# Recent Developments at the Apache Point Lunar Laser Ranging Station

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22ND INTERNATIONAL WORKSHOP ON LASER RANGING

# Talk overview

- Who am I?
- Why LLR?
- APLLRS/APOLLO overview
- NASA handoff
- Why an Absolute Calibration System (ACS)?
- 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 14+ years

My newer friend, James, for ~ 1 year

# 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

# APLLRS basics

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

**Differential** measurement

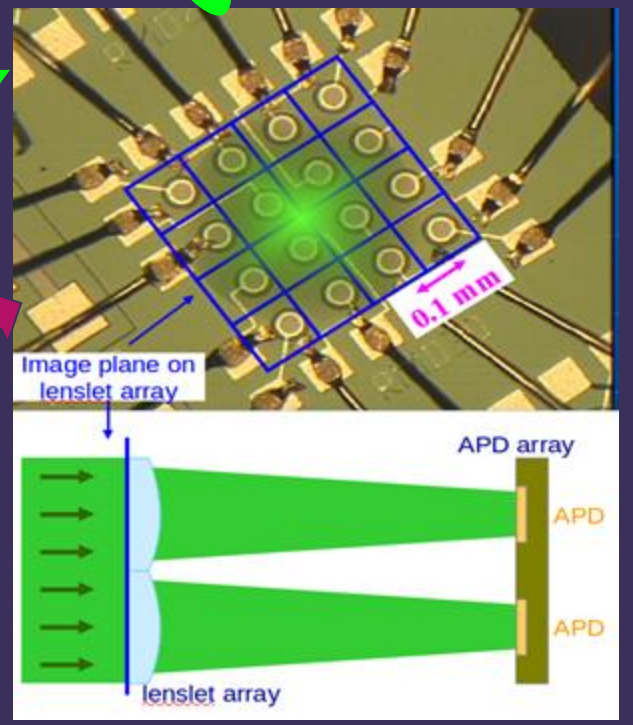
Laser: 2 W (100 ps/100 mJ pulses @ 20 Hz), 532 nm

Telescope

Earth

3.5 m @ Apache Point Observatory

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




~100 ps resolution

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

# NASA transition

Stewardship began January 2021

Operations logistics

New data quality control check

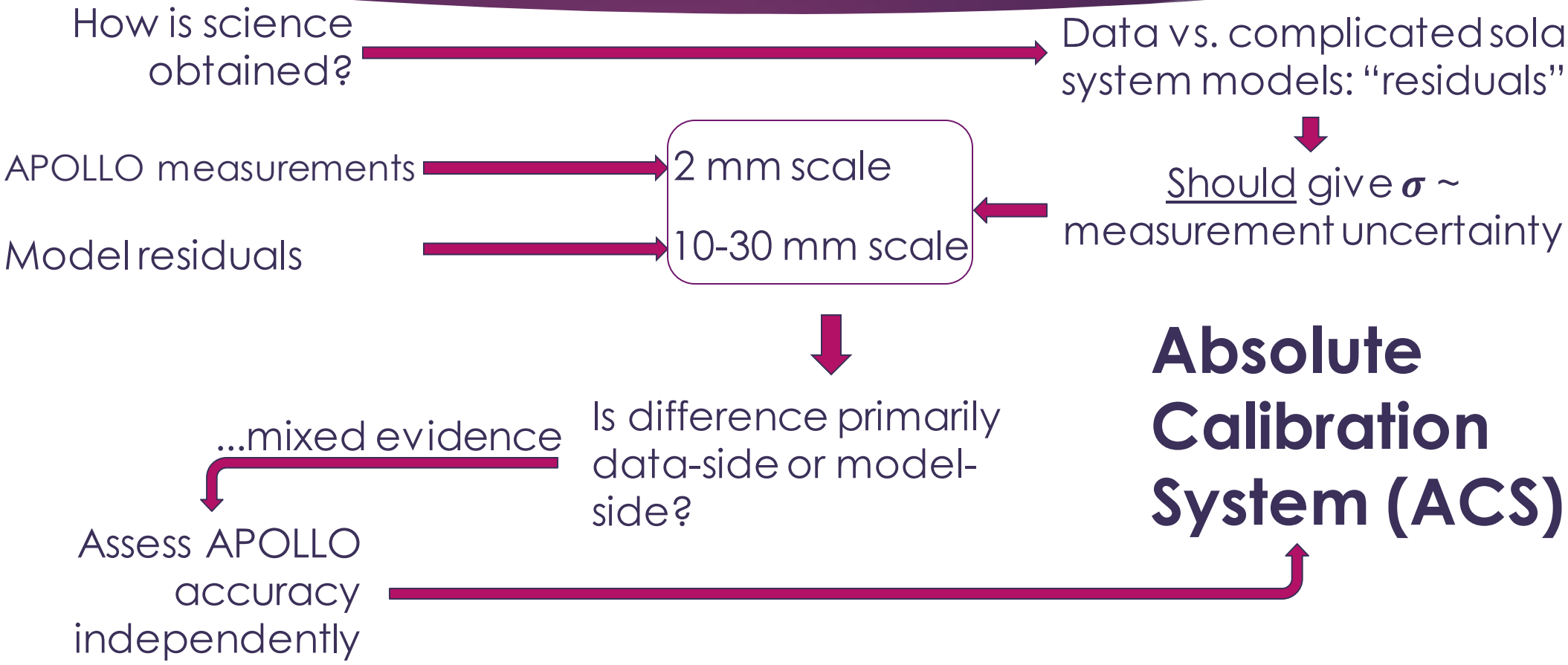
First data release

Automated seeing estimation program*

Control computer modernization (in progress)

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

# Why an Absolute Calibration System (ACS)?



# 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

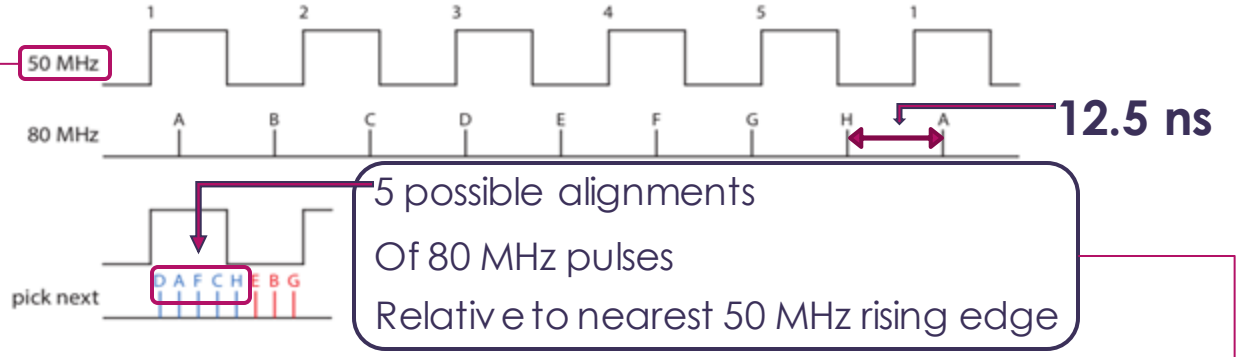
→ ~10 ps jitter @ ~few seconds pulse separation

Selectable → Pulse processing system

Short pulses → 10 ps width

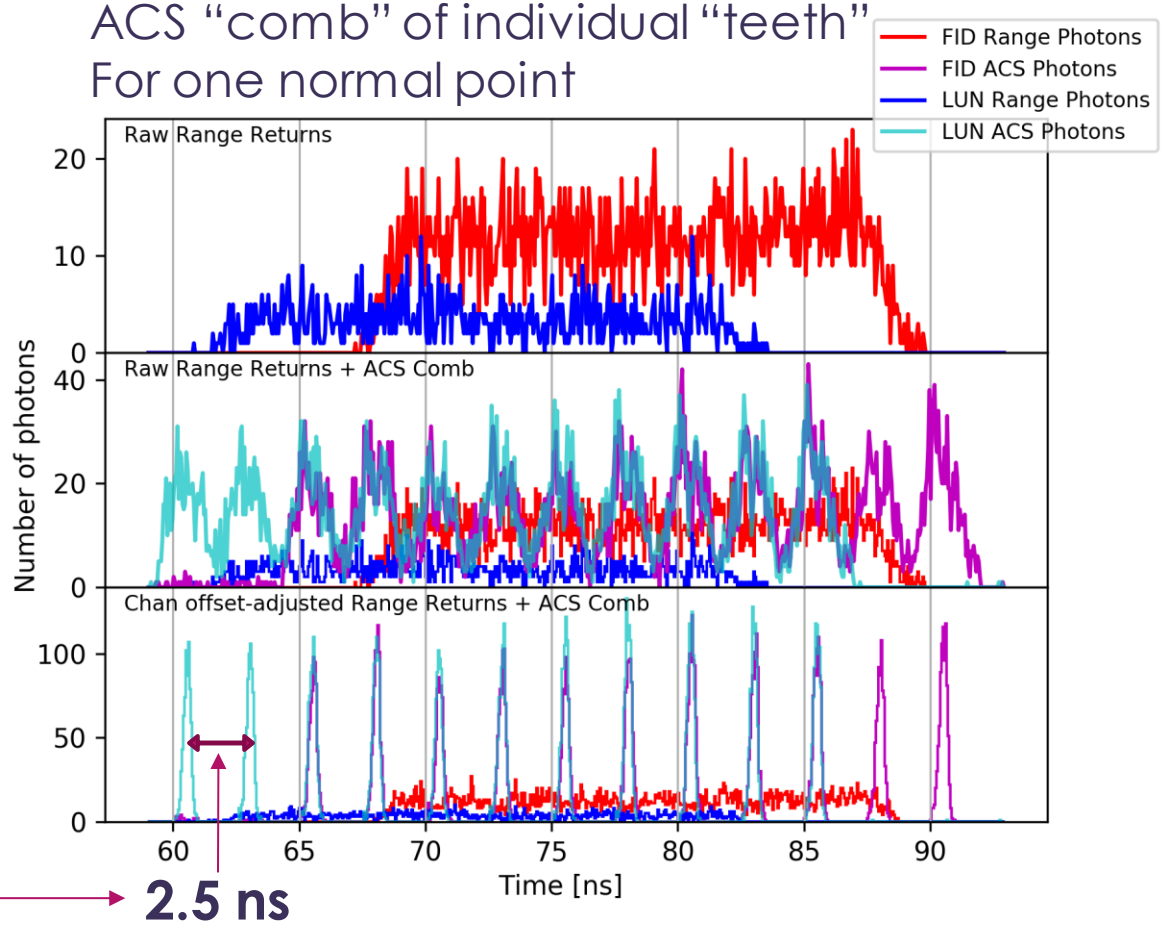
# Calibration concept

APLLRS system clock-train



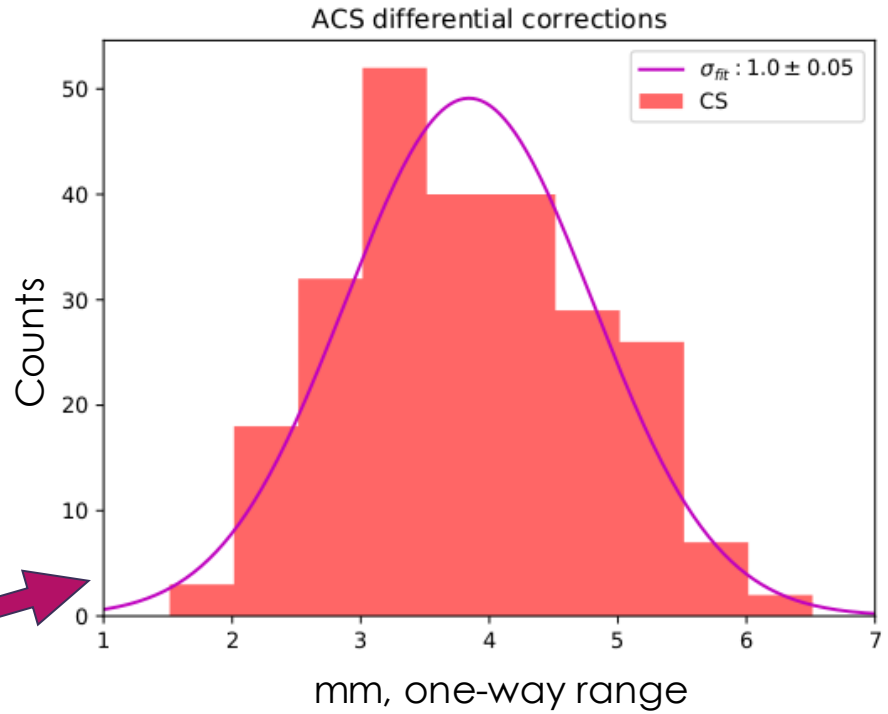

- ACS pulses sliced from 80 MHz using 50 MHz triggers
- Find unique combs for each channel + event type (FID or LUN) pair
- Assert ACS tooth pitch = 2.5 ns **exactly**
  - Interpolate
- Assign range photons calibrated timestamps ($t_{i,\,ACS}$) based on proximity to ACS teeth

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



# Calibration results

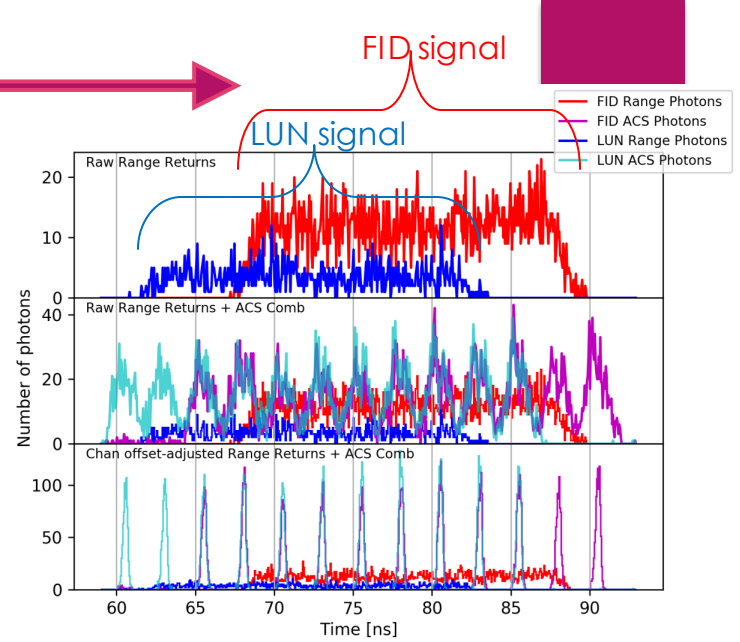
- Define **individual photon** timing correction ($C_i$)
  - $C_i \equiv t_{i,ACS} - t_{i,CALTDC}$ ← Event timer self-test routine; default calibration/used in absence of ACS
- Define **normal point** (NP) timing correction
  - Round trip time (RTT) is **differential:** stuff + $Signal_{FID} - Signal_{LUN}$
  - → 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 $C_{NP}$ for study

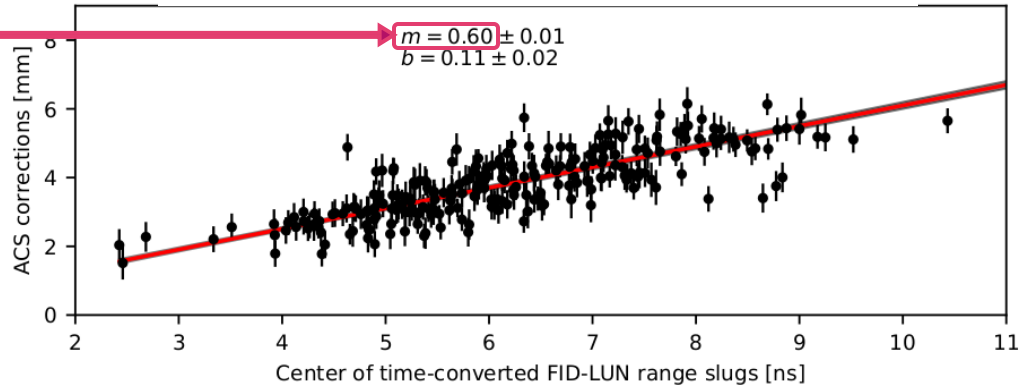


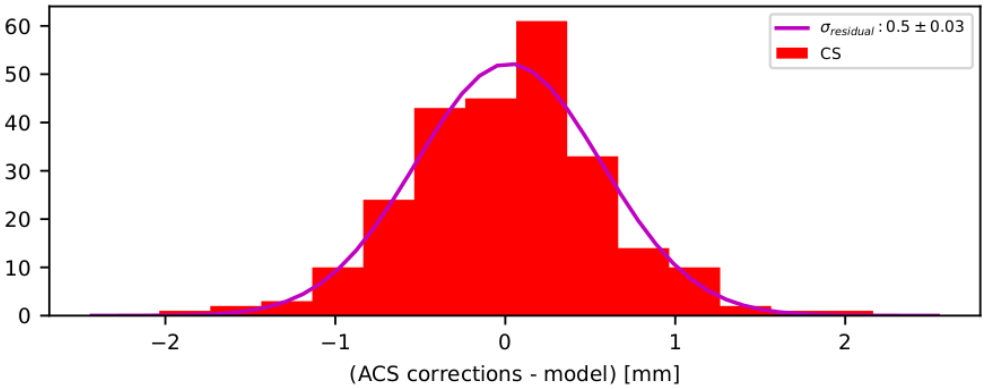

- **APOLLO never suffered large systematic errors**
- **System accuracy ~ 1 mm after ACS corrections**

# Correcting "non-ACS" runs and historic data

- Timing inaccuracies depend on what region of event timer 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% event timer range error for imperfect overlap
- Can predict timing correction w/o having ACS photons present
  - Same event timer, entire experiment



# The future…

- Updated data release, pre-2022
- 2022 data release
- Control computer modernization (continue)
- SLR targets
- New lunar targets

# References


- Colmenares, N.R., Murphy, T., Battat, J., Gonzales, D. & Sabhlok, S. (In Preparation). "Fifteen-years of millimeter accuracy lunar laser ranging with APOLLO: data reduction and calibration."
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- T. W. Murphy. Lunar laser ranging: the millimeter challenge. Reports on Progress in Physics, 76(7):076901, July 2013.

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