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

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21st International Workshop on Laser Ranging – 5-9 November 2018 – Canberra, Australia
• 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 ensemble¹,²,³
  - microwave link¹⁰ for ACES primary time transfer mode
  - 532nm laser link¹² for optical timing experiments
    • gated detector: laser pulse on target within 100ns

• 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

Source: http://www.esa.int
NASA Ames (bus)
- Univ. of Florida (OPTI)
- NRL & Univ. of Florida ground stations
- Launch expected late 2018

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

Optical train:
- 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

PESO Consultant Ltd.
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

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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
  - Uncompensated for fiber delay variations

- Initial integration complete August, 2018
- Ongoing monitoring of signals at H-maser and LTT testbed
Transferring Timing Signals to LTT Testbed

NRL CHRONOS Timing Facility

- 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
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/e²
- HW divergence
• **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)
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

1° retros (4)

~ 385 μm diam

~ 130 μm diam
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
**Step #1: Initial search**

- Two-modes: ground calibration and satellite
- For each 10-min interval, i,
  - determine direction, $\alpha_i$, 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 $\alpha_i$
    - 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

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)
• 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?