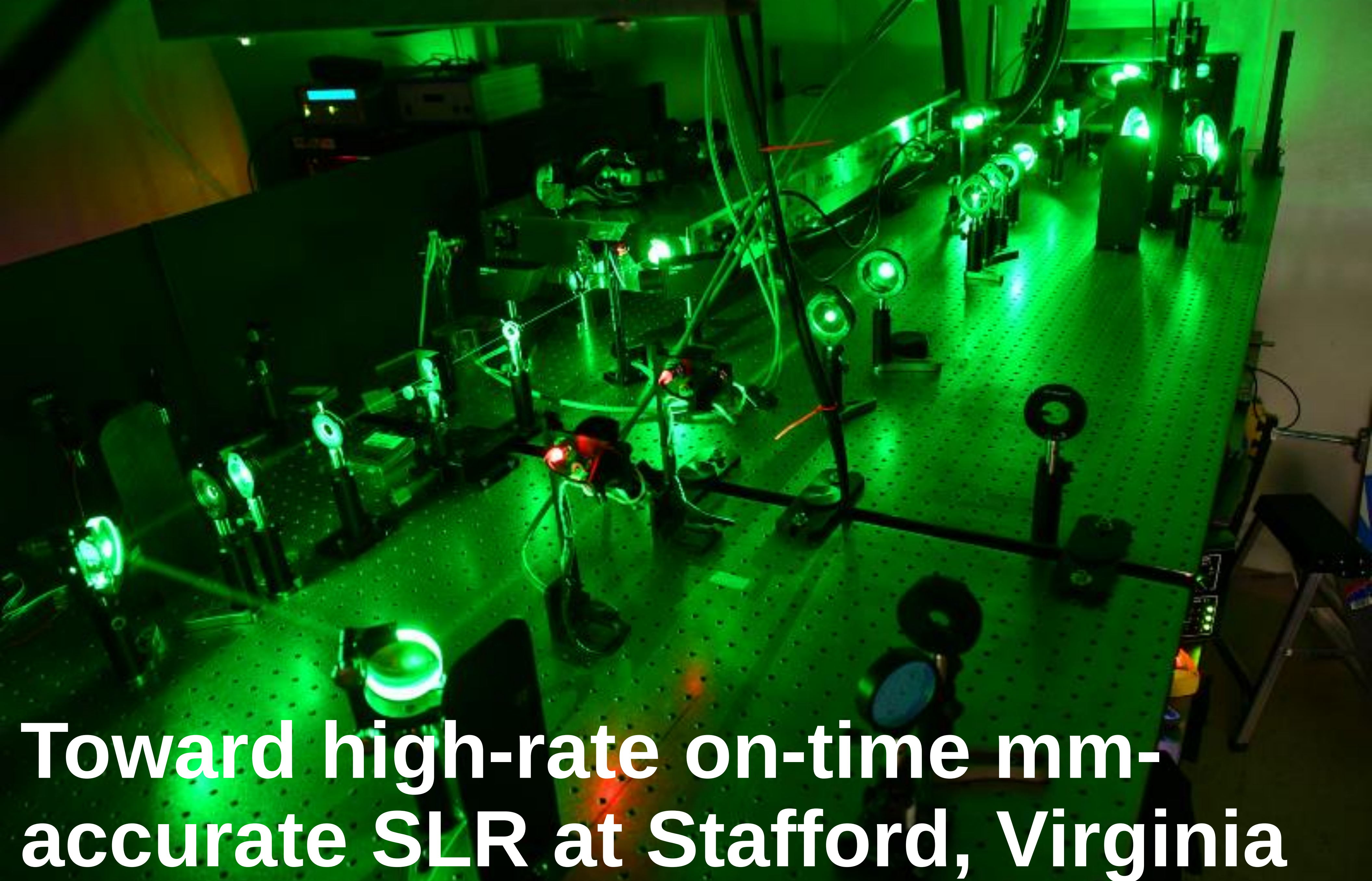


Toward high-rate on-time mm-accurate SLR at Stafford, Virginia

[1]Jake Griffiths, [1]C. Font, [1]C.I. Moore, [1]F. Santiago, [1]R. Smith, [1]A. DeRieux, [2]J. Ghiorzi, [1]L. Thomas

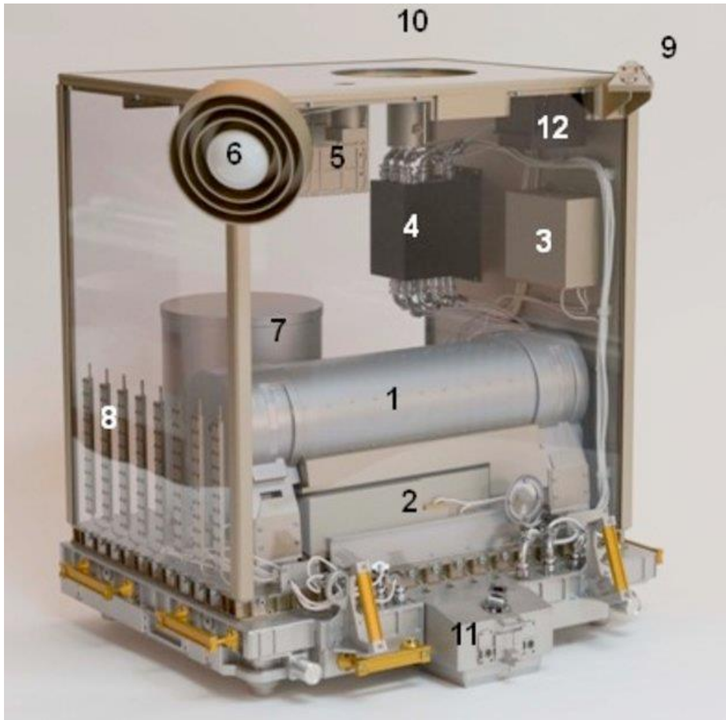
[1]Naval Research Laboratory, Washington, DC 20375
[2]R&M Technologies

21st International Workshop on Laser Ranging – 5-9 November 2018 – Canberra, Australia

Objective & Motivation

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

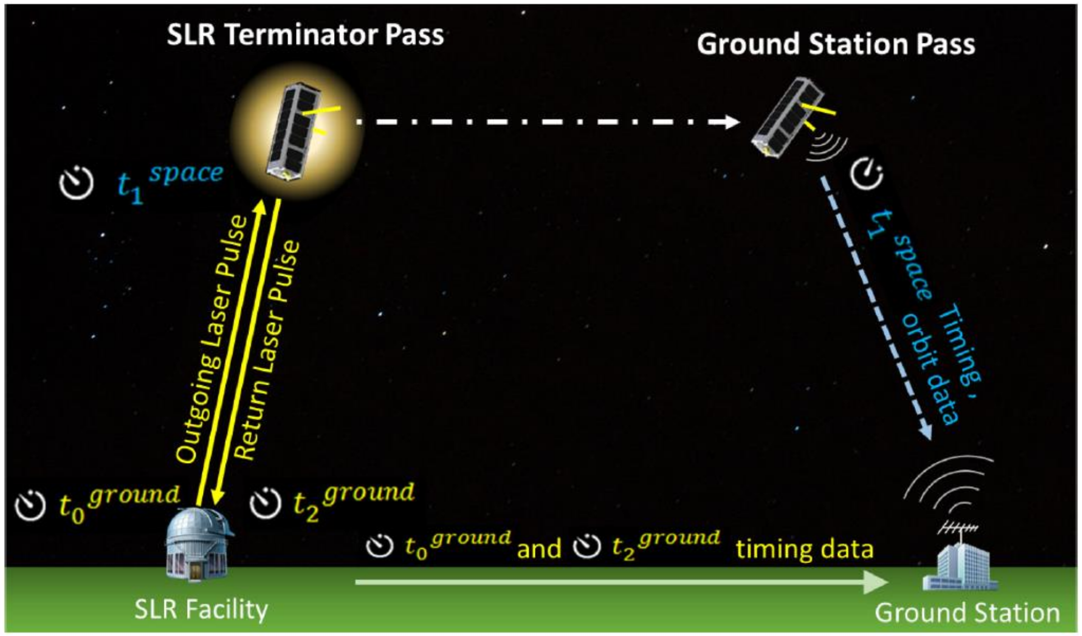
- ACES/ELT
  - launch to ISS: expected (2020?)
  - ultra-stable atomic (Cs fountain + H-maser) clock ensemble[1,2,3]
  - microwave link[10] for ACES primary time transfer mode
  - 532nm laser link[12] for optical timing experiments
    - gated detector: laser pulse on target within 100ns



Source: http://www.esa.int

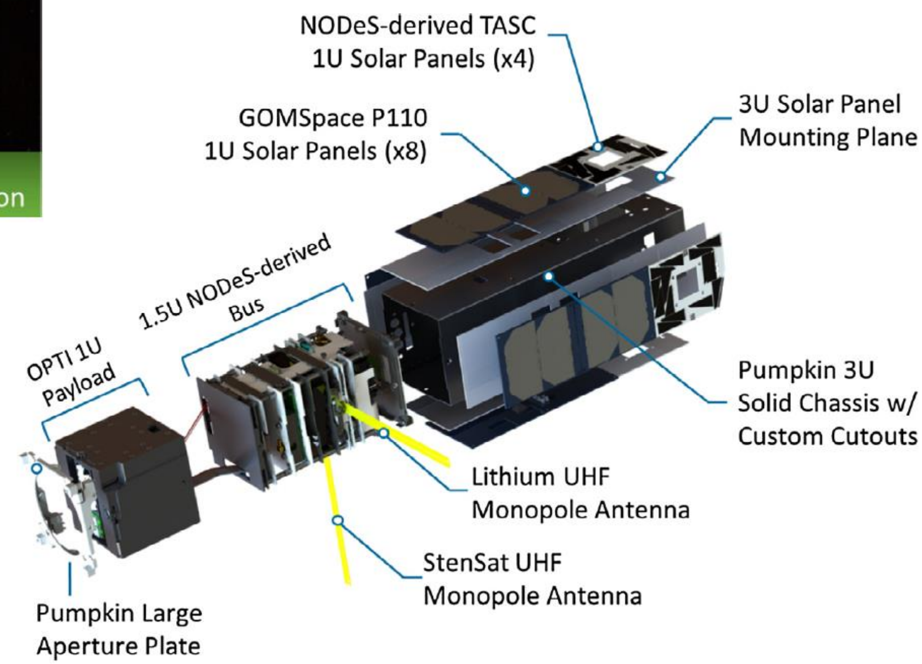
- Objectives of optical link payload:
  - evaluate limits in comparing precision ground clocks via LTT utilizing ACES timescale
  - improve atmospheric propagation models by comparing refractive index to microwave propagation delay
  - optically derived precision orbits for ISS

CHOMPTT



- NASA Ames (bus)
- Univ. of Florida (OPTI)
- NRL & Univ. of Florida ground stations
- Launch expected late 2018

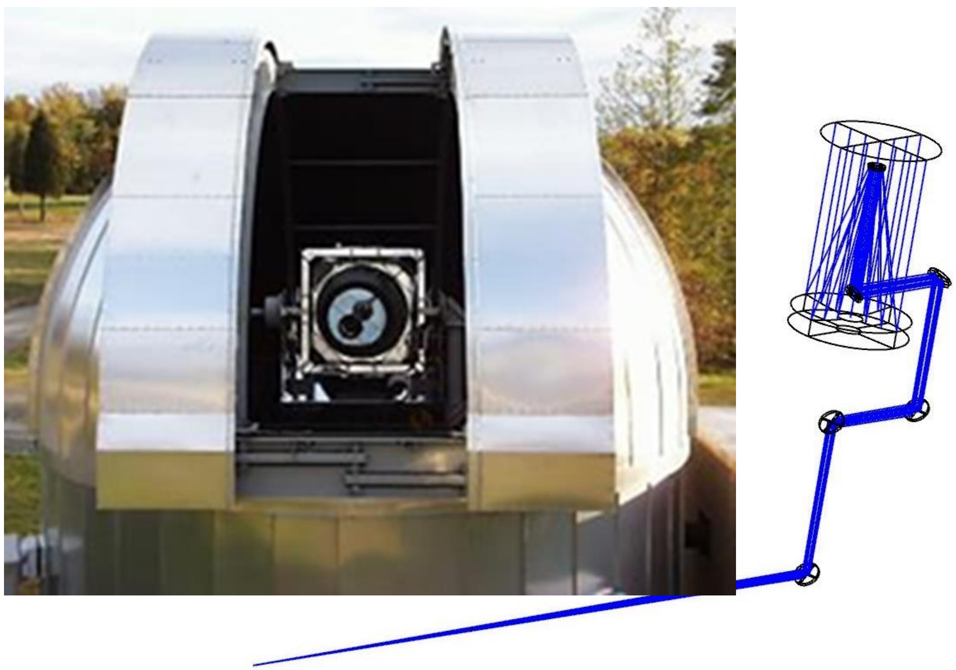
1U OPTI Payload



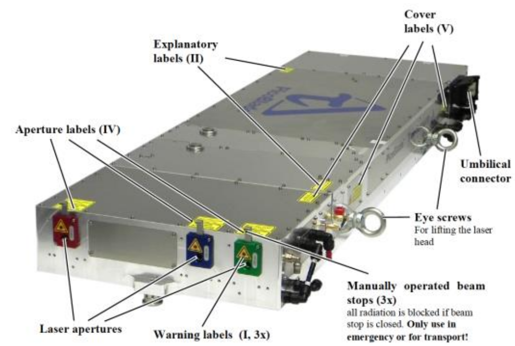
Anderson et al., in press (Adv. Space Res.)

NRL Enabling Technology (1/2)

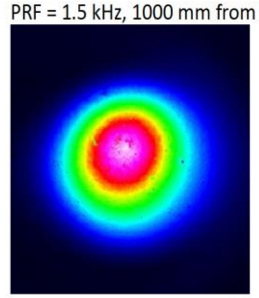
Telescope: Brashear 1 meter telescope
- All reflective design
- F#: 89
- Focal plane: @12.640 m
- Slew rates:
  - 15 degrees/sec slew rate (elevation)
  - 25 degrees/sec slew rate (azimuth)
- Pointing accuracy: <2 arcsec RMS all sky



Laser: Lumentum PicoBlade
- Ultra-short pulses, passively stabilized
  - ~28 ps (532 nm)
  - ~34 ps (1064 nm)
  - Single-shot to 20 kHz capable
  - 82 MHz oscillator (syncs to high precision external clock)



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

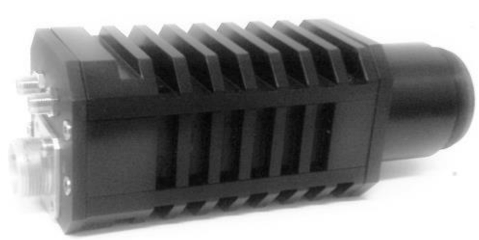


Repetition rate (kHz)	Measured power (W) λ = 532 nm	Pulse Energy (µJ) λ = 532 nm
20	5.85	292.6
10	4.57	457.0
5	3.14	627.0
3	2.04	680.8
2.5	1.73	691.6
2	1.39	693.5
1.5	1.04	693.5
1	0.90	717.8

NRL Enabling Technology (2/3)

<u>Rx detector</u>: Compensated Single Photon Avalanche Detector (C-SPAD)

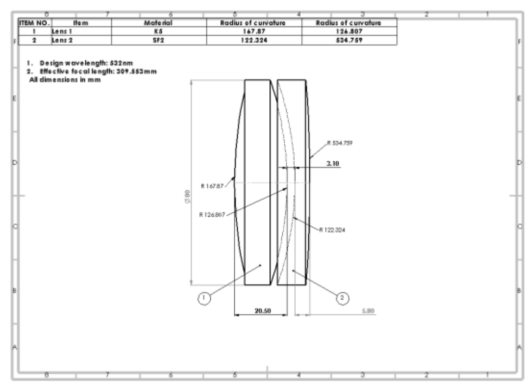
- Si APD
- 200 µm active area
- Quantum Efficiency: 40%
- AR coated for 532
- Accepts 12 mm diam beam
- FOV: 1 degree
- Active quenching circuit
  - Time walk compensation < ±10 ps



PESO Consultant Ltd.

<u>Optical train</u>:

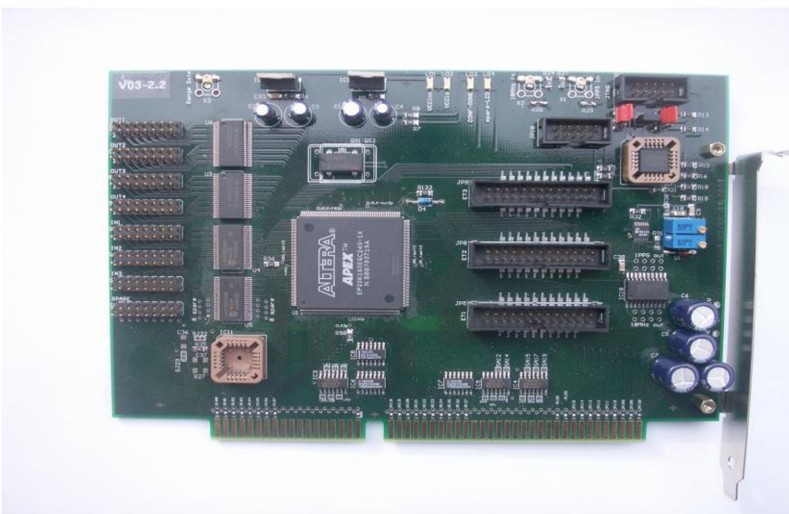
- Custom optical elements were designed at NRL for better and efficient coupling of the laser system into the telescope
- High quality optics (mirror, polarizers, lenses) were acquired for system efficiency



NRL Enabling Technology (3/3)

Detector gating: Graz Range Gate Generator

- medium Resolution Event Timer and range gate generator
- 5ns resolution in time stamping
- 500ps resolution programable range gate generator
- accurate enough for generating range gates, range residuals, and real time plots for displays



Event timing: New Picosecond Event Timer (NPET)

- supports 2kHz epoch timestamping
- <0.9ps timing jitter per channel
- <0.5ps timing drift per Kelvin
- <0.1ps/hour timing stability
- requires spectrally clean clock signal

PESO Consultant Ltd.

U.S. NAVAL RESEARCH LABORATORY

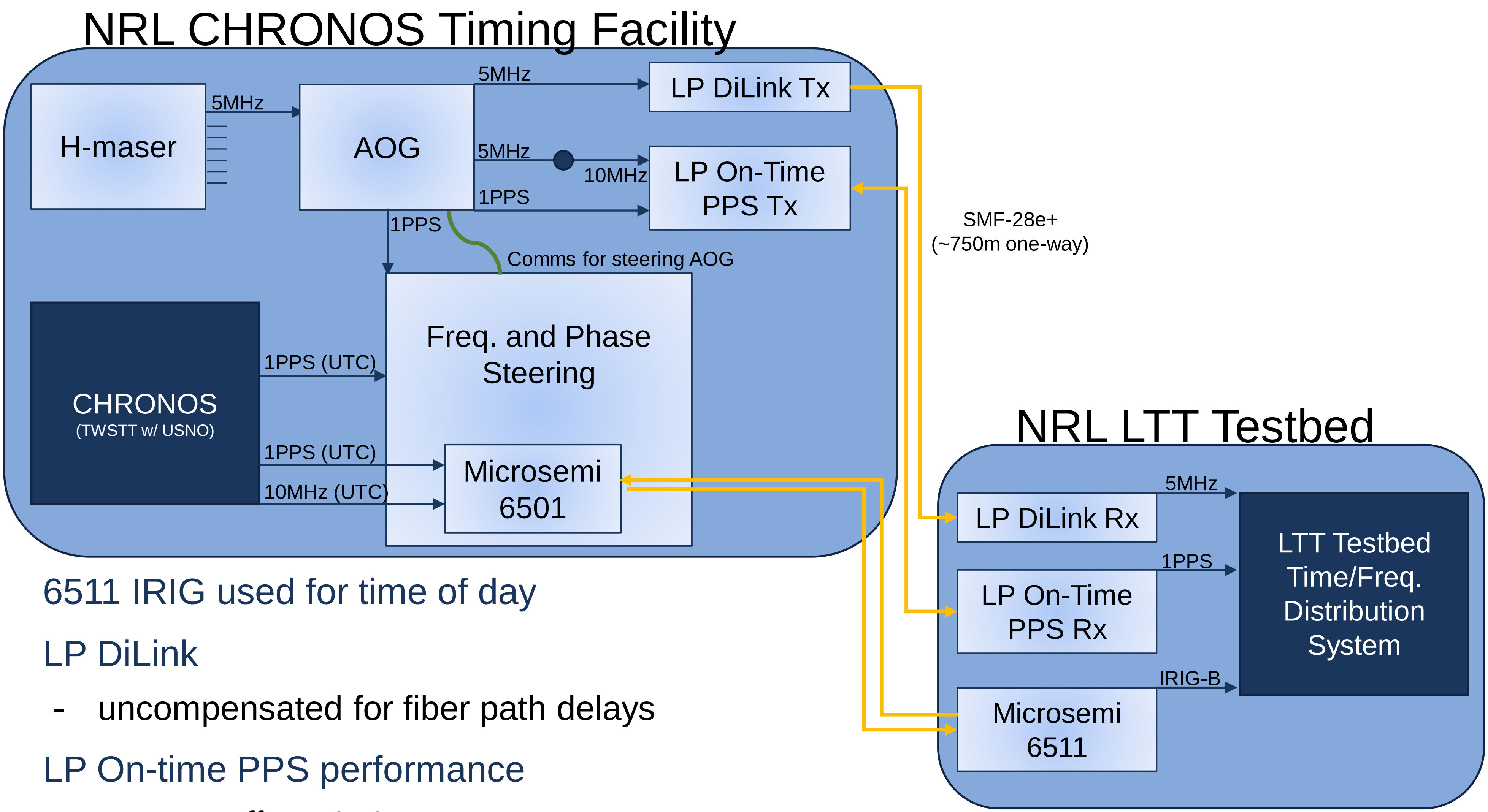
New Reference Timing Signals

- High precision atomic frequency reference
  - Microsemi H-maser w/ LPN option
  - AOG used for steering to UTC
  - Dedicated SMF-28e+ host <-> LTT testbed
    - ~750m one-way
  - Microsemi 6511 (coarse time-of-day)
    - TWTFT over fiber with CHRONOS 6501
    - <20ns performance
  - Linear Photonics On-time PPS to LTT testbed
    - PPS time marker aligned to UTC(USNO)
    - 276ps (±<1ps) static offset Tx/Rx
  - Linear Photonics DiLink to LTT testbed
    - delivers H-maser 5MHz frequency reference
    - Uuncompensated for fiber delay variations
- Initial integration complete August, 2018
- Ongoing monitoring of signals at H-maser and LTT testbed

AOG-110 Auxiliary Output Generator

U.S. Naval Research Laboratory

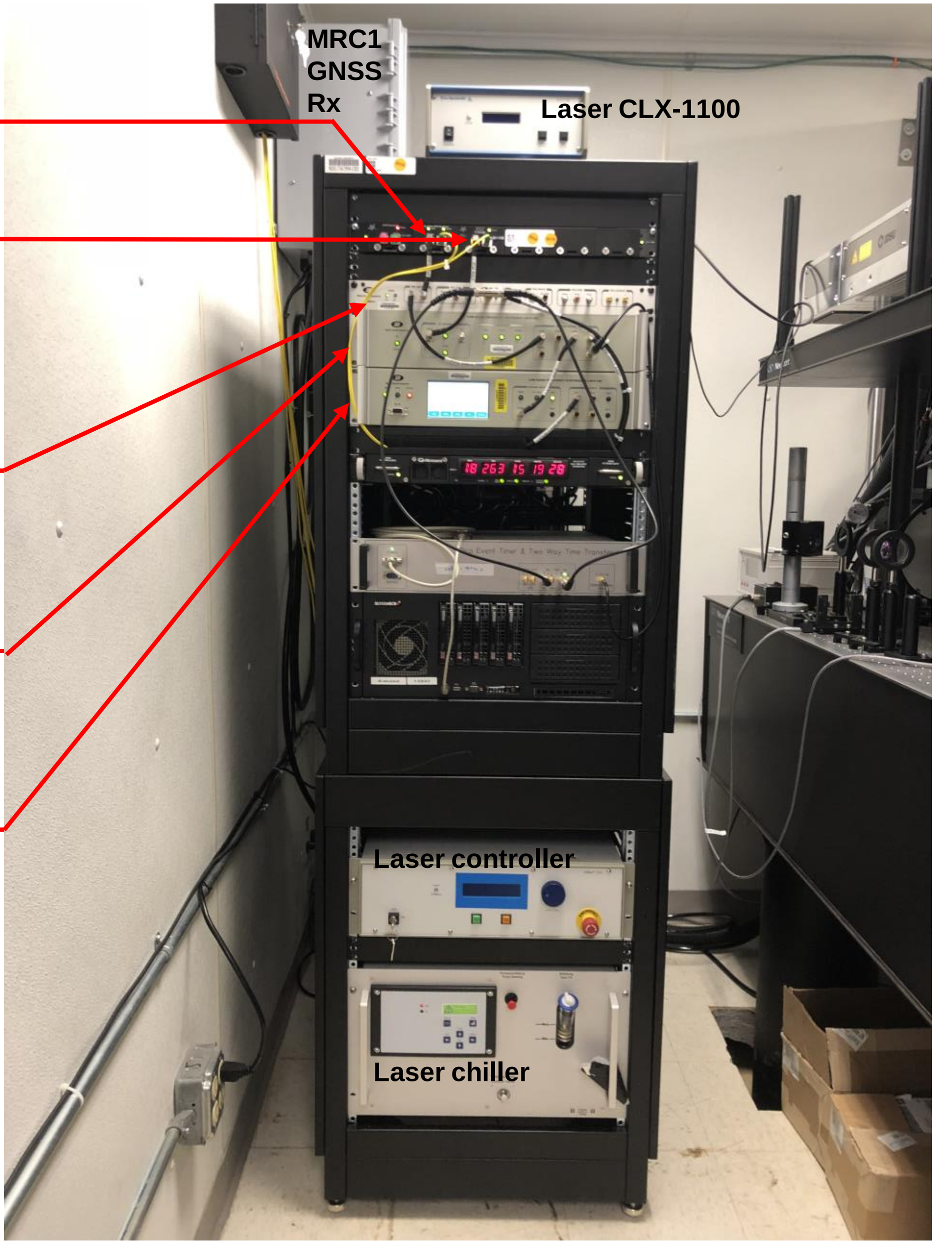
Transferring Timing Signals to LTT Testbed



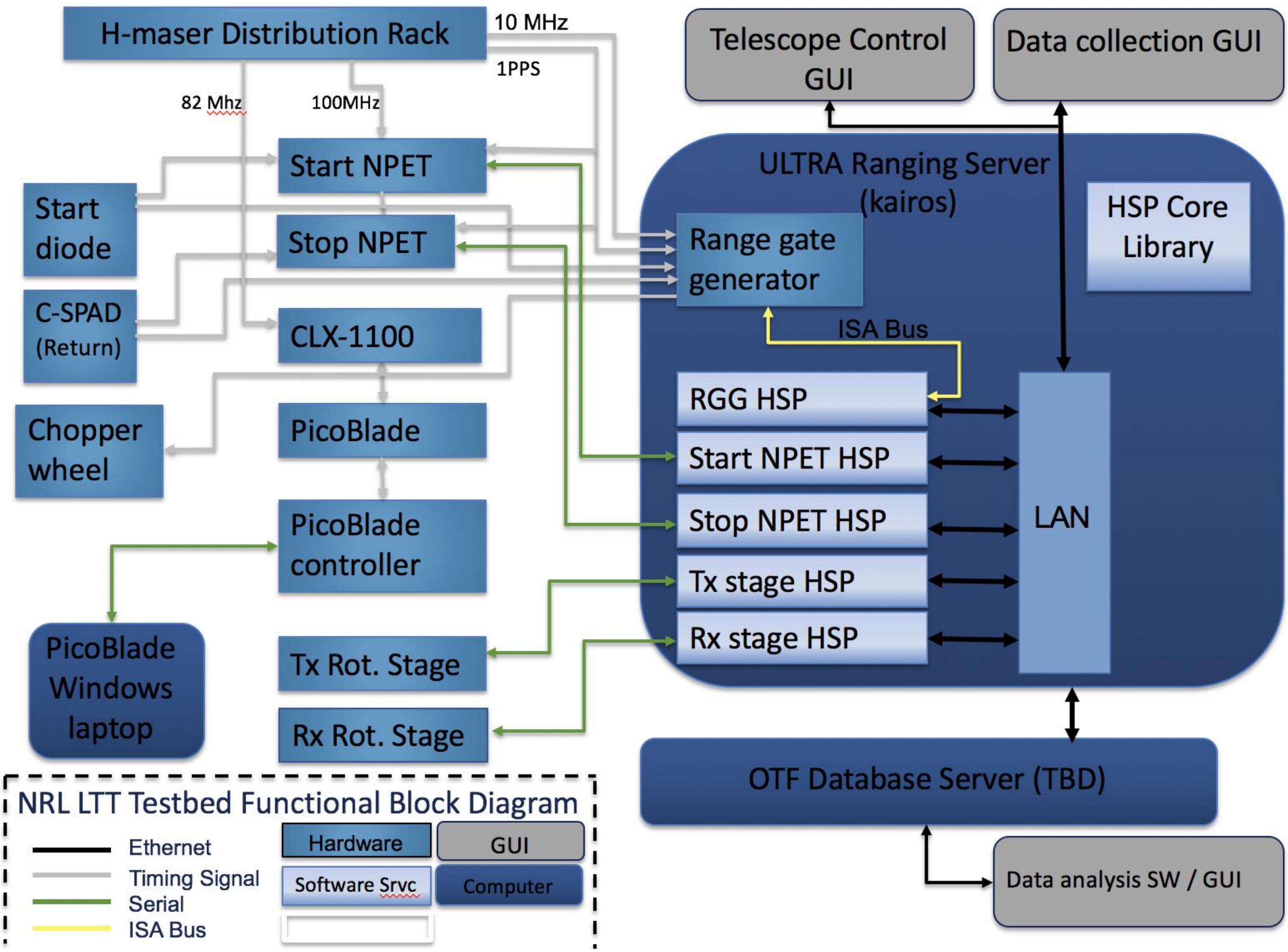
- 6511 IRIG used for time of day
- LP DiLink
  - uncompensated for fiber path delays
- LP On-time PPS performance
  - Tx – Rx offset: 276ps
  - over ~1500m roundtrip

Time & Frequency Distribution

- Linear Photonics Timelink
  - On-time PPS Rx
    - 276ps (±<1ps) static offset Tx/Rx
  - DiLink Rx
- Spectra Dynamics, Inc.
  - PPS generator
    - timing reference for event timers
    - aligned to UTC(USNO) within ~250ps
  - low-noise frequency cleanup osc.
    - 100MHz output for event timers
    - 10MHz output for synthesizer
  - low-noise frequency synthesizer
    - 82MHz for laser CLX-1100
    - CLX-1100 measures laser oscillator jitter wrt input 82 MHz = ~0.10ps
- Microsemi PPS and RF Amps
  - timing source for legacy SLR systems

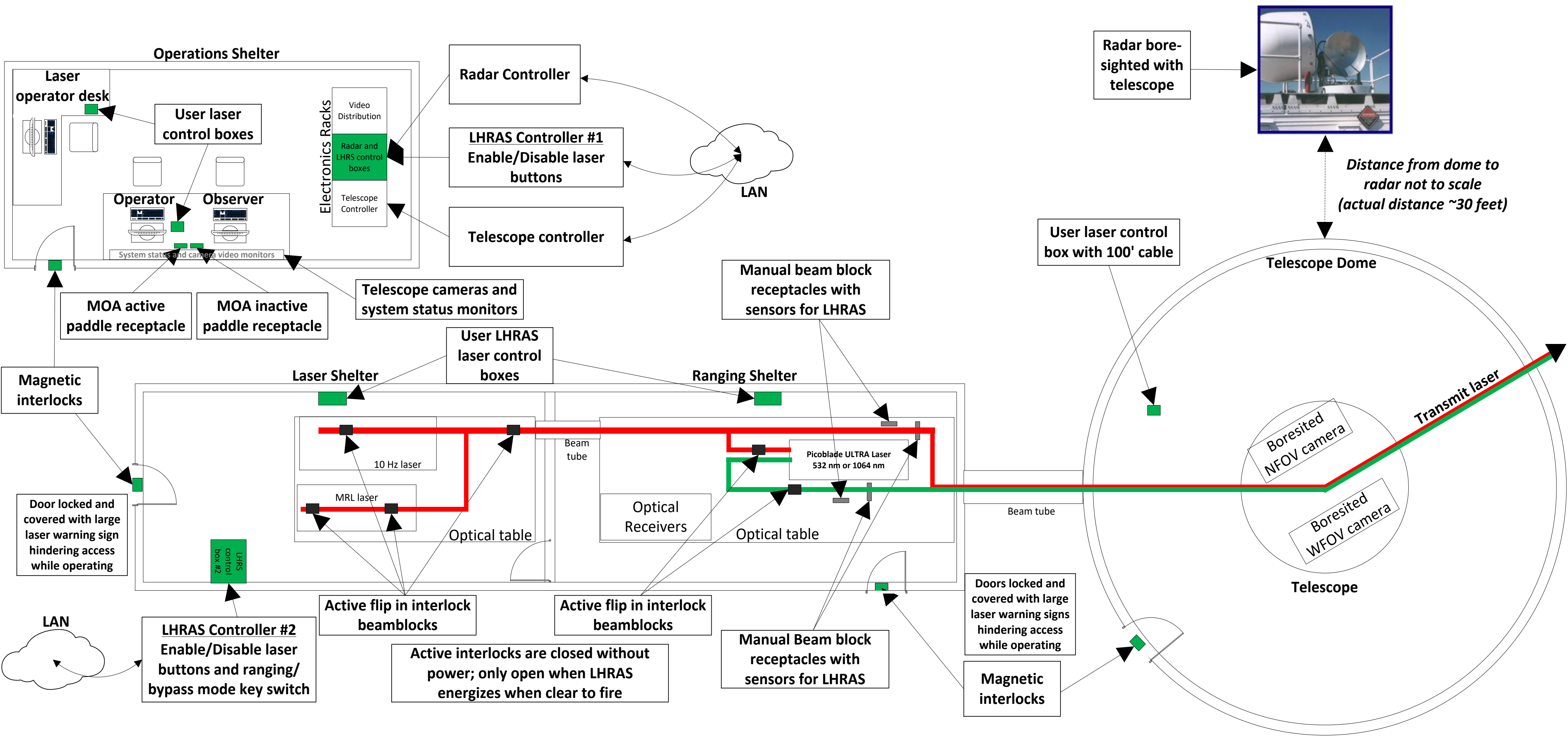


System Level Functional Diagram



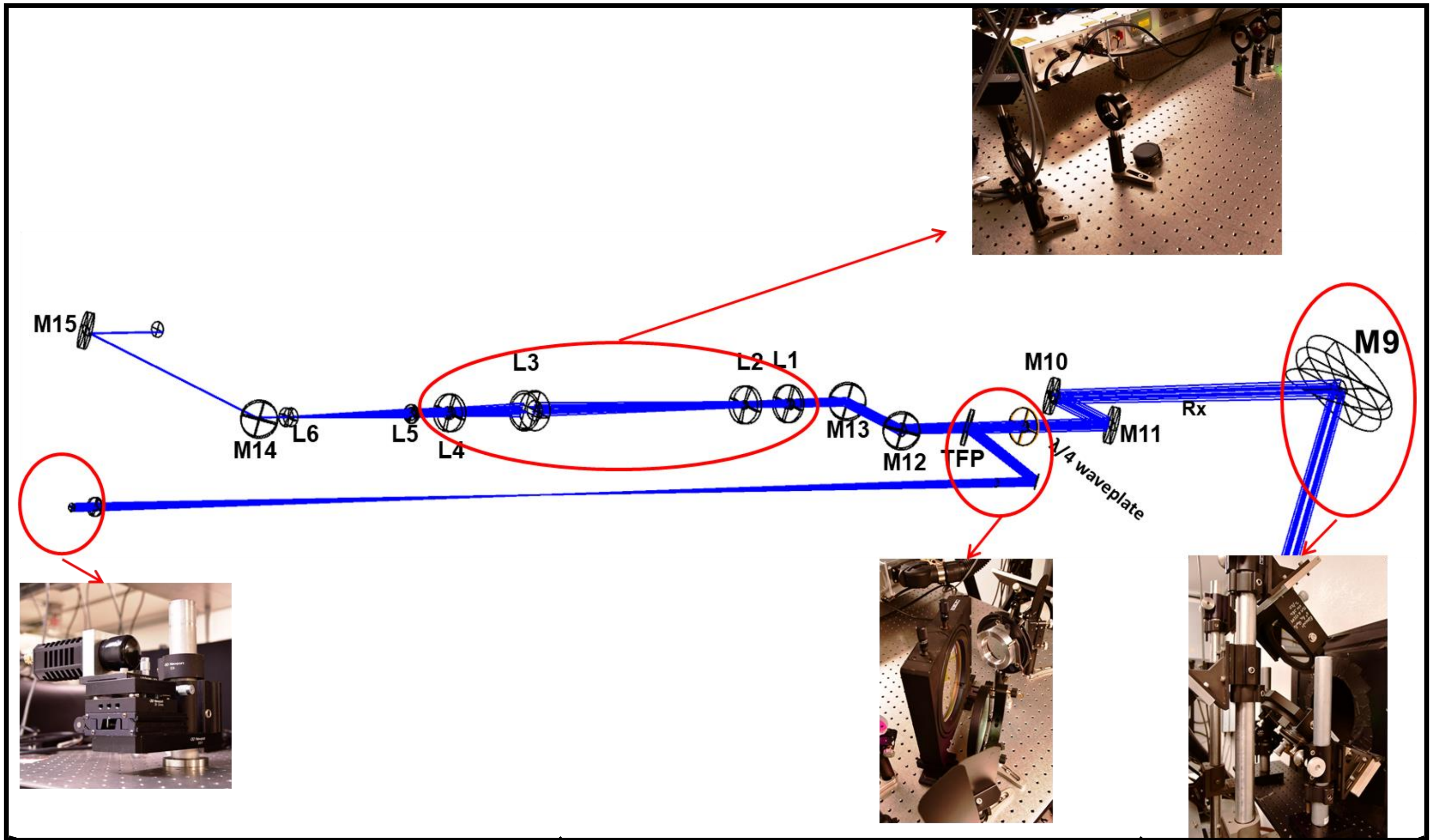
Laser Safety Infrastructure

New interlock (complete) and radar (late 2018)

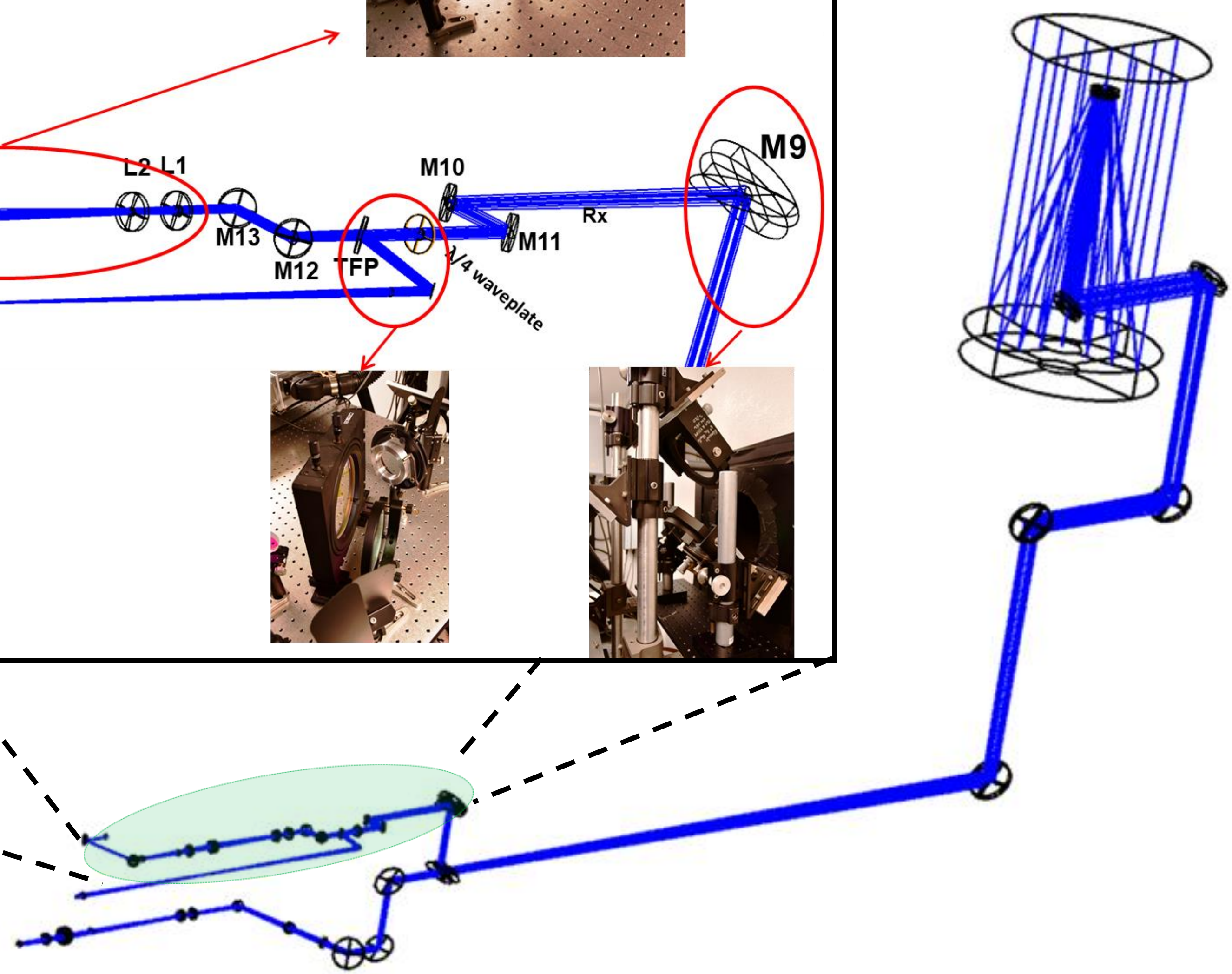


Callout boxes indicate all components in the LHRAS

NRL LTT Testbed Optical Layout



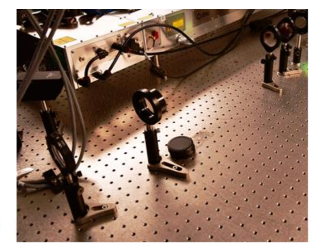
- Class 1M
- 50 μrad 1/e^2 HW divergence

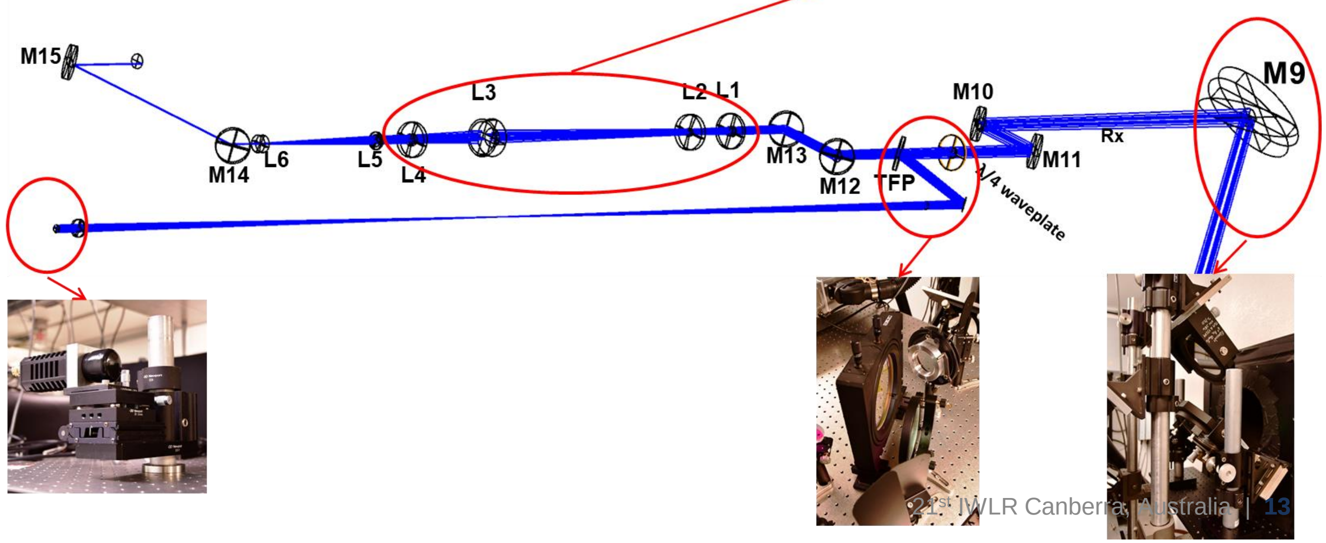


UNCLASSIFIED//FOUO

NRL LTT Testbed Optical Layout

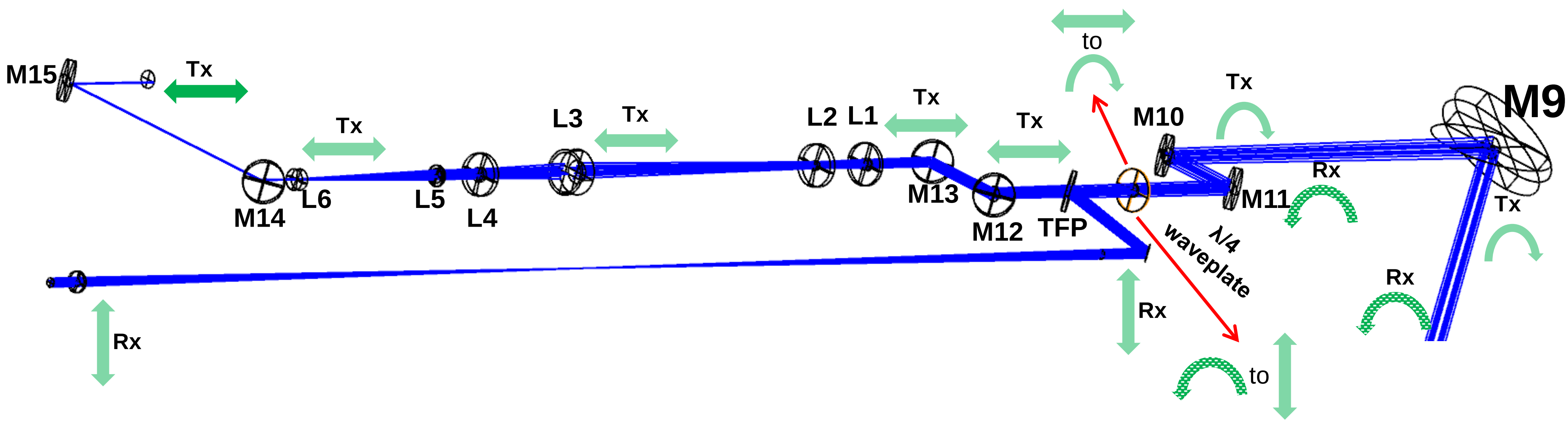
- **Transmitted beam**
  - Collimated from 1 mm to 12 mm diameter
  - Optics for matching telescope F# w/ 100 μrad FW divergence
  - Folding mirrors for fine alignment with telescope
  - Polarizing optics to separate Tx signal from Rx signal
  - Periscope insertion into telescope optics
- **Received beam**
  - Thin file polarizer splits return light into Rx arm path
  - Collimated to 12 mm diameter
  - Return photons directed and aligned onto Rx detector (C-SPAD)





NRL LTT Testbed Optical Layout

Initial design for separating Tx and Rx optical beam
by polarization components



Polarization components measured at detector position:

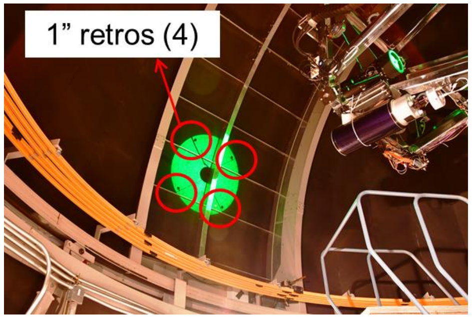
- 85% vertical
- 7% Horizontal

NRL LTT Optical System Characterization

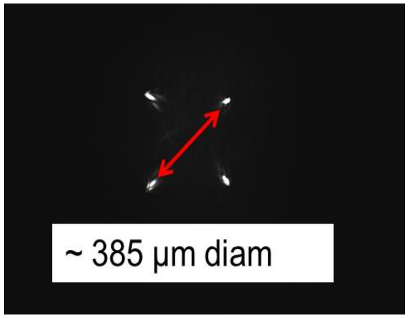
- Test Performed to the system:
  - Initial collimation: **GOOD**
  - Optical elements where tested at NRL to characterize their optical performance:
    Current loss: ~30% (will be improved by fixing collimation size)

    Total expected loss: ~ 15 to 20% (transmitting)
  - System alignment with telescope: **GOOD**
  - Polarization states maintain through the system: **GOOD**
    92% linear polarization at the detector
  - Receiving arm focusing efficiency: **GOOD**
  - System backreflections: **OK**, except >1 nJ from telescope covers (sun avoidance)
- Tests to be performed:
  - Rx effective FOV
  - Collimation out of the telescope

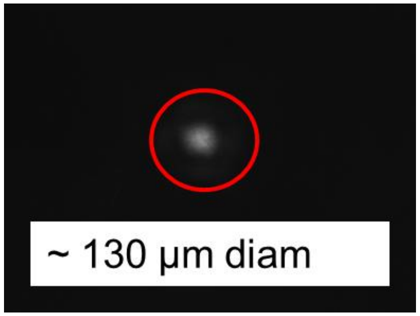
Receiving arm test, using a 75 mm fl lens



At the telescope



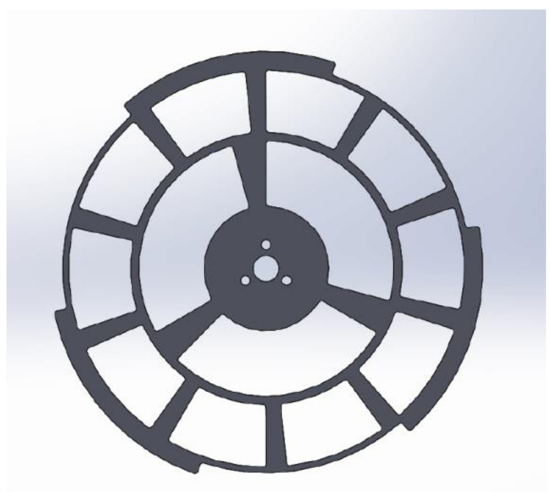
5.3 mm from system focus



At system focus

Backscatter Suppression

- Optical Chopper Blade implemented to suppress on-axis backscatter
- Custom blade designed to maximize opening for Rx signal, and protecting detector while Tx w/ gate open
- Located at focal plane on Rx leg
- Custom design:
  - sync with laser fire while modifying blocking duty cycle
  - 16% duty circle, blocks 16 µsecs while sync @ 1kHz,
  - blades sized to block area of detector while adding enough buffer to keep protecting in case of signal jitter
  - tested to sync up to 1.5 kHz
  - Inner and outer ring made to maximize opening duty cycle



Custom optical chopper blade, designed and built at NRL

Laser Start Diode → Detects laser fire signal

DG-535 → Adds necessary delay to laser fire signal to sync center of the blade with laser Tx

Chopper Blade Control Box → Receive signal and sync chopper wheel LED signal with laser firing signal

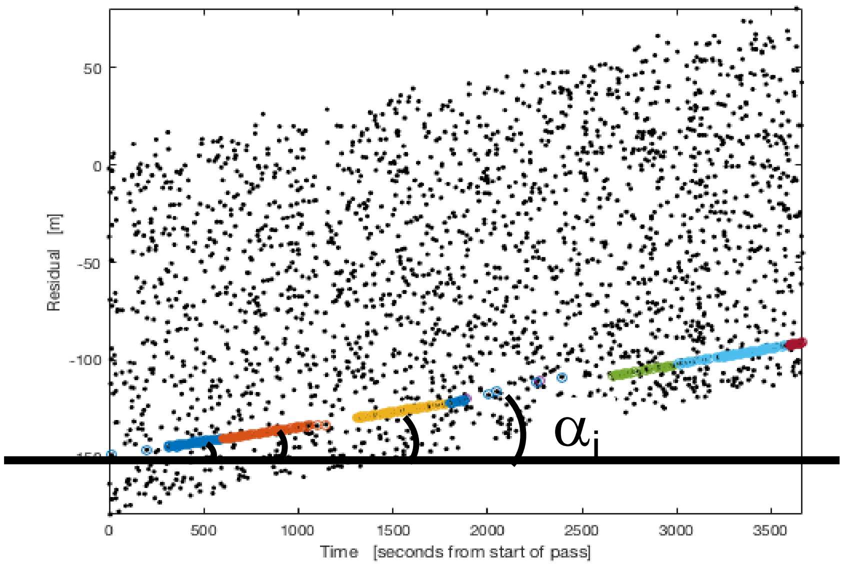
→ Block back reflections

C-995 Optical Chopper
Terahertz Technologies Inc

SLR & LTT Analysis Tools

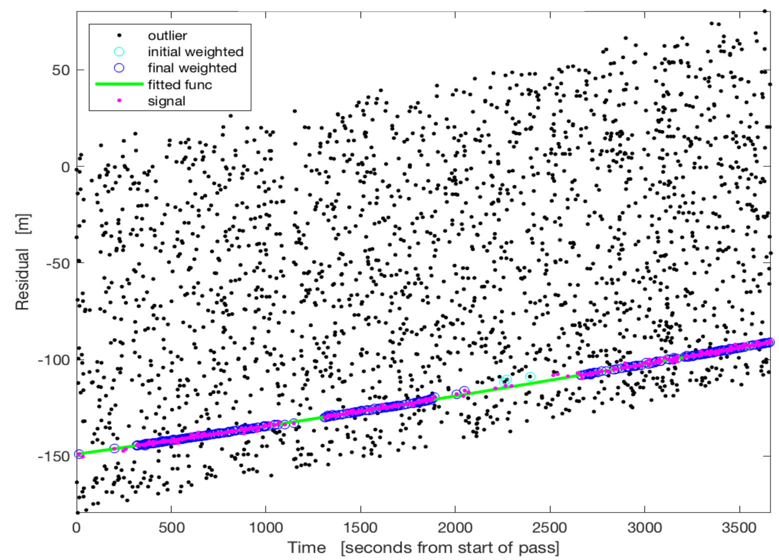
Step #1: *Initial search*

- Two-modes: ground calibration and satellite
- For each 10-min 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



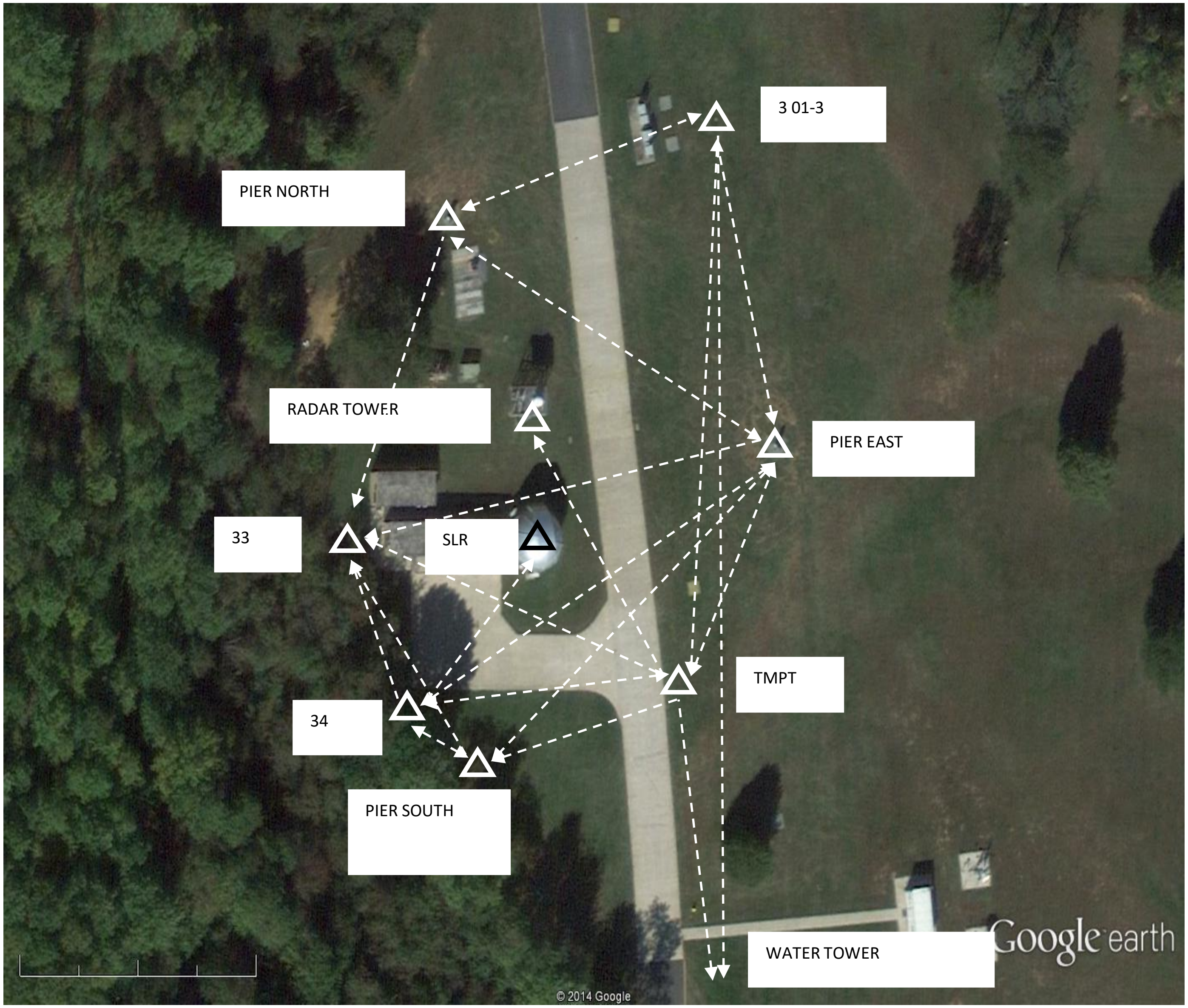
Step #2: *Outlier rejection*

- 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



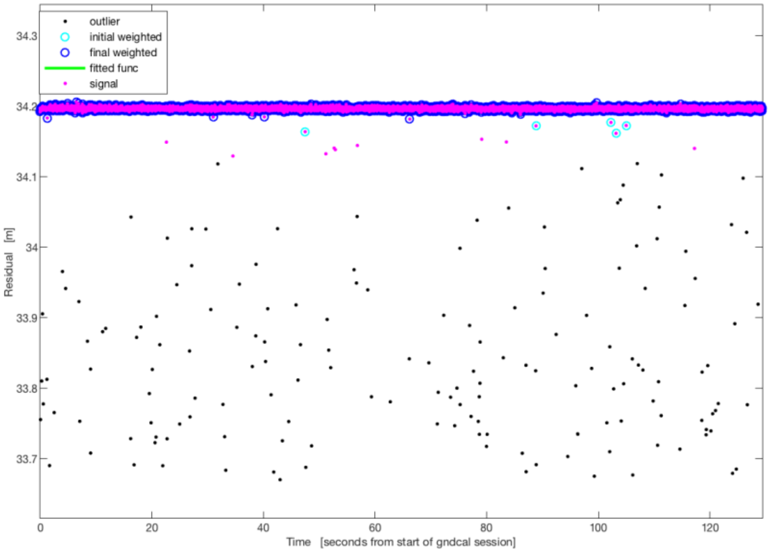
Ground Targets and New Local Tie Survey

- Completed in 2016 by NOAA NGS
- Tie between ground ranging targets and NRL telescope realized via AXIS software (Geoscience Australia)



Ground Target Testing

peas (16 Oct 2018)



delay [ps]: 114068.0
drift [ps/s]: -0.008

Compares to calculated nominal delay based on
- optical path length (zemax)
- measured cable delays
- electronic signal rise times

Validate stability (in prog)

Summary & Next Steps

- Aim to enable NRL participation in ILRS and other LTT experiments
  - initial effort engineering to design 532nm system, requirements driven by ACES/ELT
  - study potential new methods to characterize, monitor, compensate for system delays
  - evaluate limits of LTT technique
- Initial 532nm optical layout designed and integrated
  - will test polarization-based attenuation on Tx and Rx legs for controlling flux on C-SPAD
  - need to verify 100 μrad divergence
  - need to improve backscatter suppression for >1.5 kHz rates
- Initial integration of electronics and timing systems complete
  - finish testing s/w interfaces with laser, NPETs, and timing systems
  - develop technique for controlling laser fire time
- Developed a new tool for extracting full-rate signal photons
  - add simplified user interface for low-latency post-processing (and reanalysis)
  - verify accuracy of data products generated using the tools
- Calibration and validation
  - classical methods used for ongoing system checkout and characterization
  - interested to find/explore alternate methods

Questions?