Data Reduction and Calibration of the Apache Point Observatory Lunar Laser-ranging Operation

DR. NICHOLAS R. COLMENARES

1ST LUNAR LASER RANGING MEETING 2023

Talk overview

- Who am I?
- APOLLO overview
- Sequence of APOLLO events
- Reduction overview
- ACS overview
- ACS results
- Extending ACS usefulness

Who is this guy?

- Joined APOLLO in 2014
- Doctorate under Tom Murphy 2020
- Brief private sector work 2020/2021
- NASA Postdoc Program – started August 2021
- Here to continue to improve APOLLO/APLLRS operations and results; possibly help with Satellite Laser Ranging!
- Also, cat guy

My best friend, Juno, for 15+ years

My newer friend, James, of ~ 2 years

APOLLO overview

Local cornercube reflector: "fiducial", or "FID" photons

Differential measurement

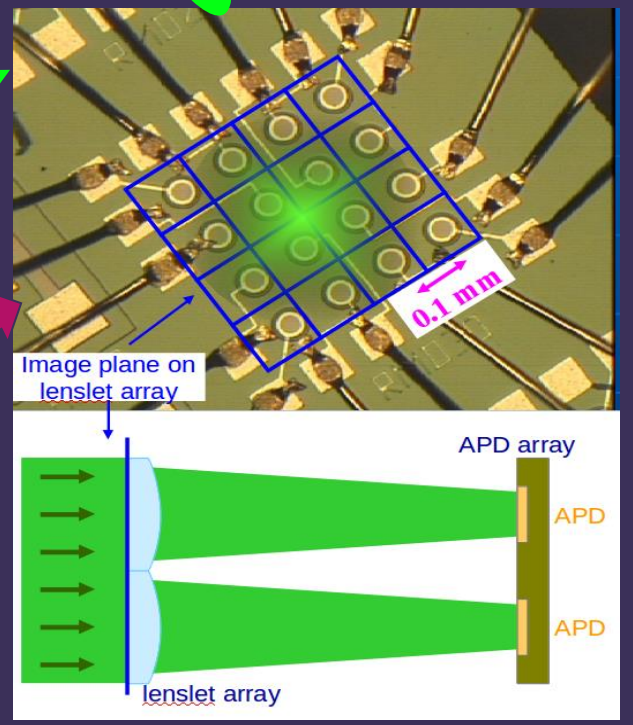
Laser: 90 ps pulses, 2W avg @ 20 Hz, 532 nm

Telescope

Earth

3.5 m @ Apache Point Observatory

4x4 avalanche photodiode detector array ("APD" array)



~100 ps resolution

Images/background: **Eric L. Michelsen**

APOLLO timing & command system

Stockpic. 2023, May 5. Pixabay.

Timebase → Before: Ovenized quartz, GPS-disciplined

Now: Cesium

PPS

"Hour" hand → Pulse per second (PPS)

PPS

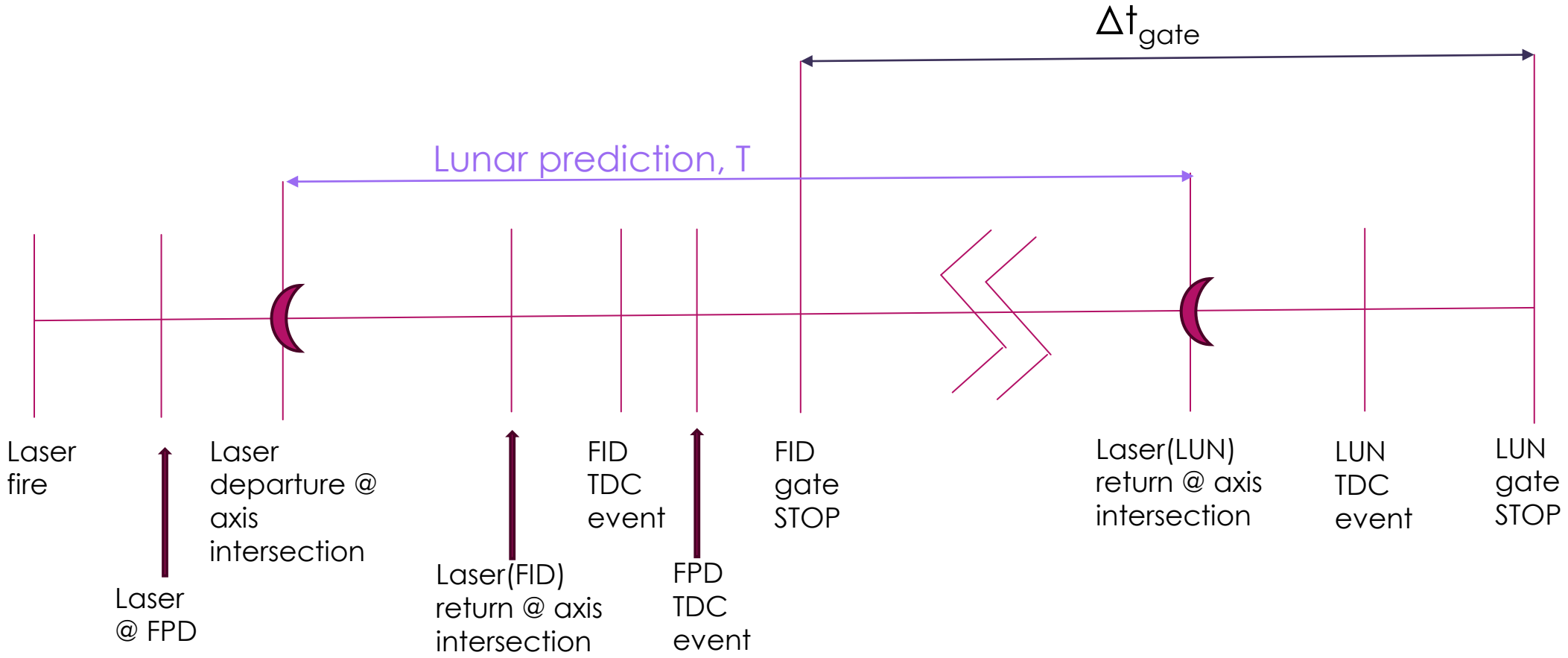
"Minute" hand → APOLLO Command Module (ACM)
20 ns resolution

Detection "gates"

"Second" hand → Time to Digital Converter (TDC)
100 ns range, 12 bits → 25 ps resolution

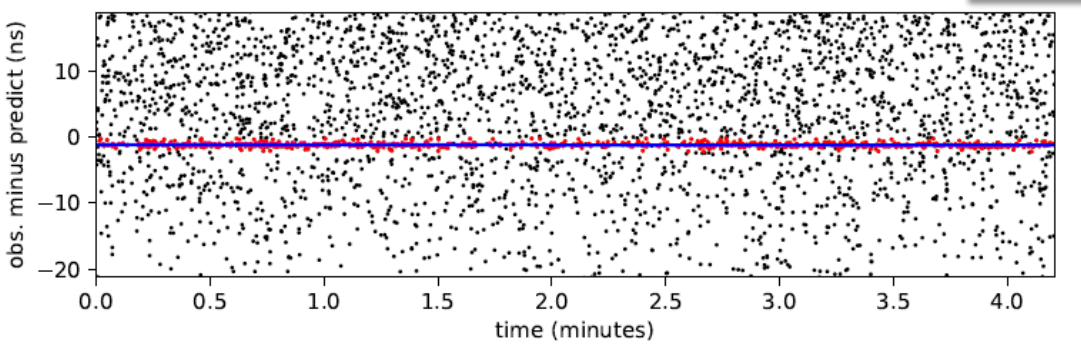
5 x 10 MHz = 50 MHz

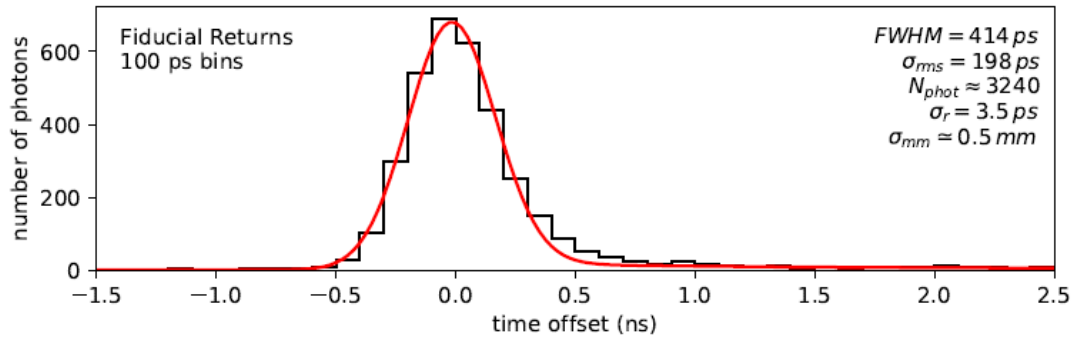
Sequence of Events

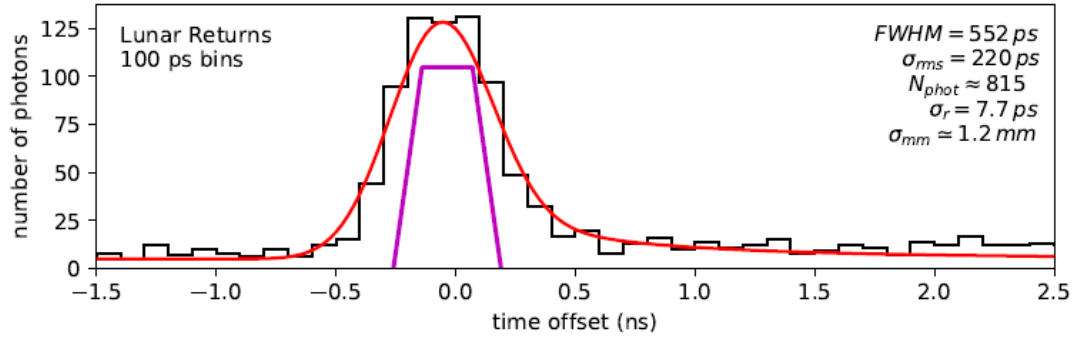


Reduction procedure overview

- FID – FPD
- Fit functional form to FID-FPD
- Form lunar "residuals"
- Remove linear trend
- Sliding fit to lunar residuals
- Add linear trend + prediction back in

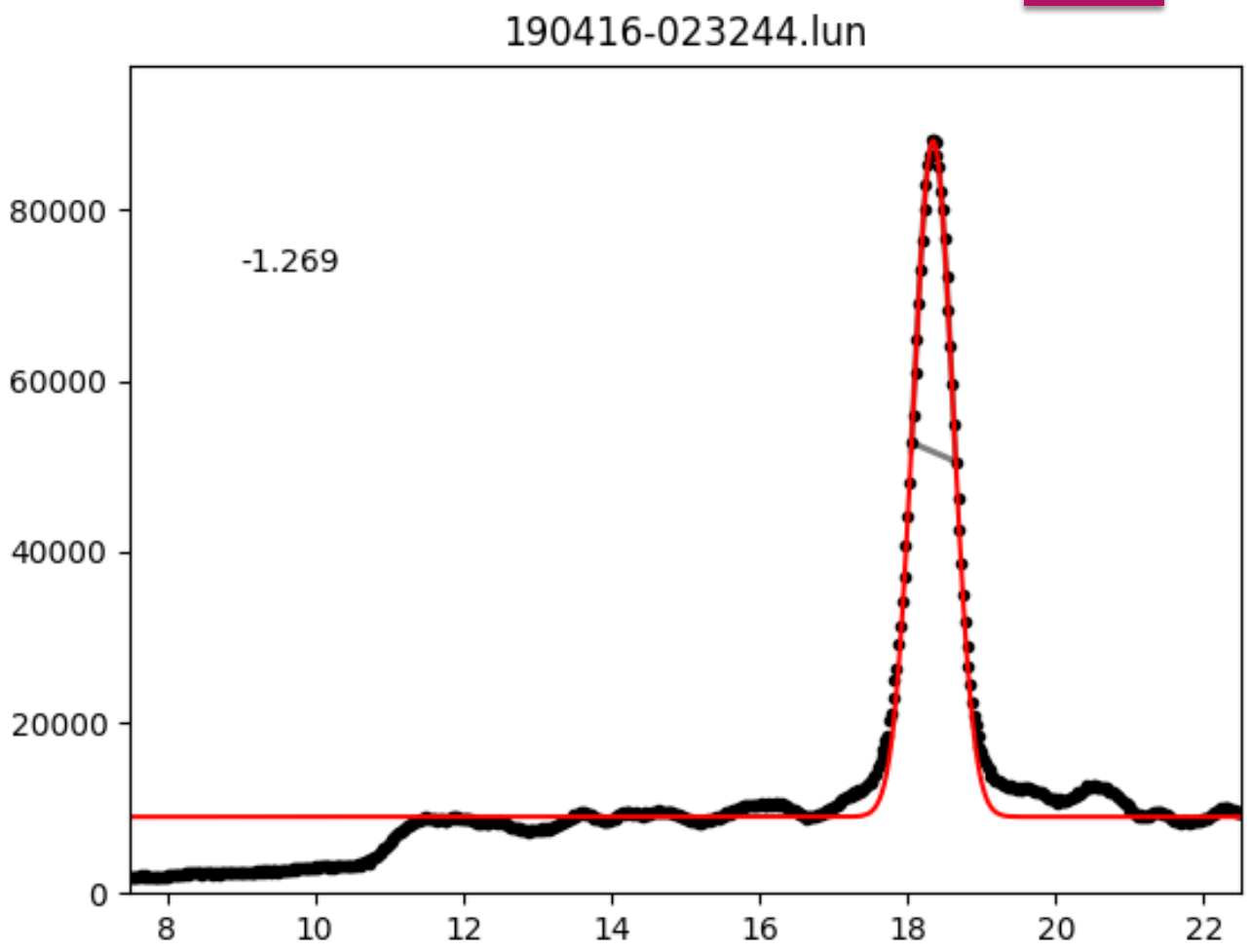




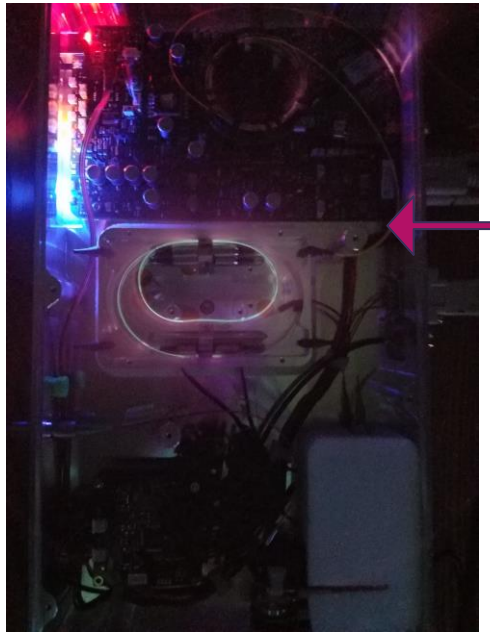


Quality Checks

- Script finds suspect NPs for user review
- User reviews NP statistics + plots
- Obvious invalid signals are tossed
- Remainder sent to analyst for precise residuals
- Make cuts on residuals, publish NPs



ACS overview



Optical "ruler" of "truth" pulses sent to detector

Laser with High rep-rate → 1064 nm fiber cavity semiconductor saturable absorber mirror (SESAM) → 80 MHz

→ 2 x frequency: 532 nm

Well-timed → Phase-locked to Cesium standard

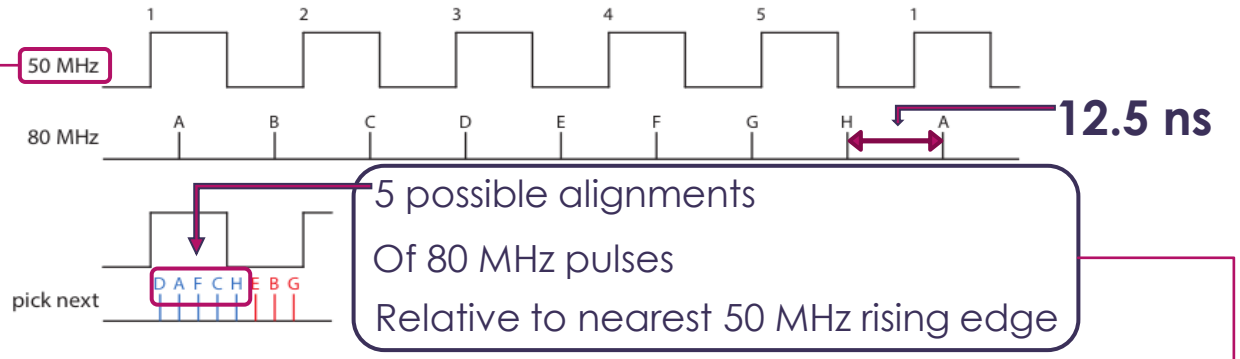
→ ~10 ps jitter @ ~few seconds pulse separation

Selectable → Pulse processing system

Short pulses → 10 ps width

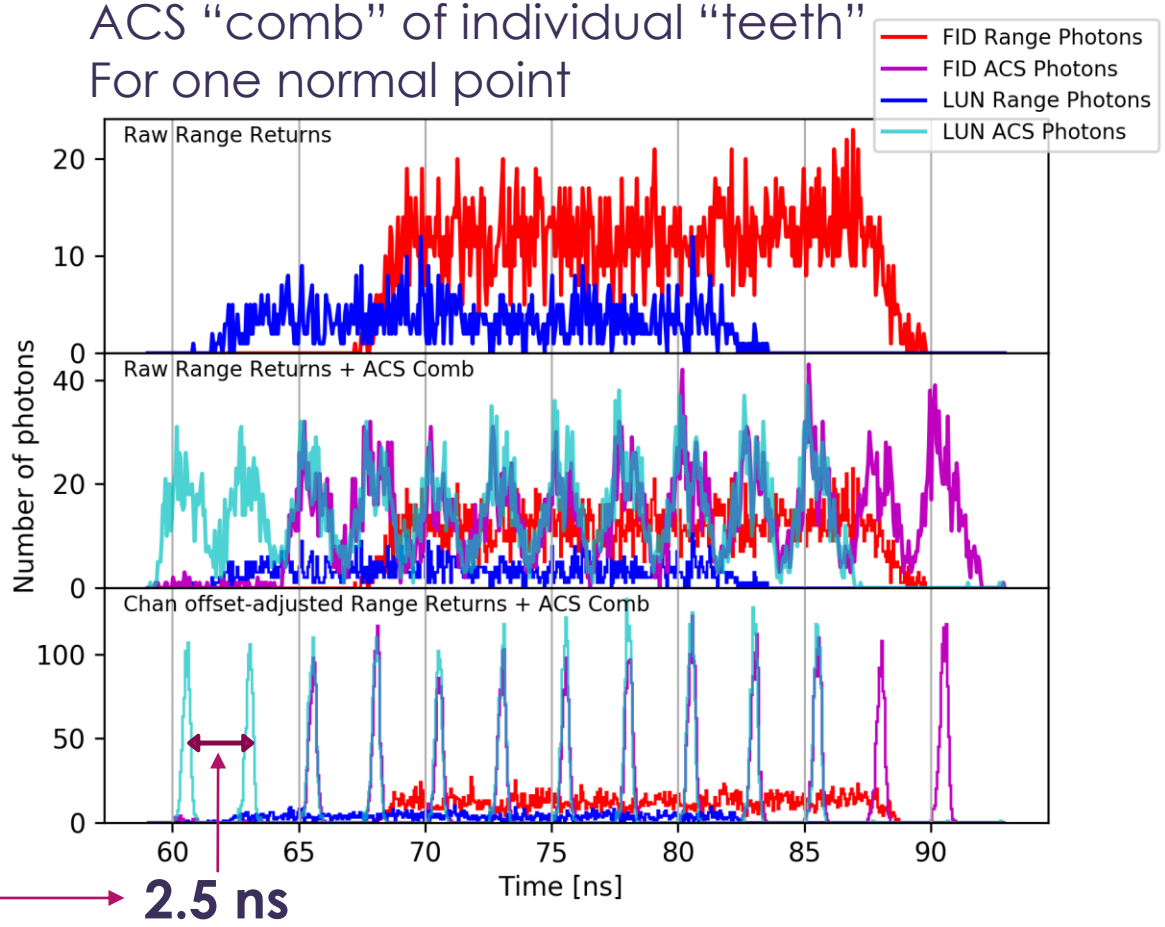
Calibration concept

APLLRS system clock-train



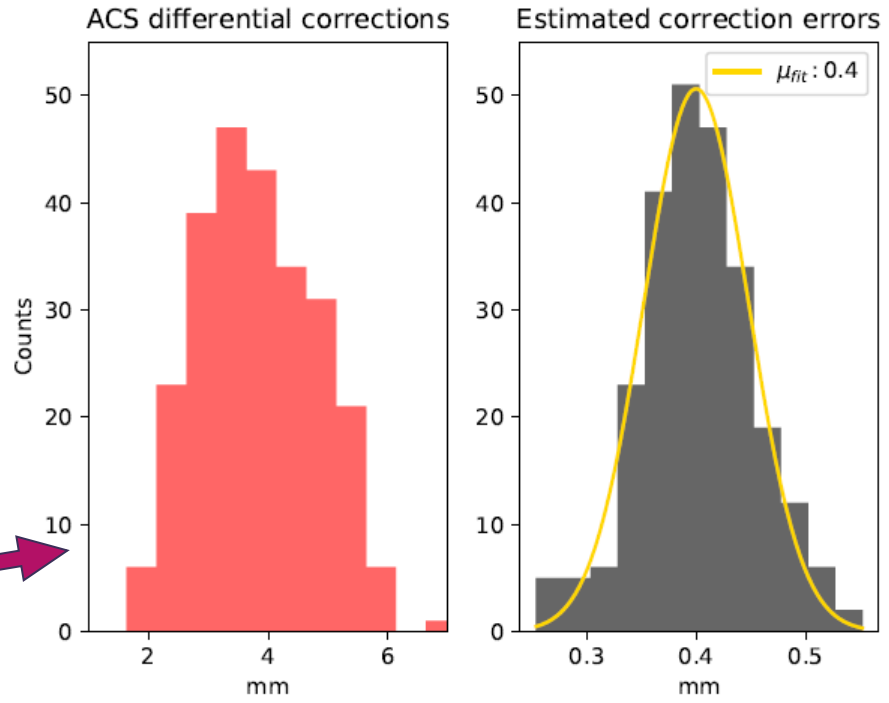
- ACS pulses sliced from 80 MHz using 50 MHz triggers
- Find unique combs for each channel + gate type (FID or LUN) pair
- Assert ACS tooth pitch = 2.500 ns **exactly**
  - Interpolate
- Assign range photons calibrated timestamps ($t_{i,\,ACS}$) based on proximity to ACS teeth

ACS "comb" of individual "teeth"
For one normal point



Calibration results

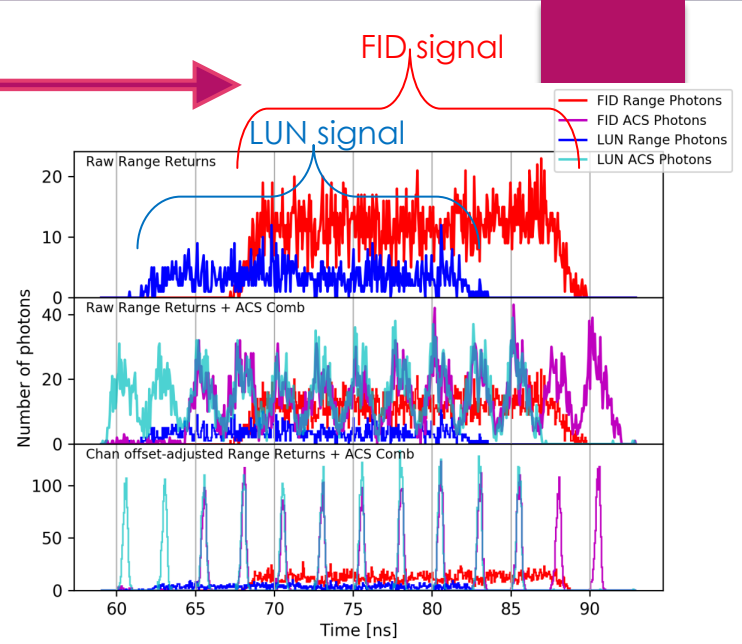
- Define **individual photon** timing correction (C_i)
  - $C_i \equiv t_{i,ACS} - t_{i,CALTDC}$ ← TDC self-test routine; default calibration/used in absence o ACS
- Define **normal point** (NP) timing correction
  - Round trip time (RTT) is **differential:** $\text{stuff} + Signal_{FID} - Signal_{LUN}$
  - → NP correction is also **differential:** $C_{NP} \equiv C_{FID} - C_{LUN}$
    - $c_{FID} \equiv {\Sigma_i^N c_{i\,[FID]}}/{N}$
    - $c_{LUN} \equiv {\Sigma_j^M c_{j\,[LUN]}}/{M}$
- Make a histogram of C_{NP} and associated errors for study

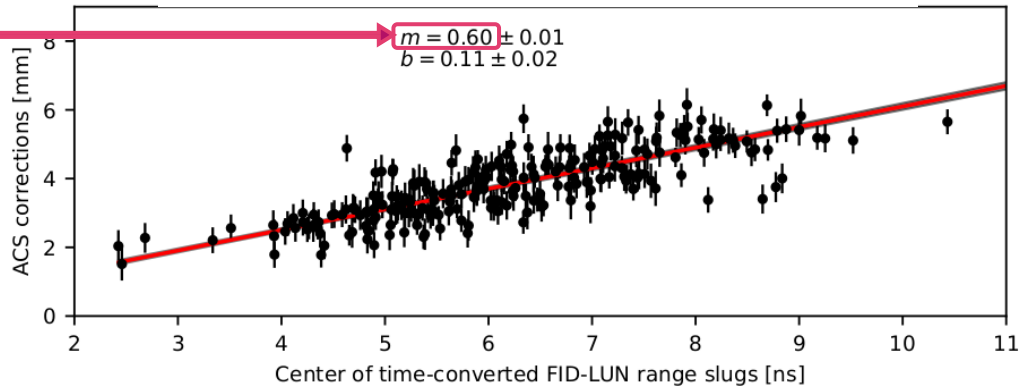


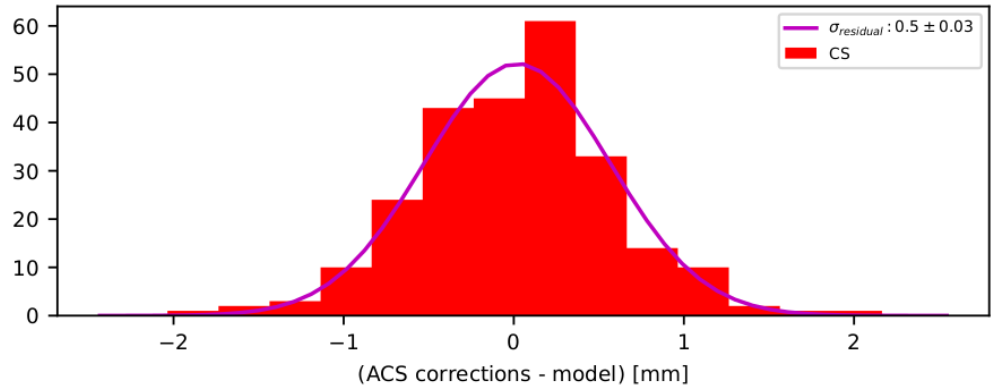
- **APOLLO never suffered large systematic errors**
- **System accuracy < 1 mm after ACS corrections**

Correcting "non-ACS" runs and historic data

- Timing inaccuracies depend on what region of TDC detection window is sampled
  - FID, LUN signals not necessarily overlapped
- **ACS allows us to characterize this scale**
  - ACS corrections correlated w/ mean FID, LUN overlap
  - 0.4% TDC range error for imperfect overlap
- Can predict timing correction w/o having ACS photons present
  - Same TDC, entire experiment







The future…

- Data releases
- Control computer modernization (continue)
- SLR targets
- New lunar targets

Full author list

Nicholas R. Colmenares[1, 4]
James B. R. Battat[2]
Daniel P. Gonzales[3]
Evan D. Hoffman[4]
Frank G. Lemoine[4]
Russet McMillan[5]
Stephen M. Merkowitz[4] [**P.I.**]
Thomas W. Murphy Jr.[3]
Sanchit S. Sabhlok[3]
Vishnu Viswanathan[4, 6]

[1]Oak Ridge Associated Universities, Oak Ridge, TN., USA.
[2]Department of Physics, Wellesley College, Wellesley, MA., USA.
[3]Center for Astrophysics and Space Sciences, University of California San Diego, San Diego, CA., USA.
[4]NASA Goddard Space Flight Center, Greenbelt, MD., USA.
[5]Apache Point Observatory, Sunspot, NM., USA.
[6]Center for Space Sciences and Technology, University of Maryland Baltimore County, Baltimore, MD., USA.

References

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- Battat, J., Adelberger, E., Colmenares, N.R., et al. (Provisionally accepted: PASP). "Fifteen years of millimeter accuracy lunar laser ranging with APOLLO: dataset characterization." https://arxiv.org/abs/2304.11128
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(Extra slides to follow, if needed during Q+A)

NASA transition

Stewardship began January 2021

Operations logistics

New data quality control check

2021, 2022, partial 2023 data release

Automated seeing estimation program*

Control computer modernization (in progress)

*Developed by our 2022 summer intern Joshua Batstone; University of Maryland, Annapolis, MD., USA.

Why LLR?

Gravity and quantum at odds

Gravity more suspect

Earth/Moon high quality gravitational lab

…and additionally, info about Earth/Moon!

- LLR is sensitive to:
  - Equivalence principle
  - Secular evolution of G
  - Gravitomagnetism
  - Geodetic precession
  - Lunar interior
  - Earth orientation

Why an Absolute Calibration System (ACS)?