New Timing Calibration Capability for the APOLLO LLR experiment

James Battat
Wellesley College

IWLR 2016 – Potsdam
October 11, 2016

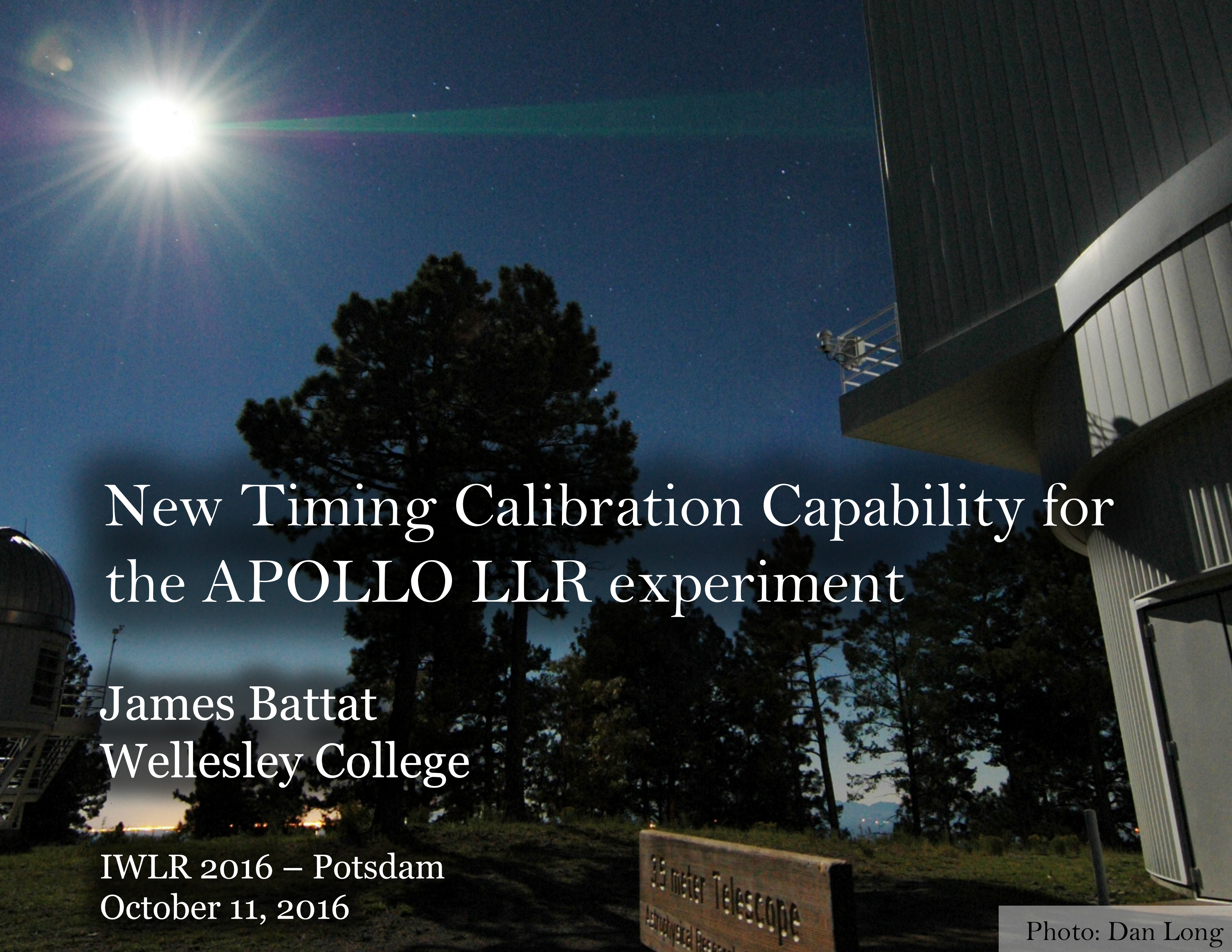
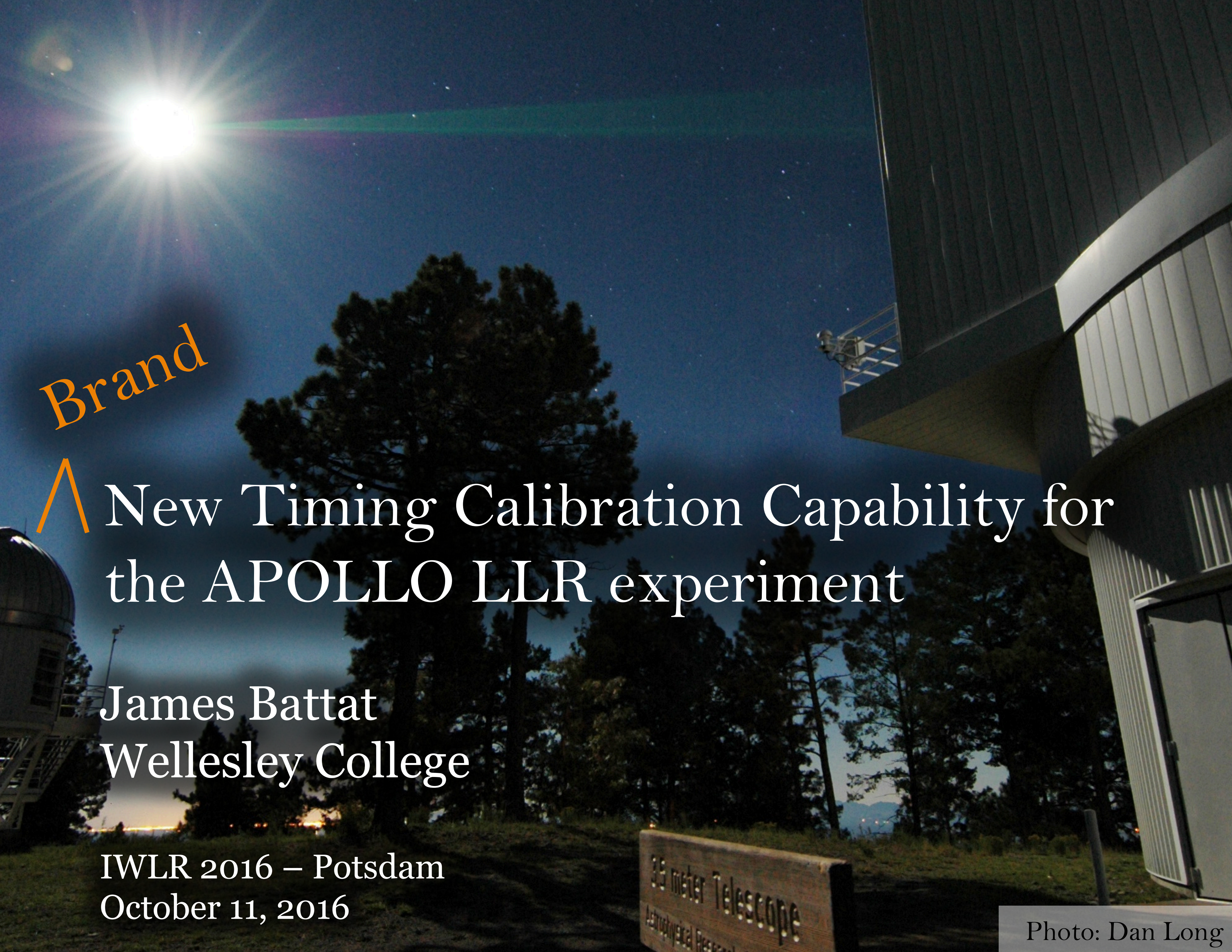


Photo: Dan Long



Brand New Timing Calibration Capability for the APOLLO LLR experiment

James Battat
Wellesley College

IWLR 2016 – Potsdam
October 11, 2016

Photo: Dan Long

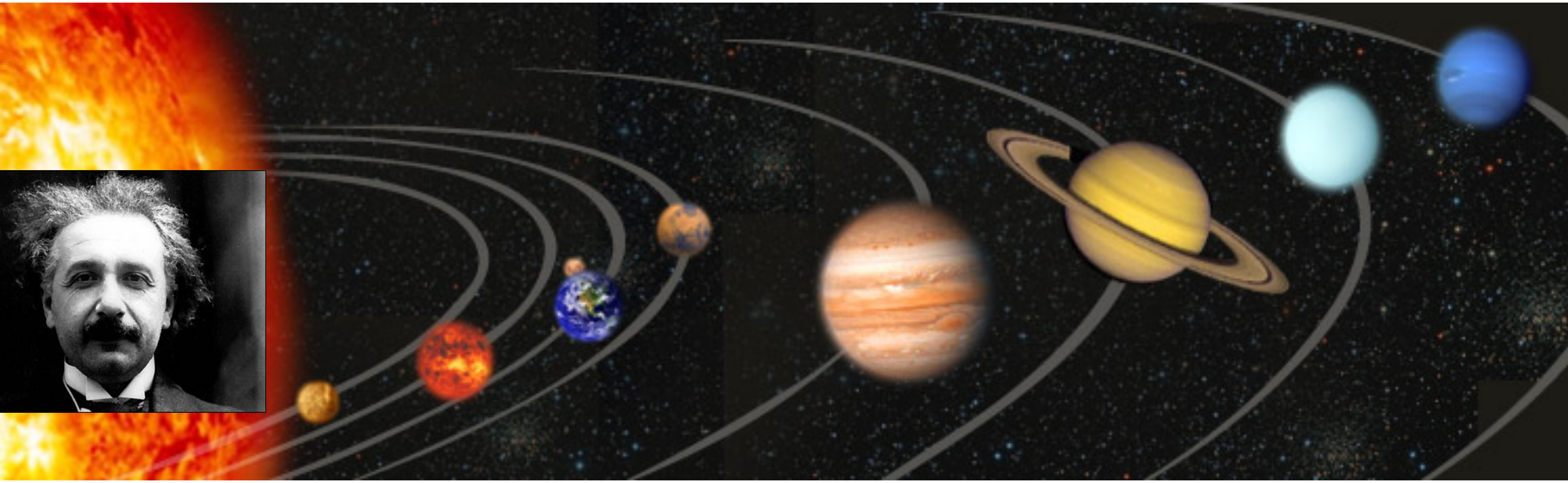
Overview

- Brief introduction to APOLLO
  science goals and instrument description
- Description and early results from our "Absolute Calibration System"

APOLLO, through the lens of yesterday

- For us, the target selection is trivial!
- Shot-by-shot calibration using a retro-reflector mounted to the secondary mirror.
- Shared facility (1h sessions, 8-10x per lunar month)
- No daytime operation
  (telescope restrictions on sun avoidance)
- Large aperture (3.5m), same for transmit & receive
- Seeing at site is very good (0.9 arcsec, median), but lose ~1/3 of our time to weather

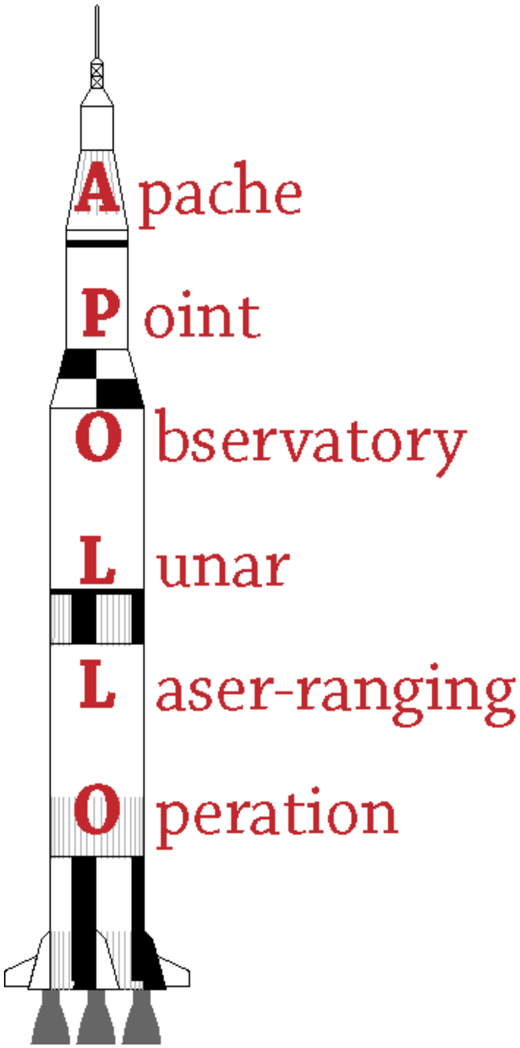
APOLLO: science motivation



Test fundamental physics through astrophysics

* Gravitation (post-Einstein)
* N>4 dimensional theories (braneworld gravity)
* Lorentz symmetry

APOLLO Collaboration



UCSD
Tom Murphy (PI)
Bob Reasenberg
Nick Colmenares
Shruti Singh

U. Washington
Eric Adelberger
Erik Swanson

Wellesley College
James Battat
Louisa Huang Ruixue
Sanaea Rose
Else Schlerman

Harvard
Christopher Stubbs
John Chandler
Irwin Shapiro

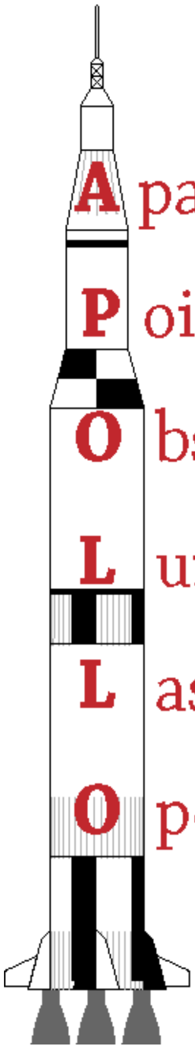
Humboldt State U.
C. D. Hoyle

Northwest Analysis
Ken Nordtvedt

Apache Point Observatory
Russet McMillan

APOLLO Collaboration

The ACS development team



Apache
Point
Observatory
Lunar
Laser-ranging
Operation

UCSD
Tom Murphy (PI)
Bob Reasenberg
Nick Colmenares
Shruti Singh

Morehouse College
Rodney Davis*

U. Washington
Eric Adelberger
Erik Swanson

Wellesley College
James Battat
Louisa Huang Ruixue*
Sanaea Rose
Else Schlerman

Harvard
Christopher Stubbs
John Chandler
Irwin Shapiro

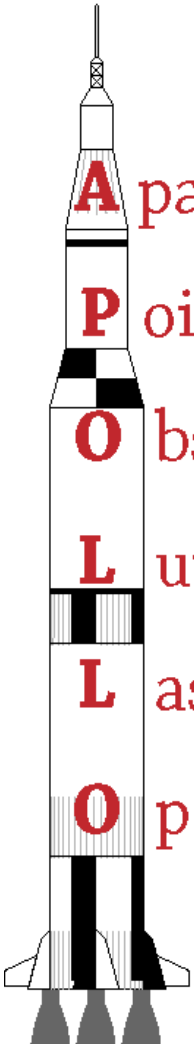
Humboldt State U.
C. D. Hoyle

Northwest Analysis
Ken Nordtvedt

Apache Point Observatory
Russet McMillan

APOLLO Collaboration

The ACS development team



Apache
Point
Observatory
Lunar
Laser-ranging
Operation

UCSD
Tom Murphy (PI)
Bob Reasenberg
Nick Colmenares
Shruti Singh

Morehouse College
Rodney Davis*

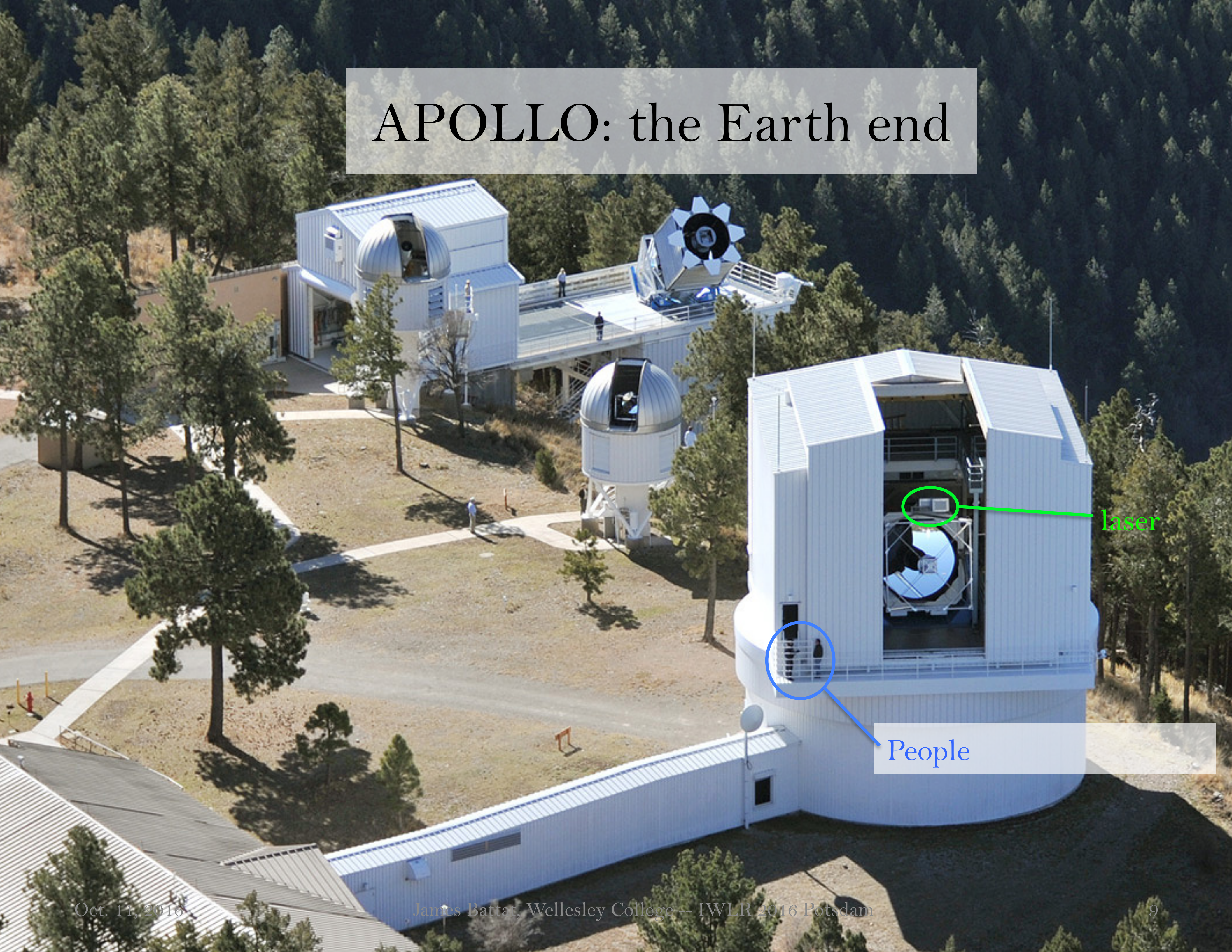
U. Washington
Eric Adelberger
Erik Swanson

Wellesley College
James Battat
Louisa Huang Ruixue*

Harvard
Christopher Stubbs
John Chandler

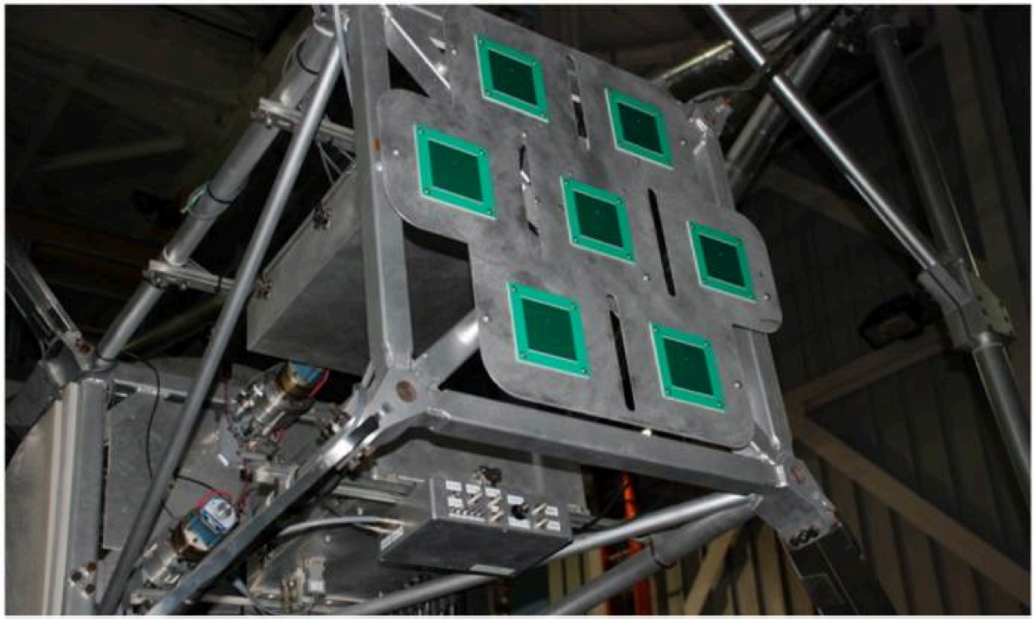
Special thanks to Christoph Skrobol and Konrad Birkmeier (Toptica)

APOLLO: the Earth end



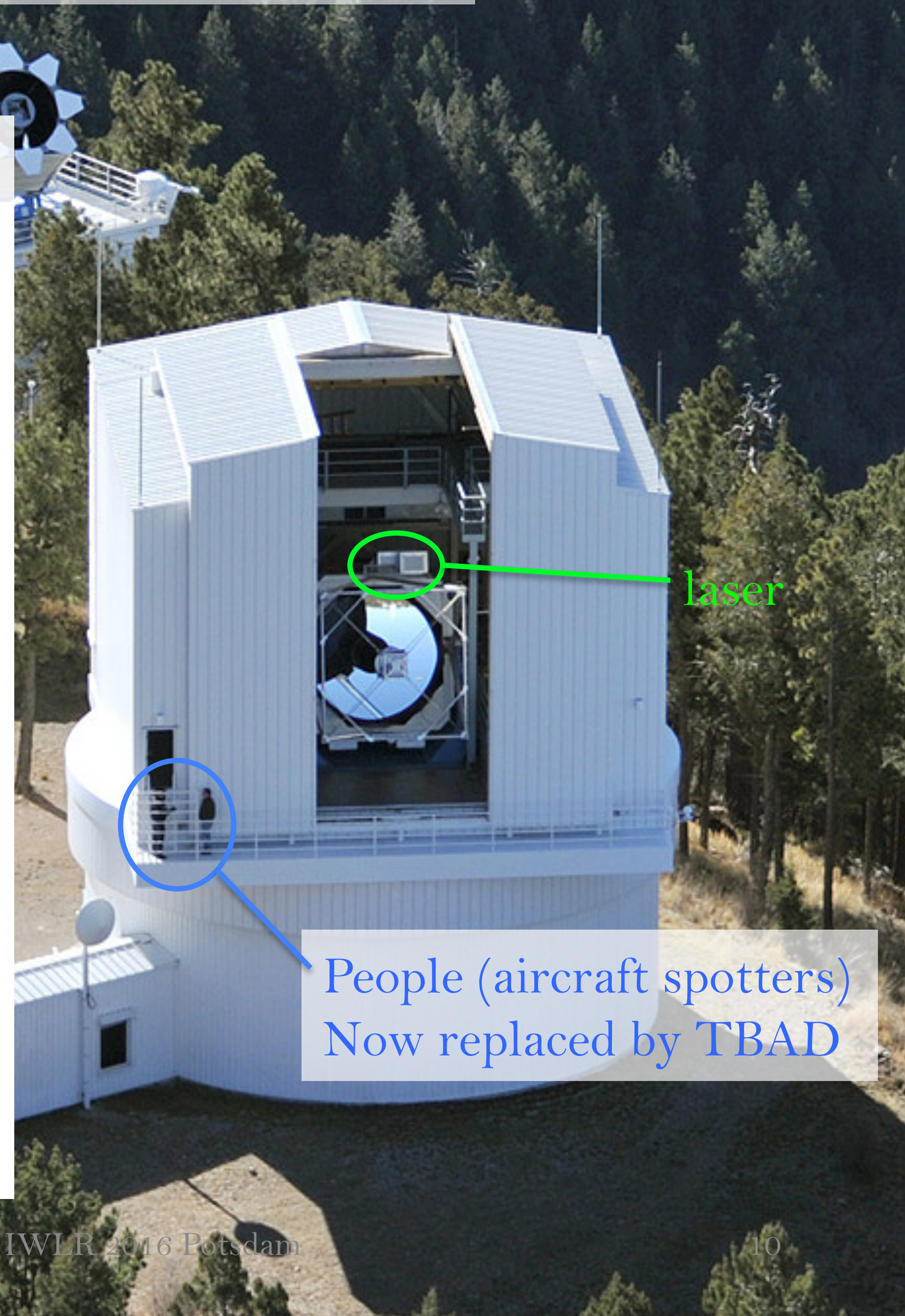
APOLLO: the Earth end

Transponder-Based Aircraft Detector



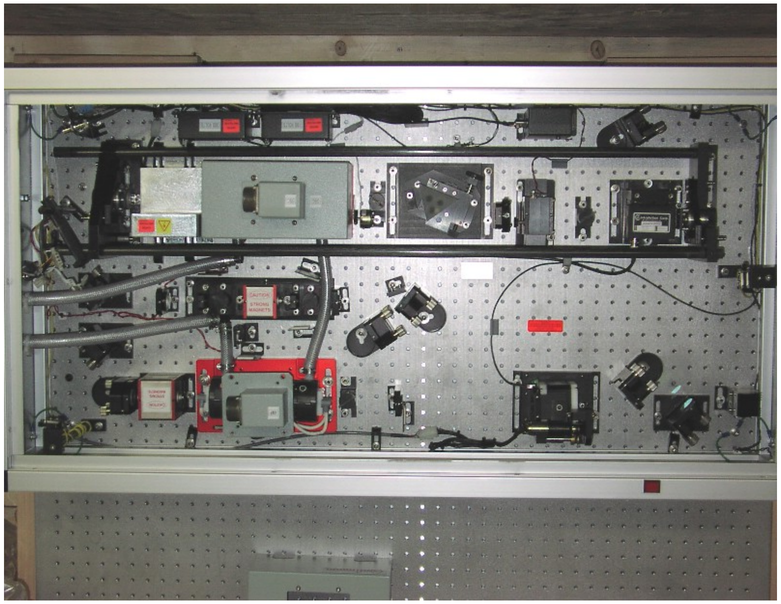
Coles, Murphy et al., PASP 124 (2012)
arXiv:0910.5685

FIG. 7.—The antenna array mounted on the sky-facing side of the secondary mirror support structure on the APO 3.5 m telescope. The electronics box with white labels visible below the antenna plate contains the RF electronics, and consumes only 3 W of power.See the electronic edition of the *PASP* for a color version of this figure.

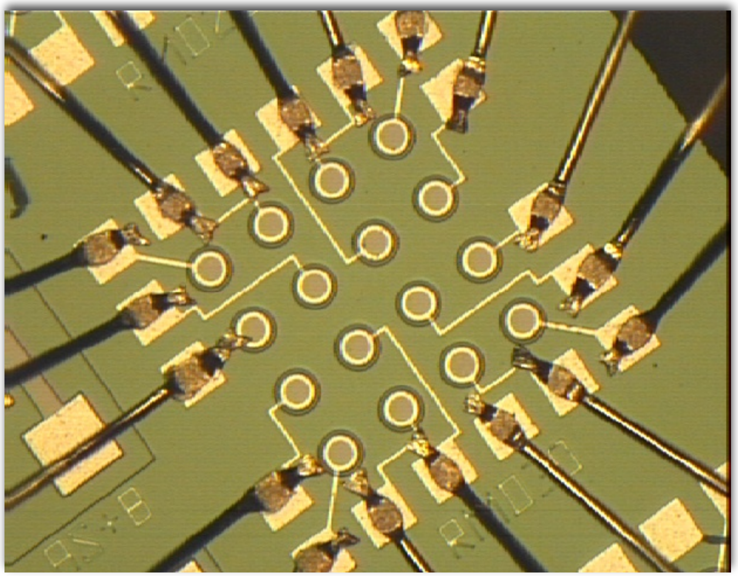


APOLLO: Instrument

T. Murphy et al. PASP 120:20-37 (2008) [arXiv:0710.0890]

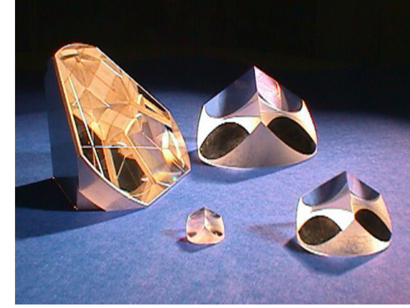


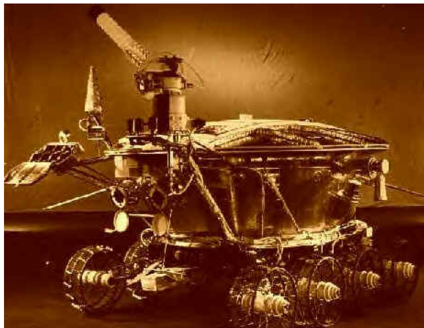
- Laser:
  - 532 nm Nd:YAG, mode-locked, cavity-dumped
  - 90 ps pulse width
  - 115 mJ per pulse
  - 20 Hz repetition rate
  - 2.3 W average power



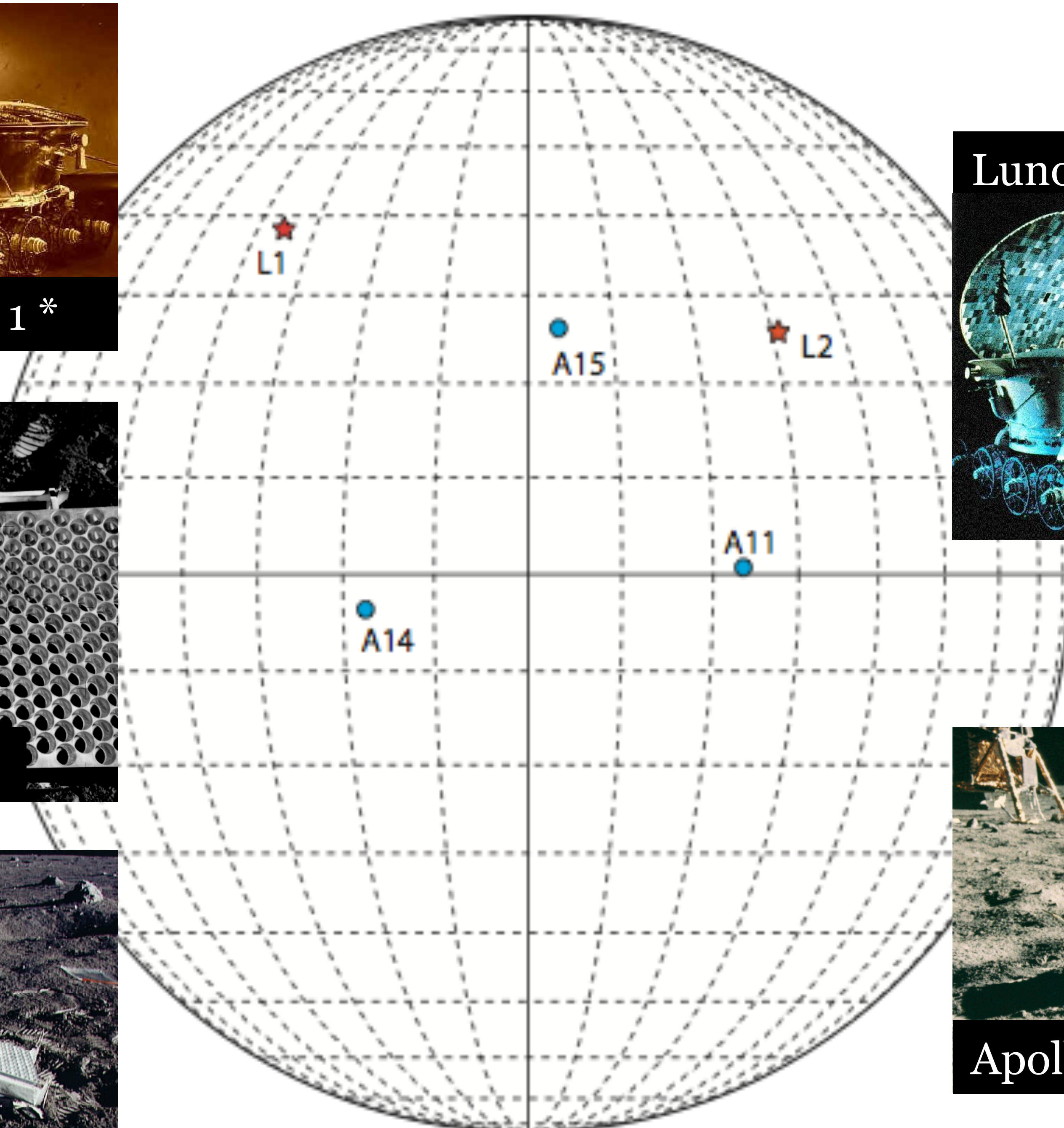
- Detector: Silicon APD Array
  - 4×4 made by Lincoln Laboratory
  - 30 µm elements, 100 µm centers
  - lenslet array recovers fill-factor
  - 1.4 arcsec on a side (0.35 arcsec/element)
  - allows multi-photon returns
  - permits real-time tracking

The Moon end

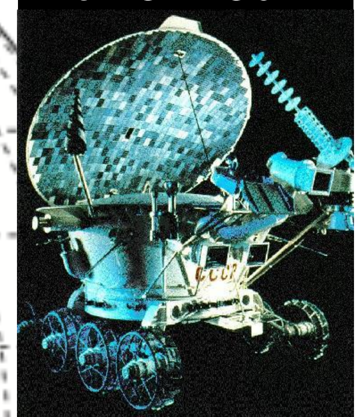


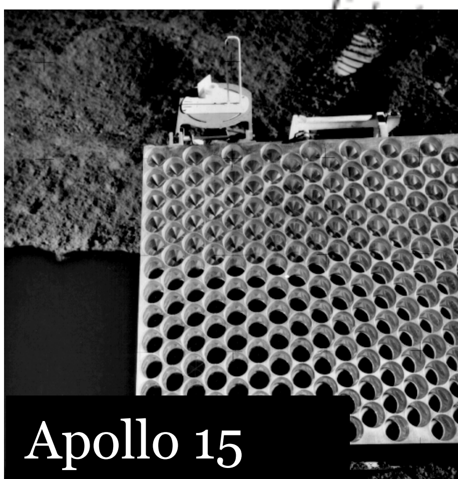


Lunokhod 1 *



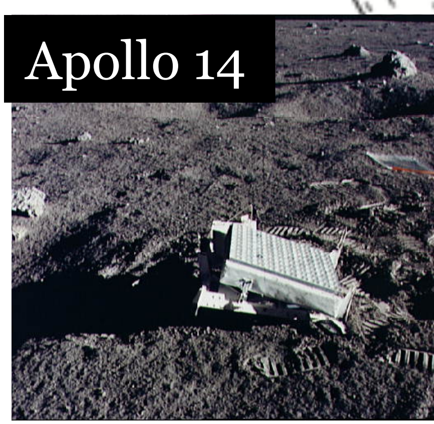
Lunokhod

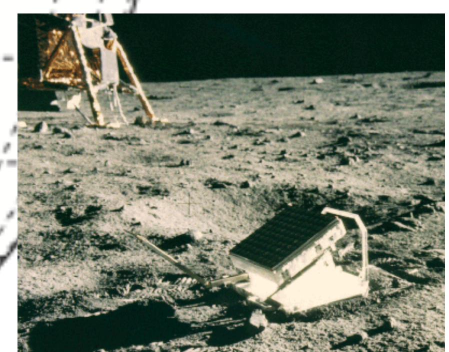




Apollo 15

Apollo 14



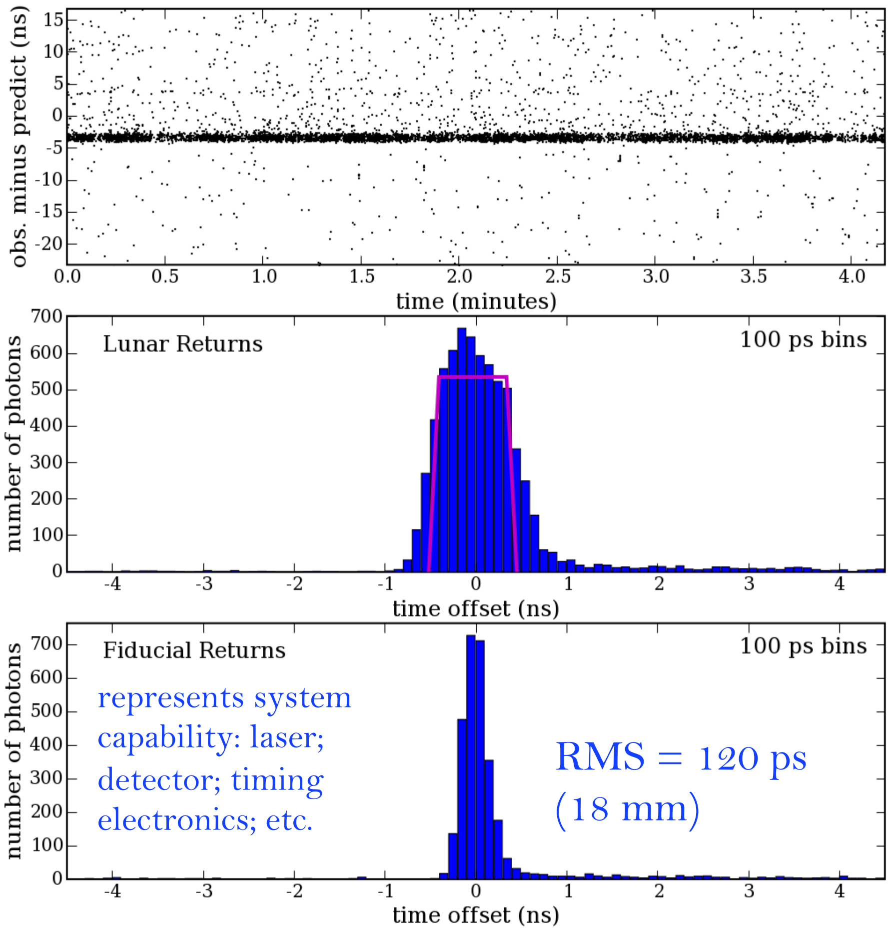


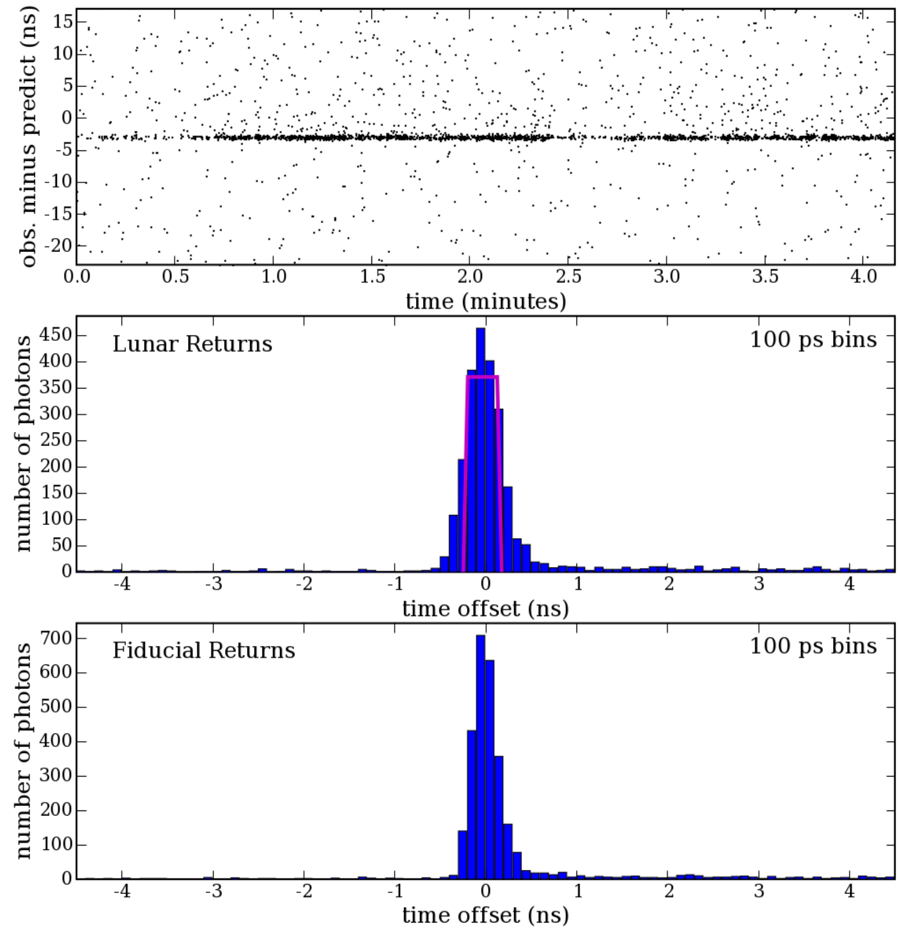
Apollo 11

APOLLO Example Data

Apollo 15 2007.11.19 Apollo 11

magenta curves are theoretical profiles: convolve with fiducial to make lunar return

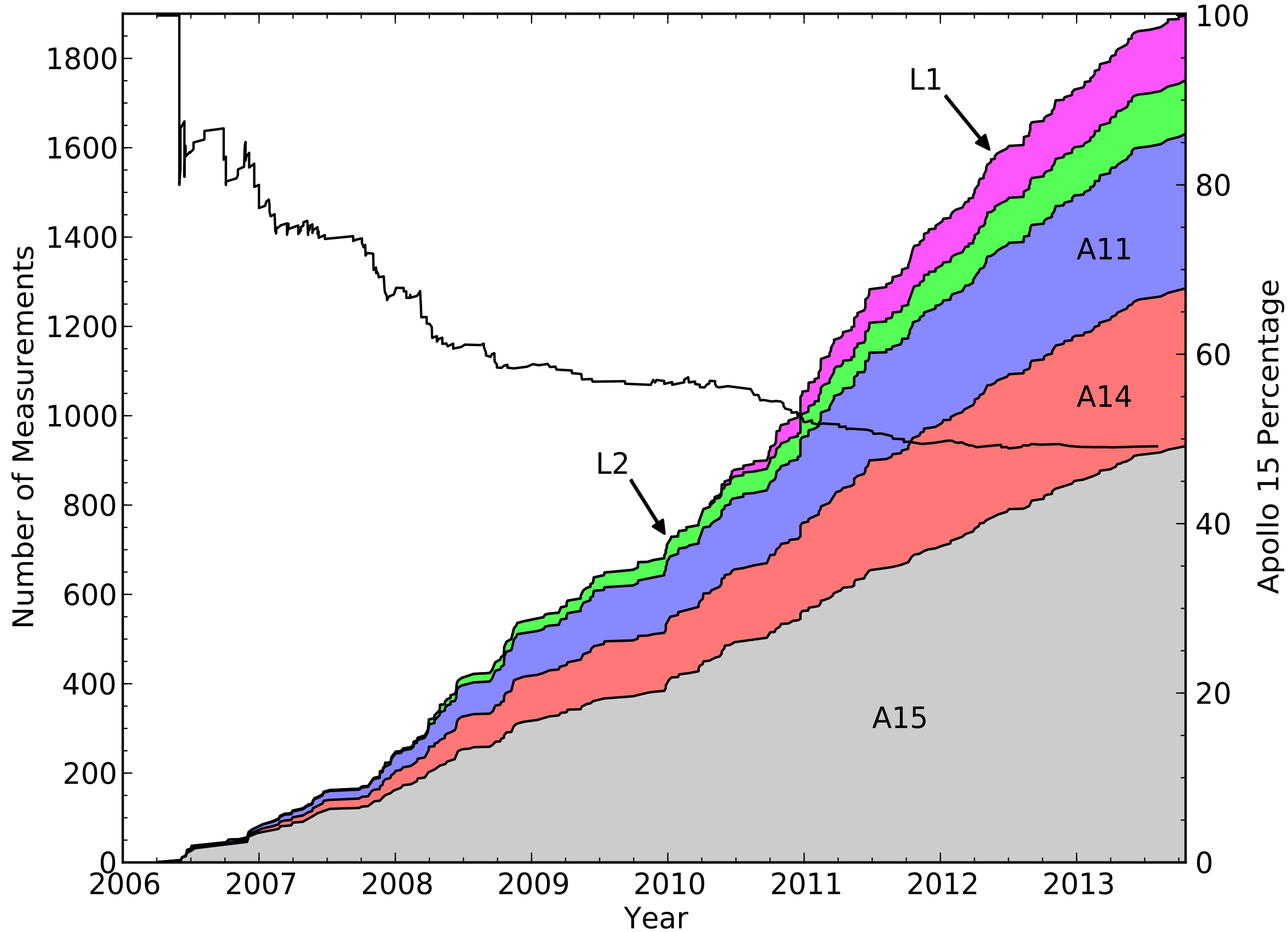




- 6624 photons in 5000 shots
- 369,840,578,287.4 ± 0.8 mm
- 4 detections with 10 photons

- 2344 photons in 5000 shots
- 369,817,674,951.1 ± 0.7 mm
- 1 detection with 8 photons

APOLLO Data & Precision



* Ranging to all five reflectors (re-discovered L1 in 2010)
* Less reliance on A15 over time.
* Median nightly range error is 1.4mm

Quantify system timing *accuracy*

Comparison with lunar range models

- But… residuals of few-cm RMS
- Models under active development
  (see e.g. talks in this session, + JPL & PEP)

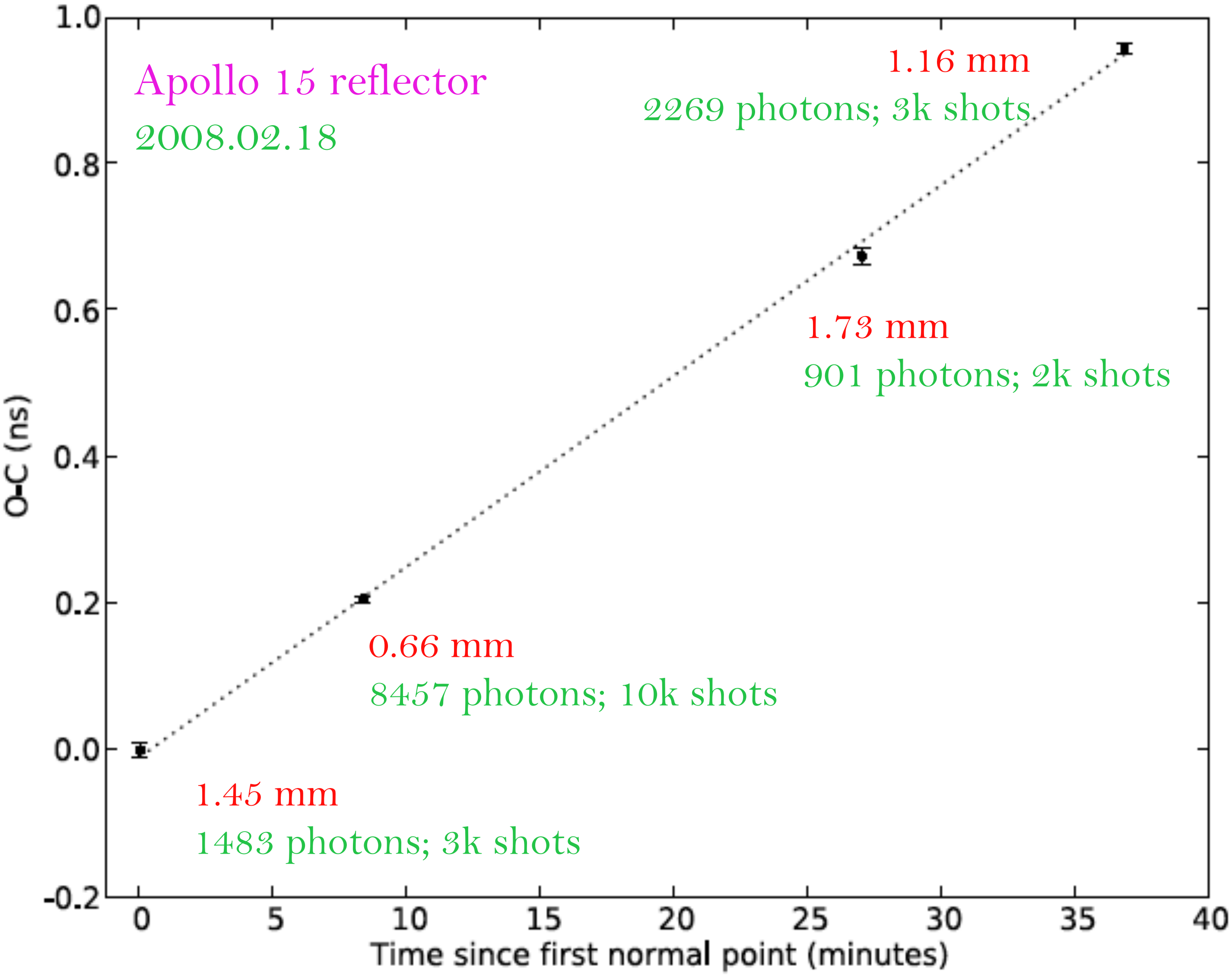
Few (but positive) internal APOLLO tests

- In a single night, NP scatter (about linear trend) consistent with quoted statistical uncertainties. Linear trend consistent with single change in site location.
  Battat, PASP 121:29-40 (2009)

- Ranging to ≥ 3 reflectors in a session constrains lunar orientation, which builds confidence in NP uncertainty

(as described at previous IWLR meetings by Tom Murphy)

Compare segments over ~0.5 hr



We can get 1 mm range precision in single "runs" (< 10 minutes)

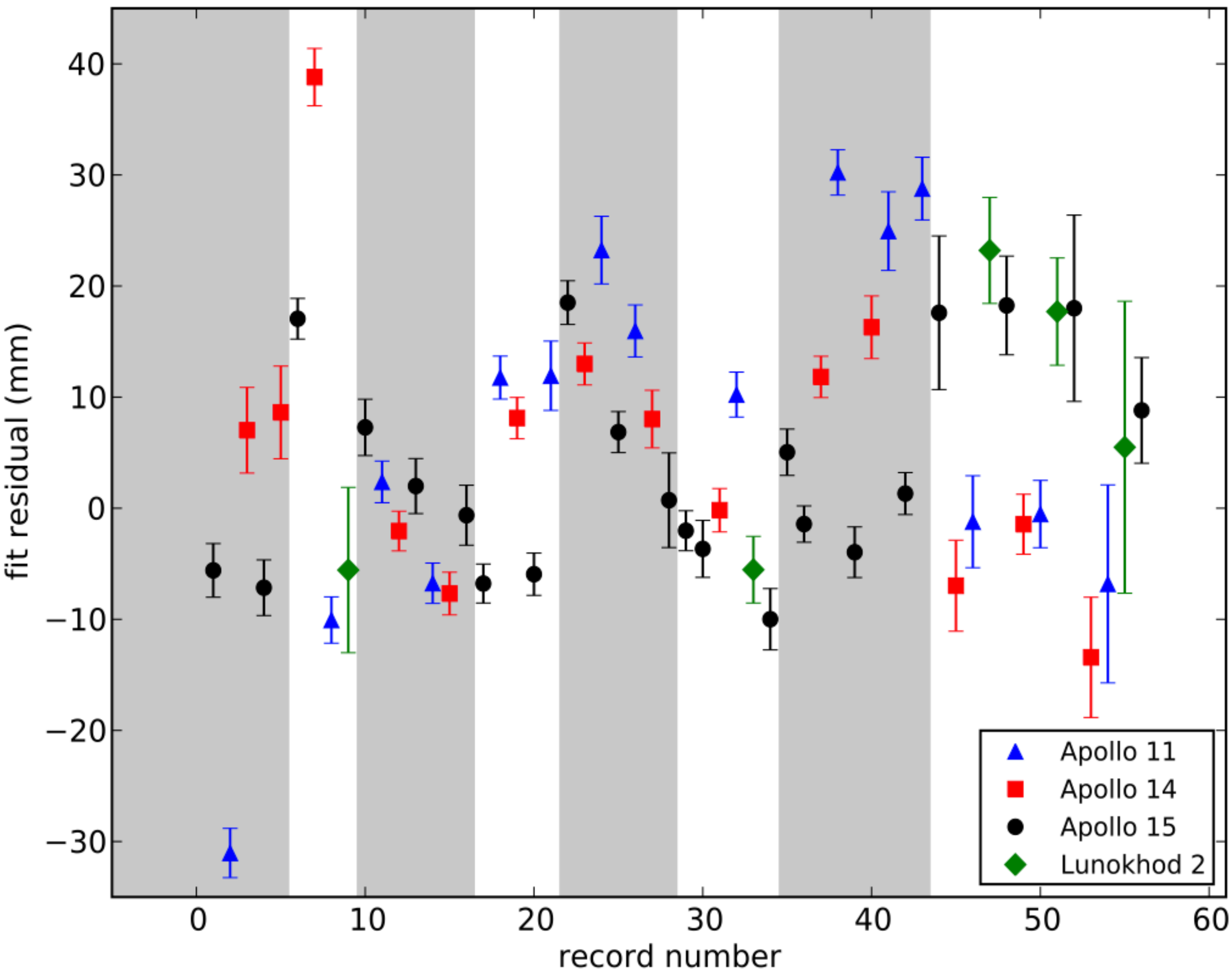
The scatter about a linear fit is small: consistent with estimated random error (true for all nights studied this way)

0.5 mm effective data point for Apollo 15 reflector on this night

J. Battat et al. PASP 121:29-40 (2009)

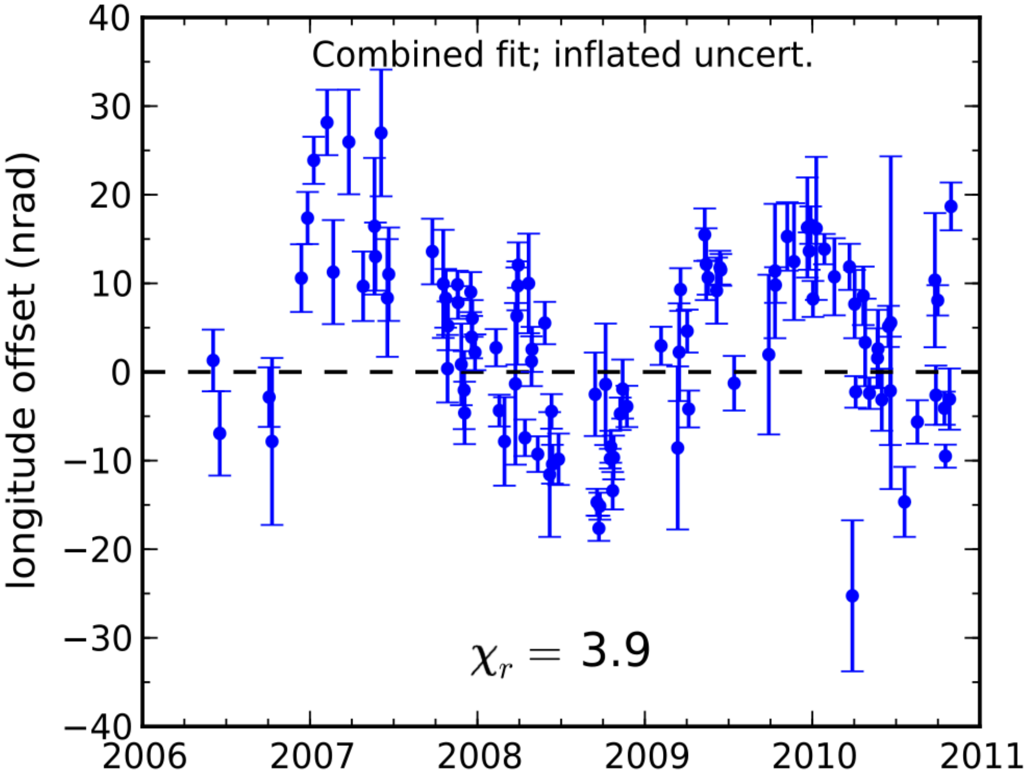
Constraining lunar libration

Residuals if APOLLO data downweighted by 15mm RSS

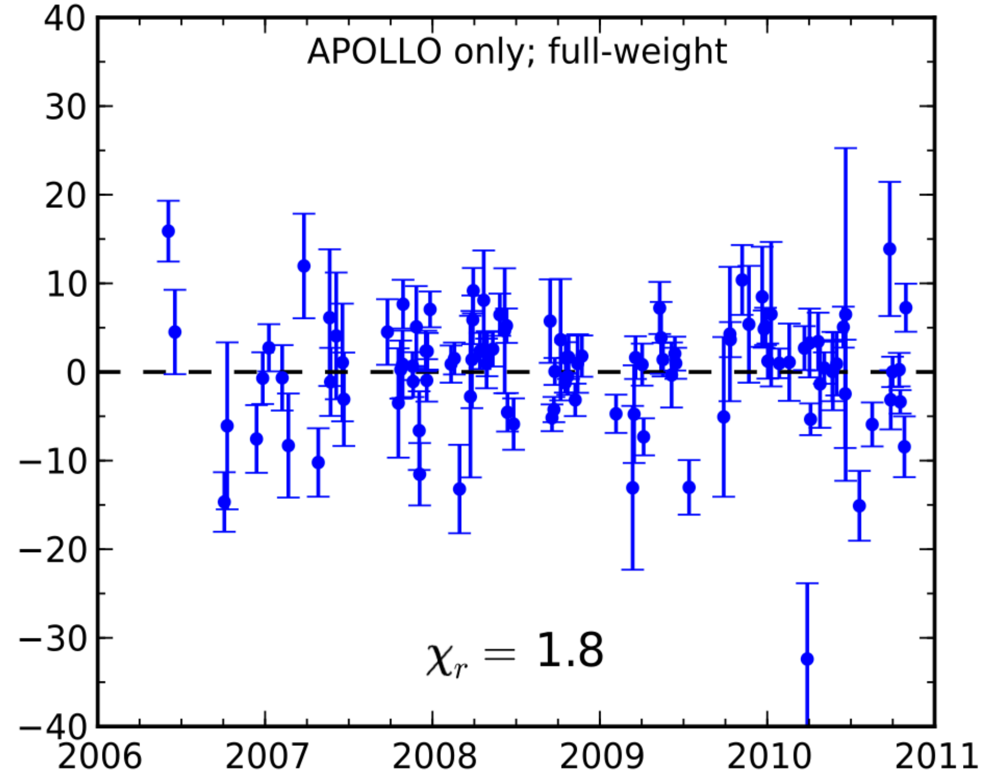


Constraining lunar libration

When ≥ 3 reflectors, estimate ad-hoc libration correction per night



APOLLO data down-weighted by 15mm RSS. Large, unmodeled libration is indicated.



APOLLO data at full weight largely eliminates the libration offset.

1 nrad is 1.7 mm lateral motion on lunar surface

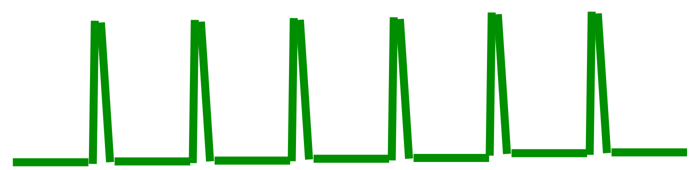
Absolute Calibration System

- Measure timing of short calibration laser pulses inserted at a known, stable rate
- Simultaneous with lunar ranging

An "optical ruler" overlaid on data.

Cs Frequency Standard
Microsemi 5071A
df/f ~ 10^{-12}

Fiber Laser
Toptica
PicoFYb
80 MHz



12.5 ns period
< 10ps pulse width

Laser locked to Cs with sub-ps jitter.

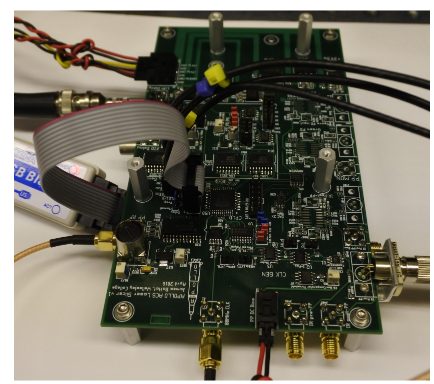
Absolute Calibration System

- Phase 1: Clock comparison: Cs vs. GPS

  Installed February 2016

- Phase 2: Laser (ranging with the ACS on)

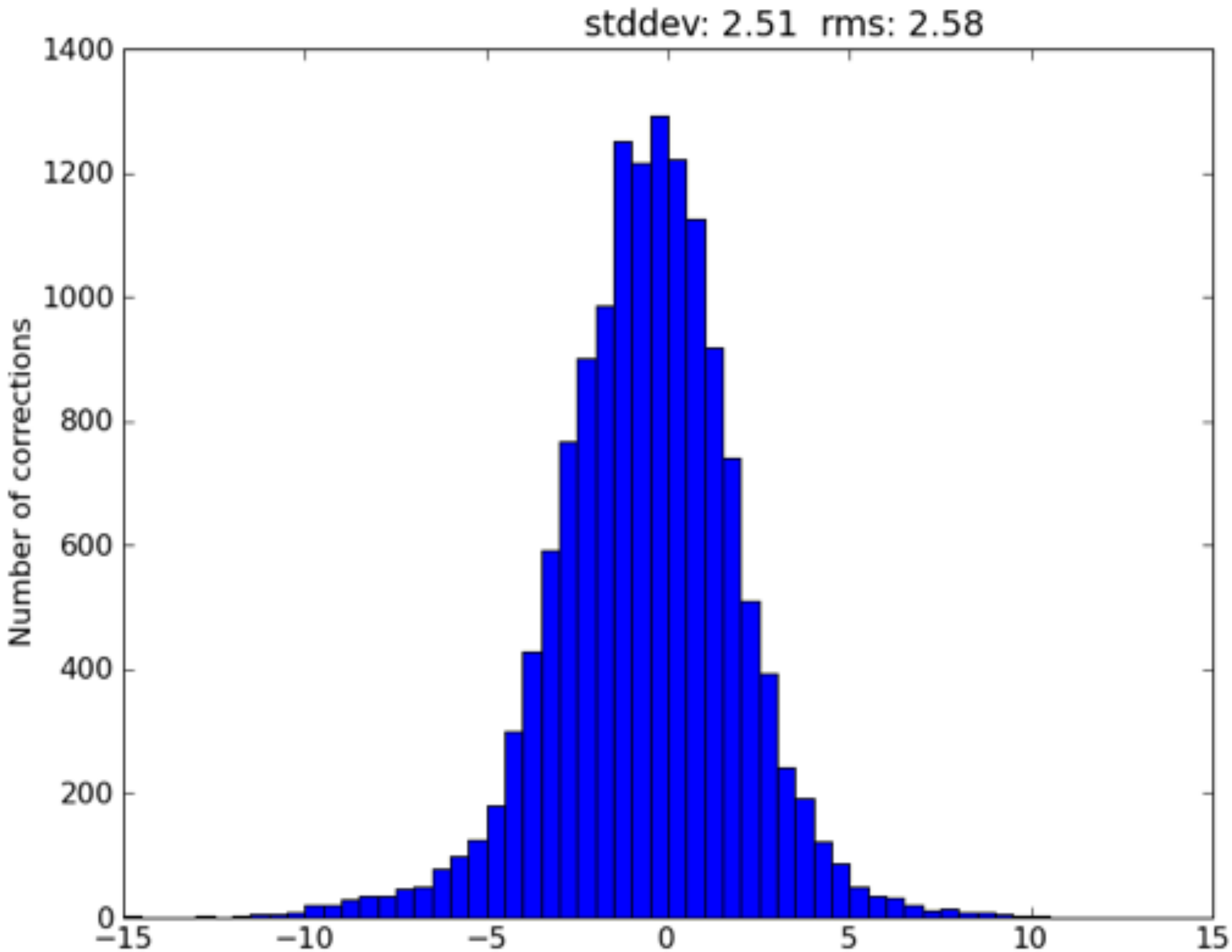
  Installed August 2016



"Laser Slicer Board"

Phase 1: Clock installation (Feb. 2016)

Measure GPS clock offsets



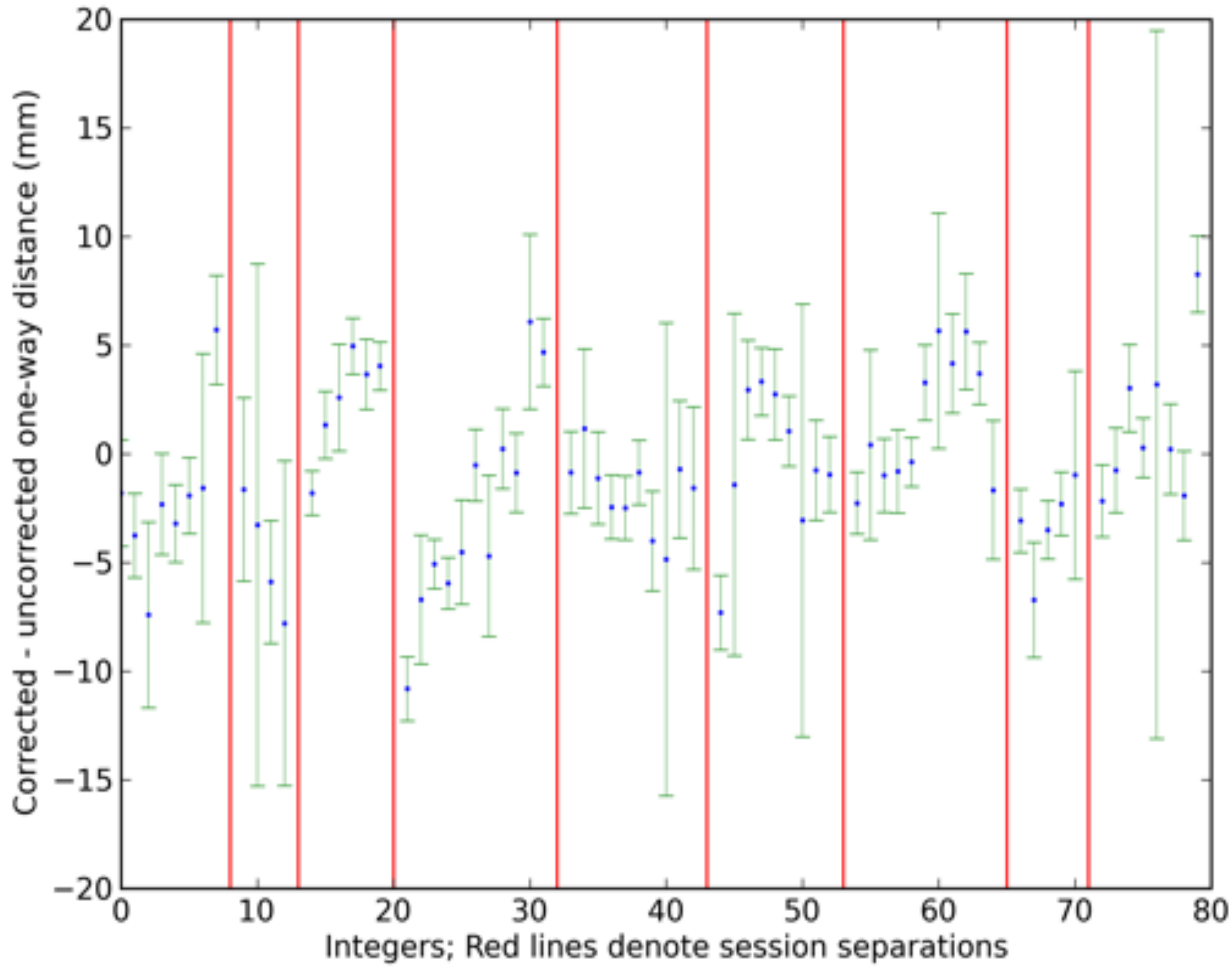
GPS clock offset [mm one-way lunar range]

From frequency difference between Cs and GPS clocks (measured by UC)

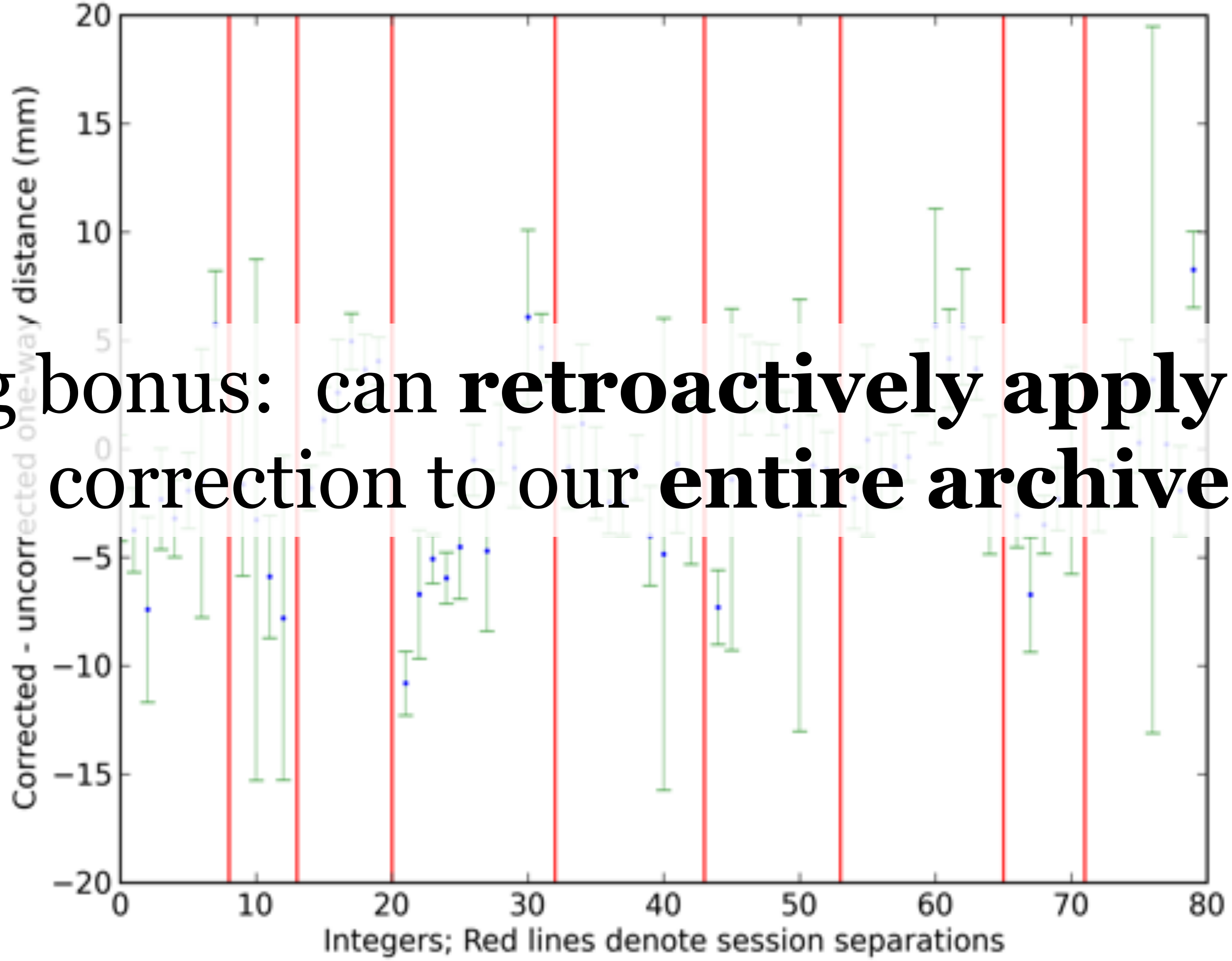
GPS clock offsets equivalent to ~2.5mm added in quadrature to the raw range precision

APOLLO NPs already included 1.4mm in quadrature as an estimate of this

Correct for GPS clock offsets

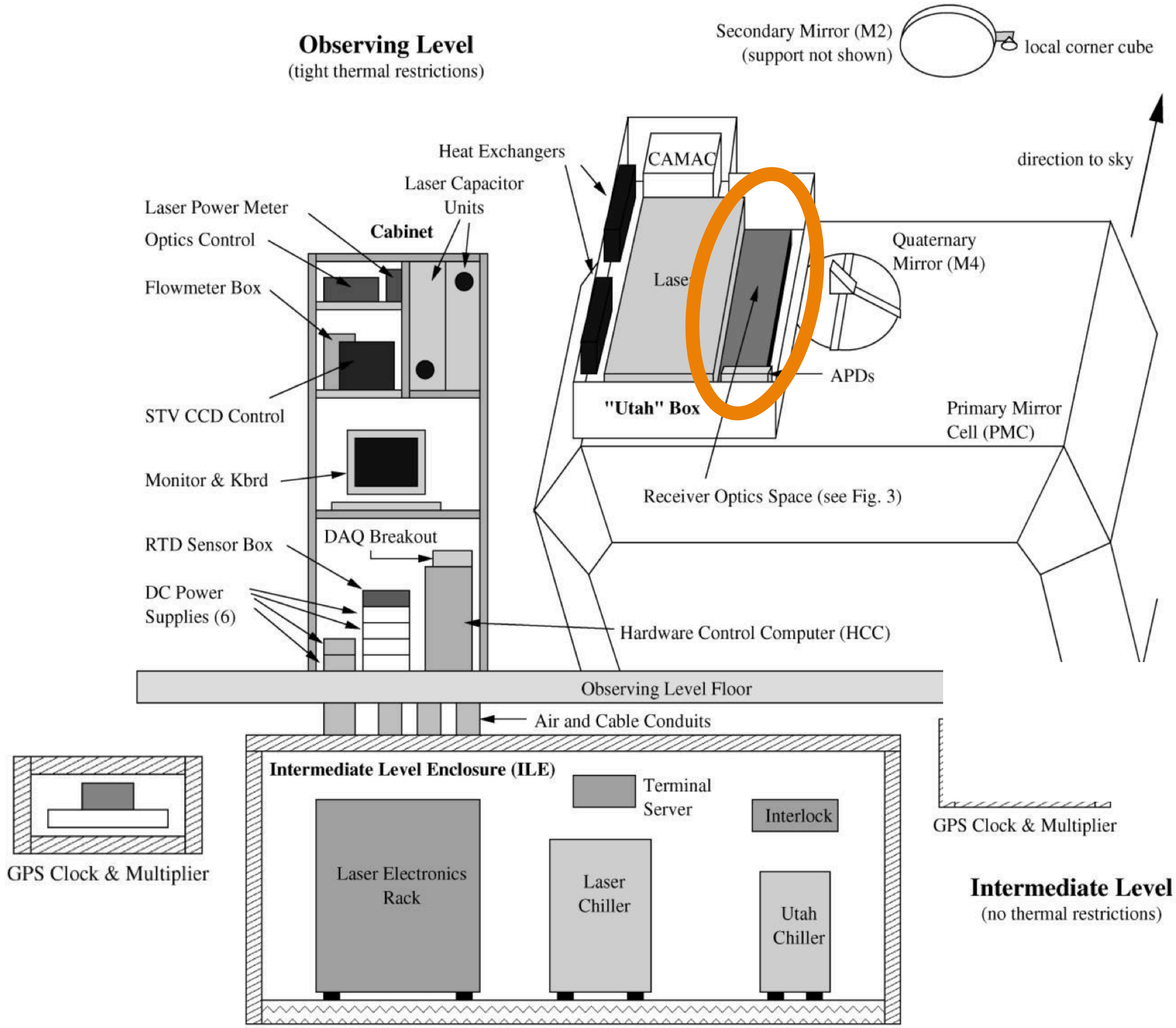


Correct for GPS clock offsets

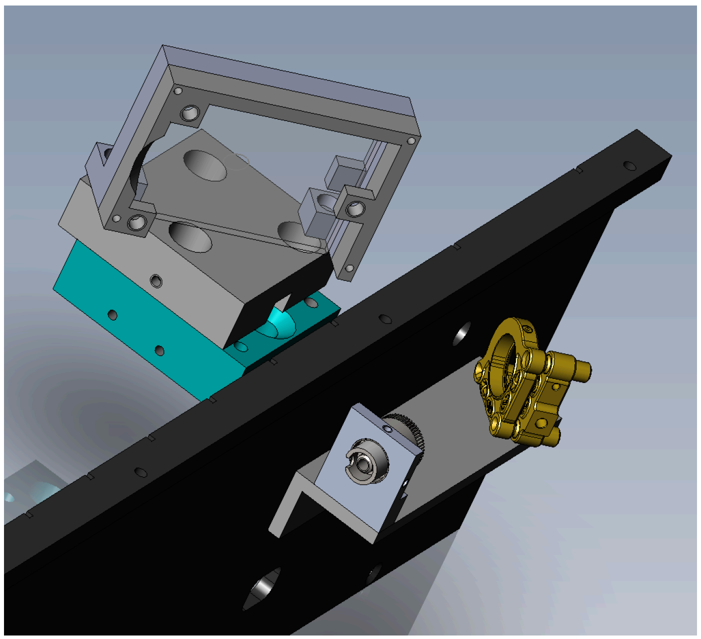


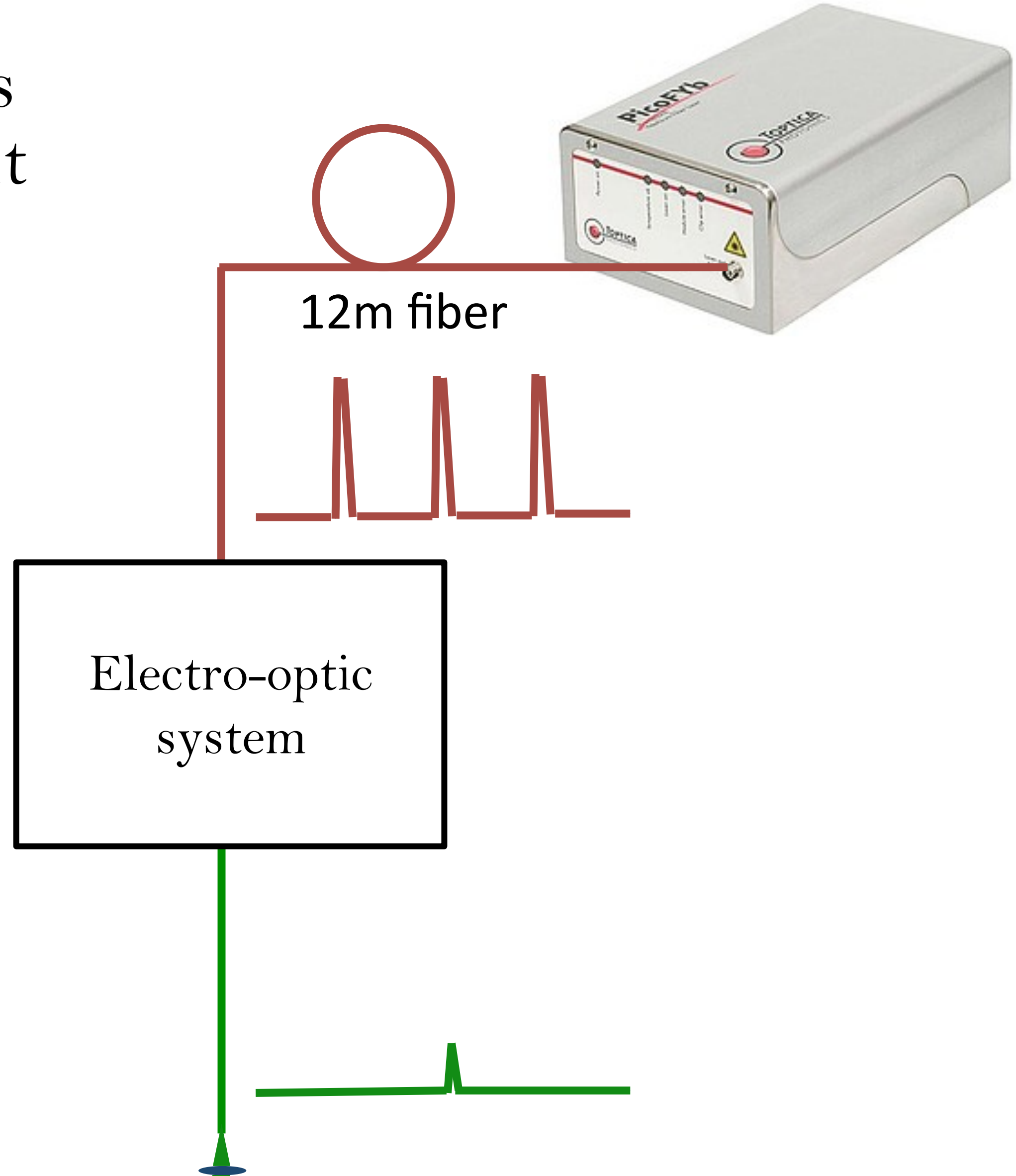
Big bonus: can **retroactively apply** this correction to our **entire archive**

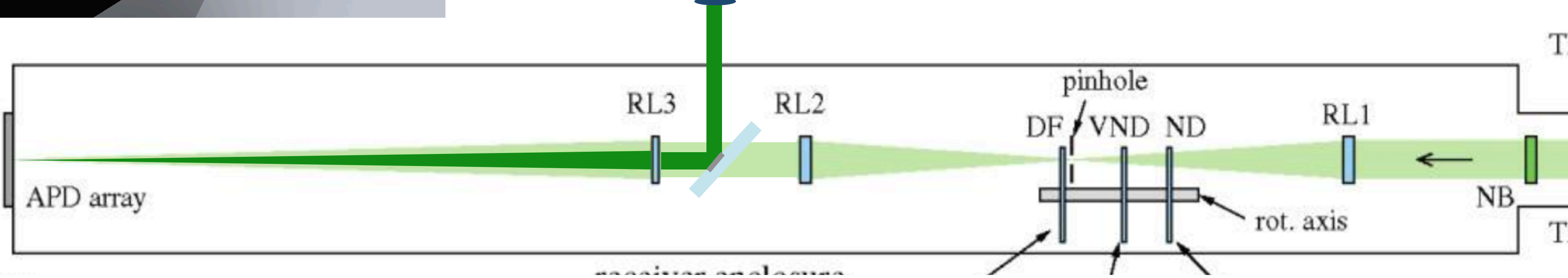
Phase 2: Laser + Electronics installation (August 2016)

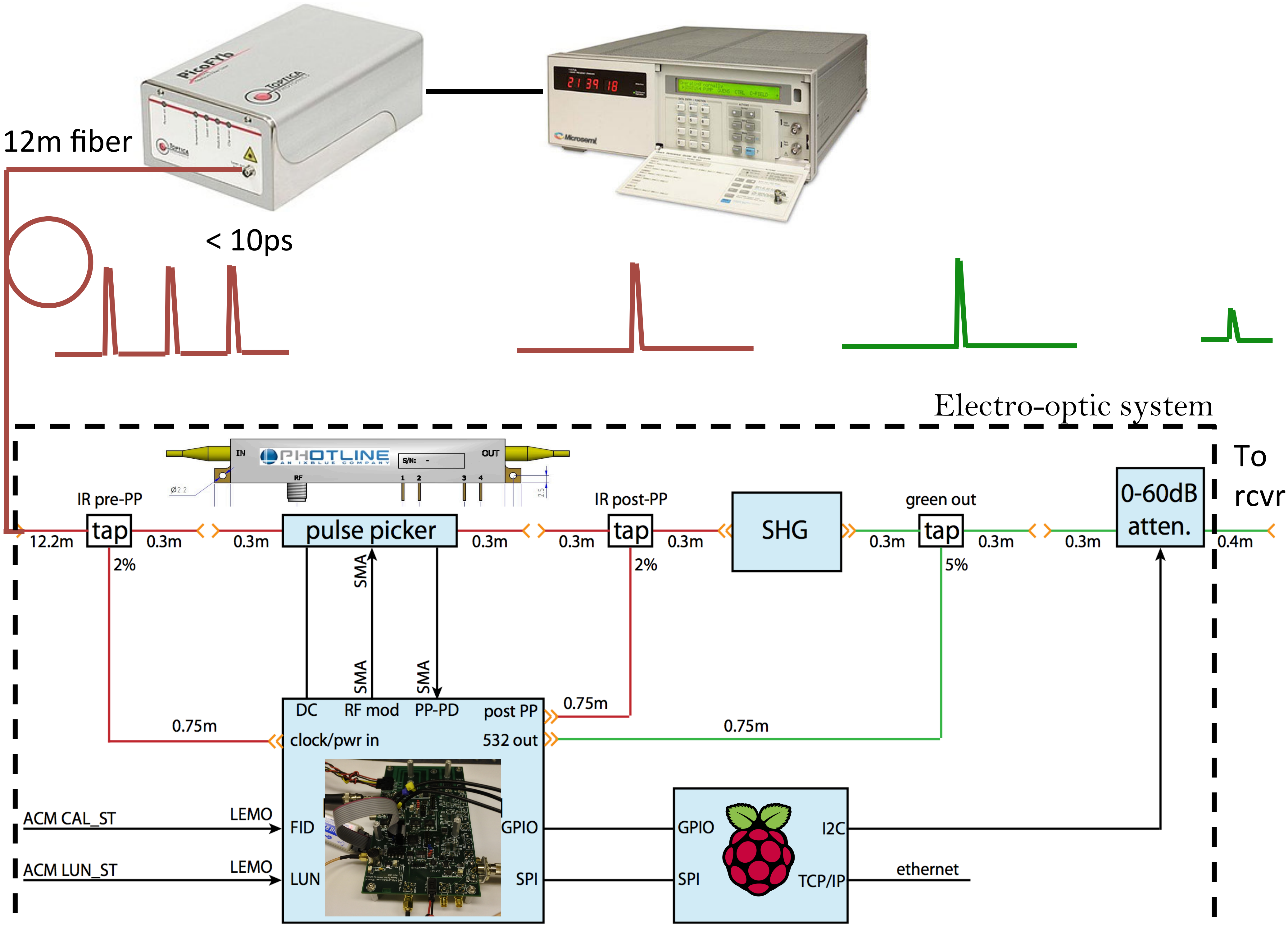


Couple calibration photons into optical system without disruption to lunar ranging (45-deg mirror patch in shadow of secondary mirror)

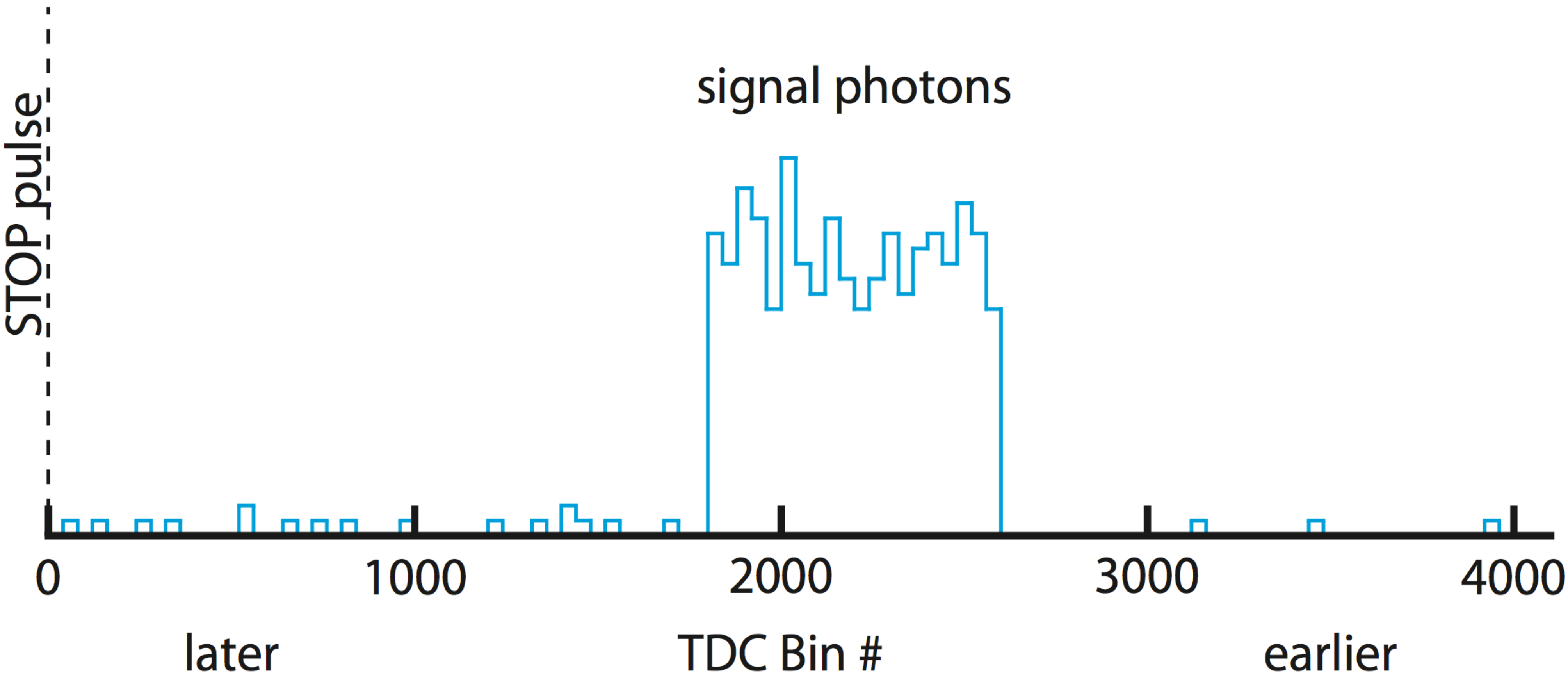






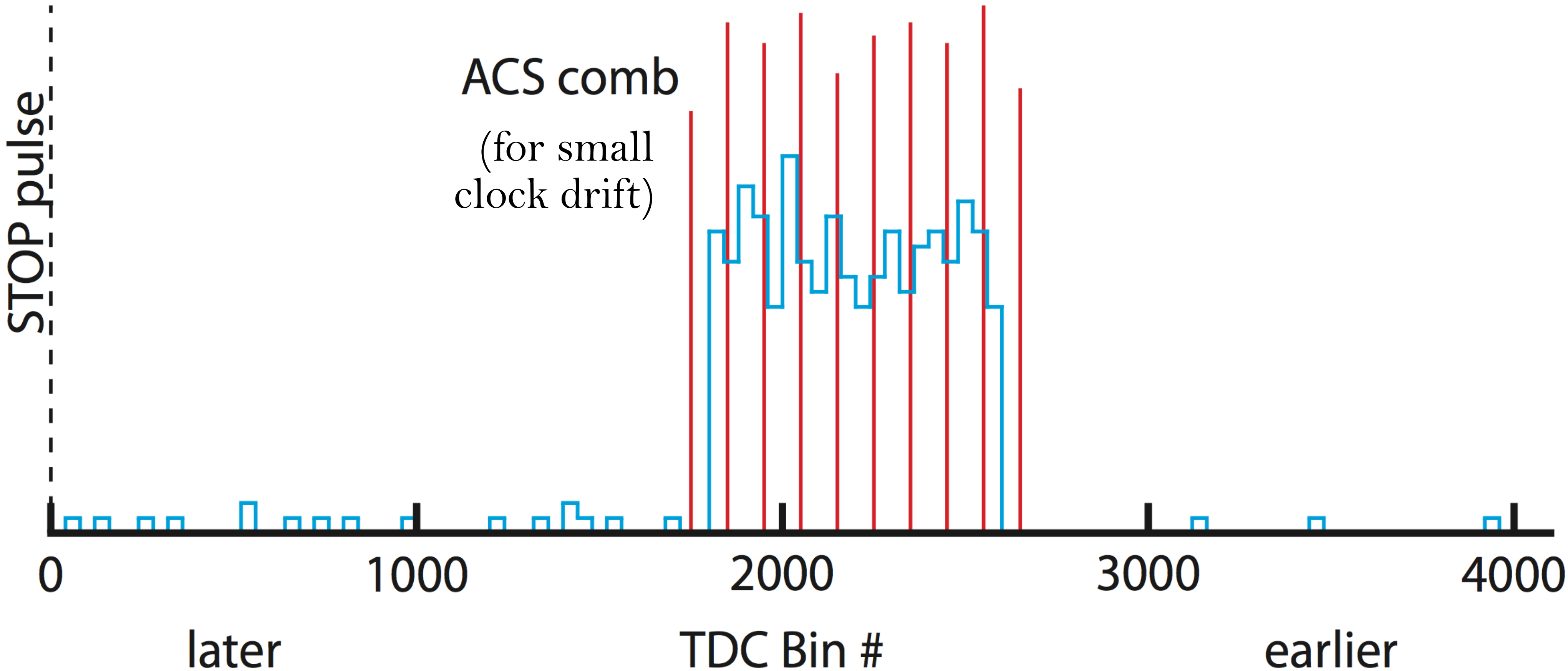

12m fiber
< 10ps
PicoFYb
Electro-optic system
To
rcvr
PHOTLINE
IN
OUT
RF
IR pre-PP
tap
12.2m
0.3m
2%
0.3m
pulse picker
0.3m
SMA
SMA
SMA
0.3m
IR post-PP
tap
0.3m
2%
SHG
0.3m
green out
tap
0.3m
5%
0.3m
0-60dB
atten.
0.4m
DC
RF mod
PP-PD
post PP
0.75m
0.75m
clock/pwr in
532 out
0.75m
ACM CAL_ST
LEMO
FID
GPIO
ACM LUN_ST
LEMO
LUN
SPI
GPIO
I2C
SPI
TCP/IP
ethernet

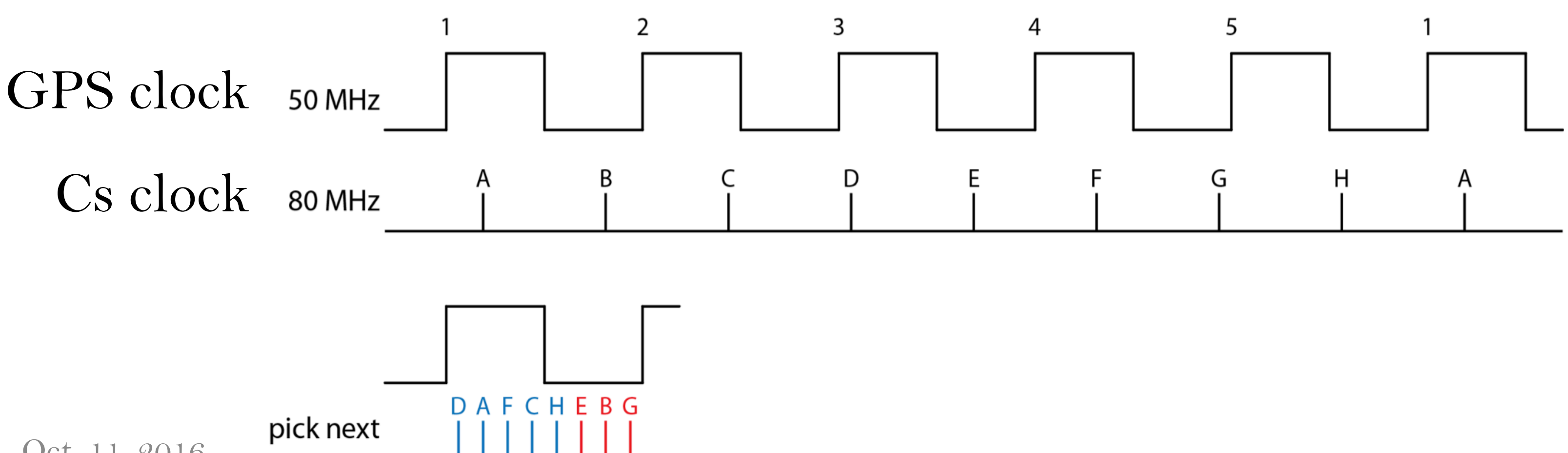
Lunar return distribution



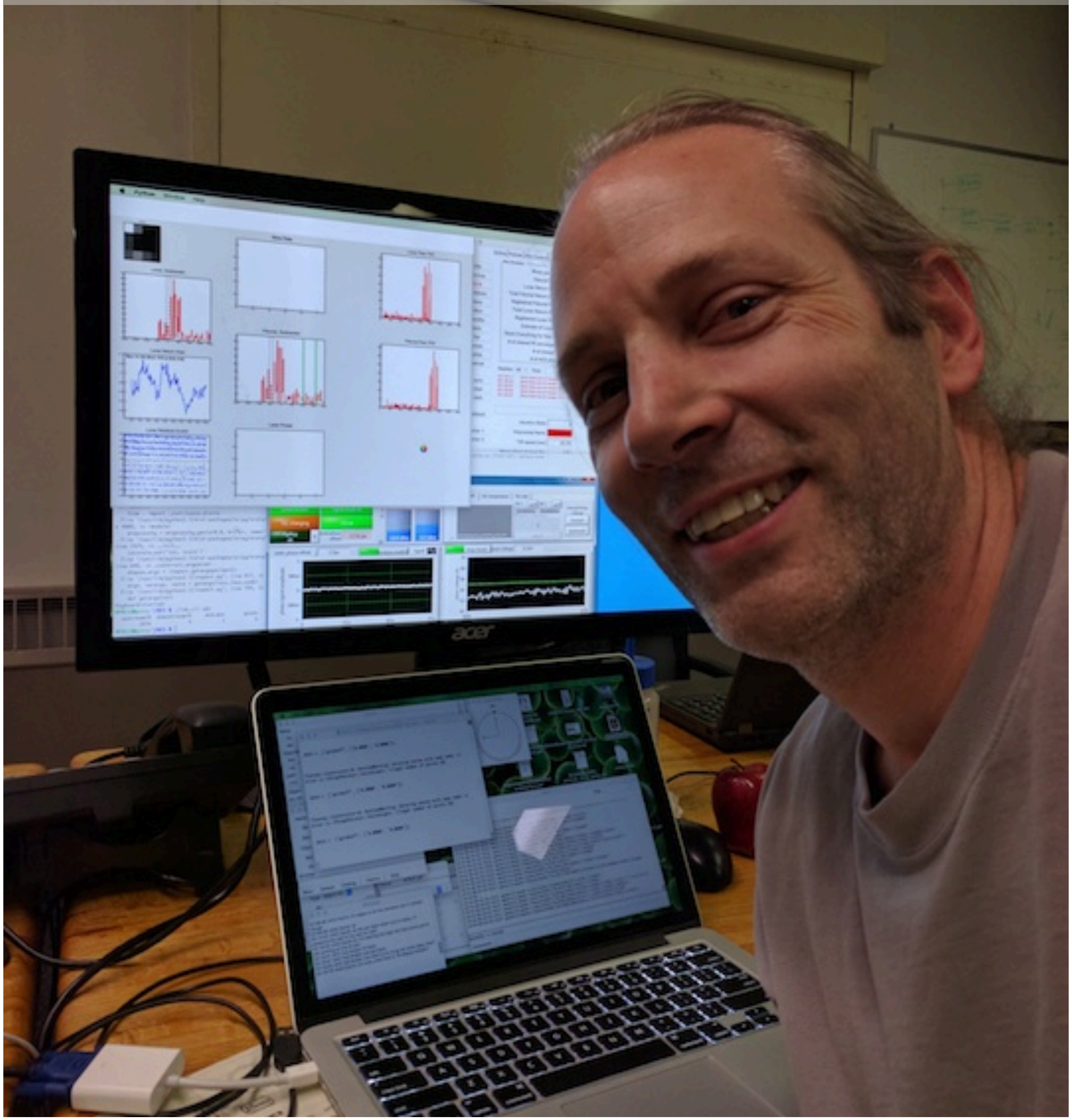
Lunar returns are not synchronous with our 50 MHz system clock
Uniformly populate a 20ns-wide range of our timing space.
TDC = time-to-digital converter. 4096 channels, 100ns range: 25ps/bin

ACS: an optical ruler

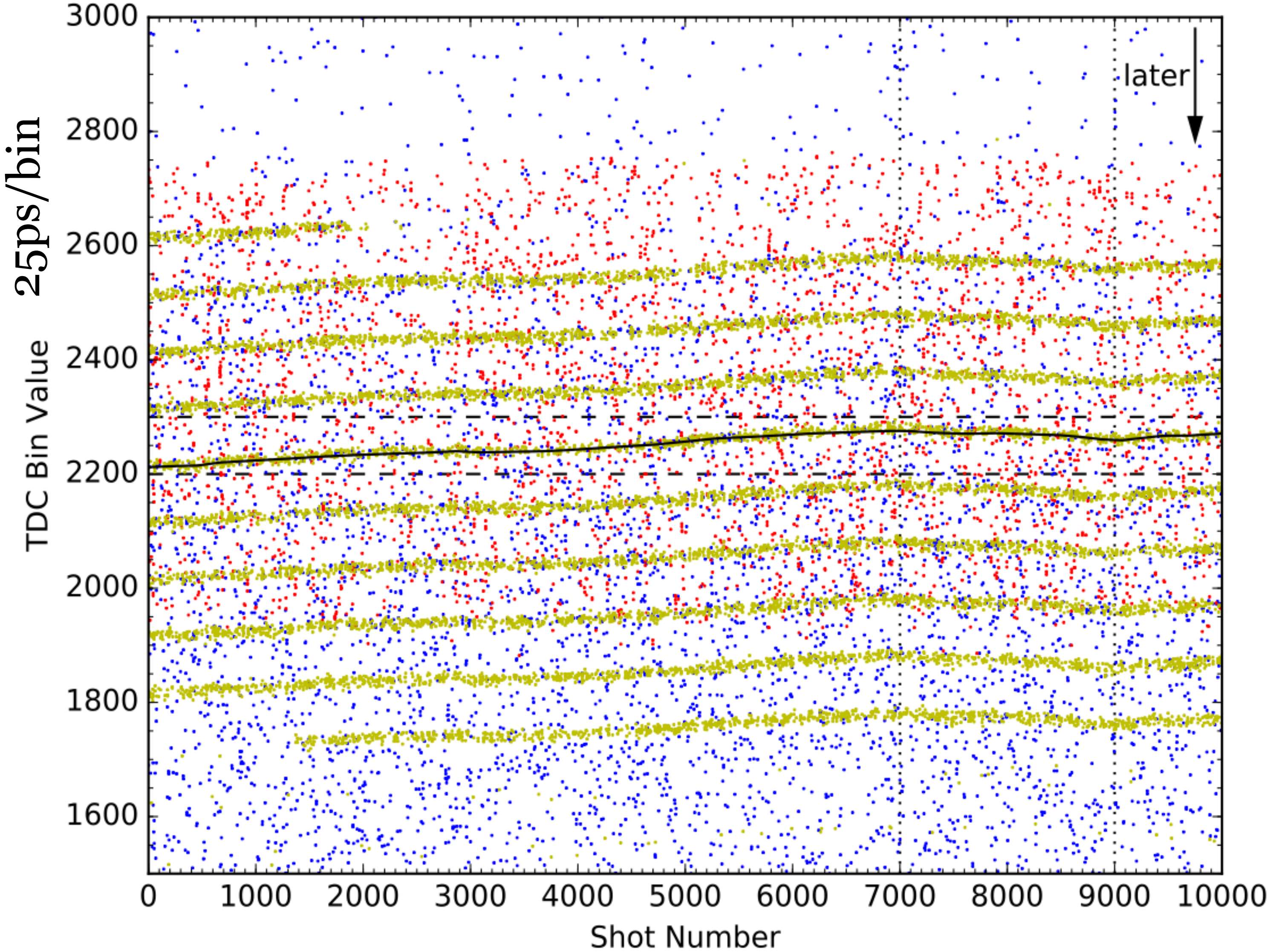




First comb 2016.08.03



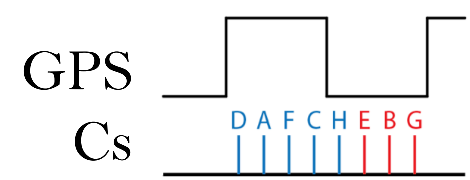
ACS Observations atop Lunar Returns 2016.09.12



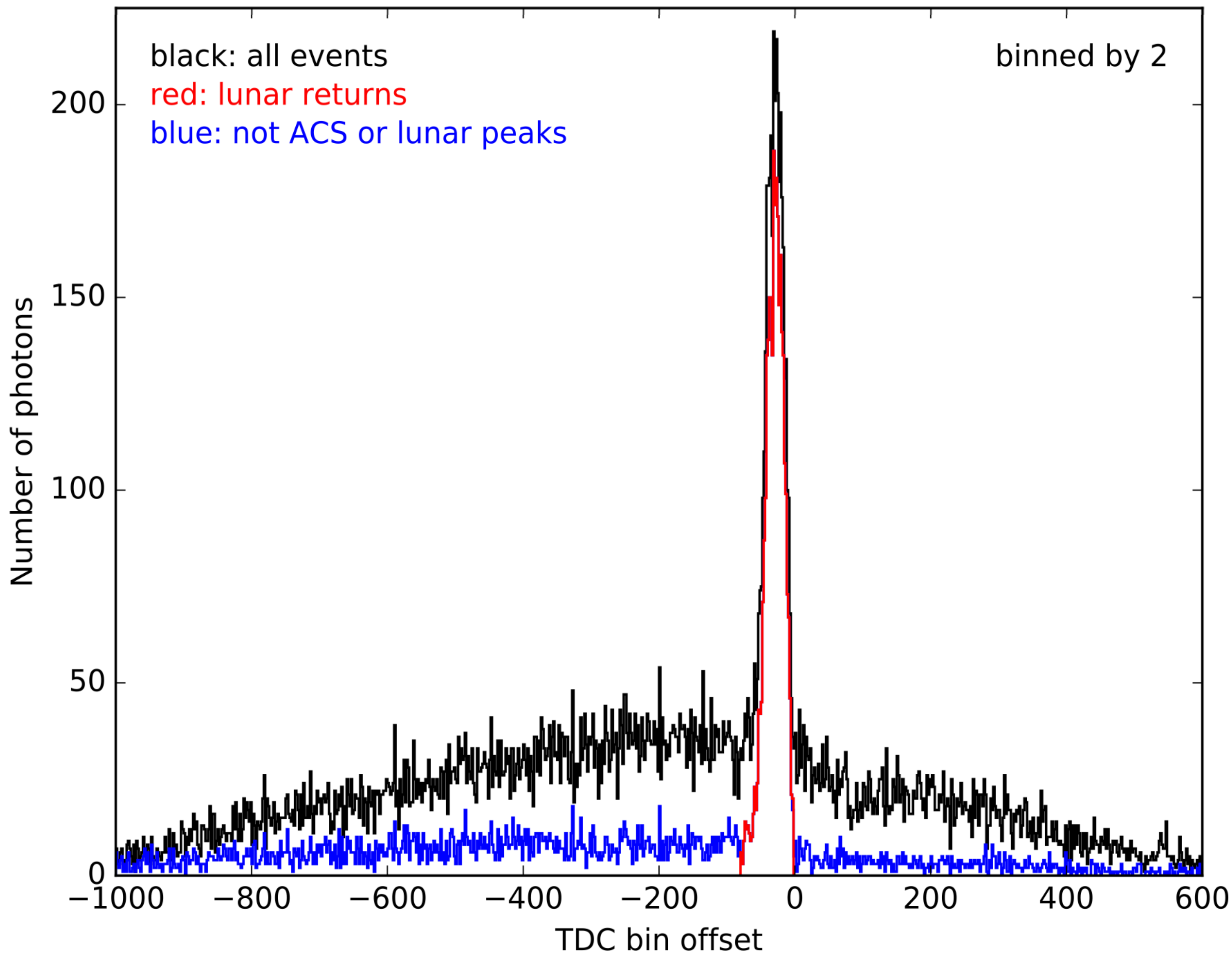
Total shots 10k
ACS photons (11k)
Lunar returns (3k)
Neither (bkg)
– clock comparison

Can tag ACS photons very efficiently even when overlaid with Lunar returns.

Use knowledge of ACS phase relative to GPS



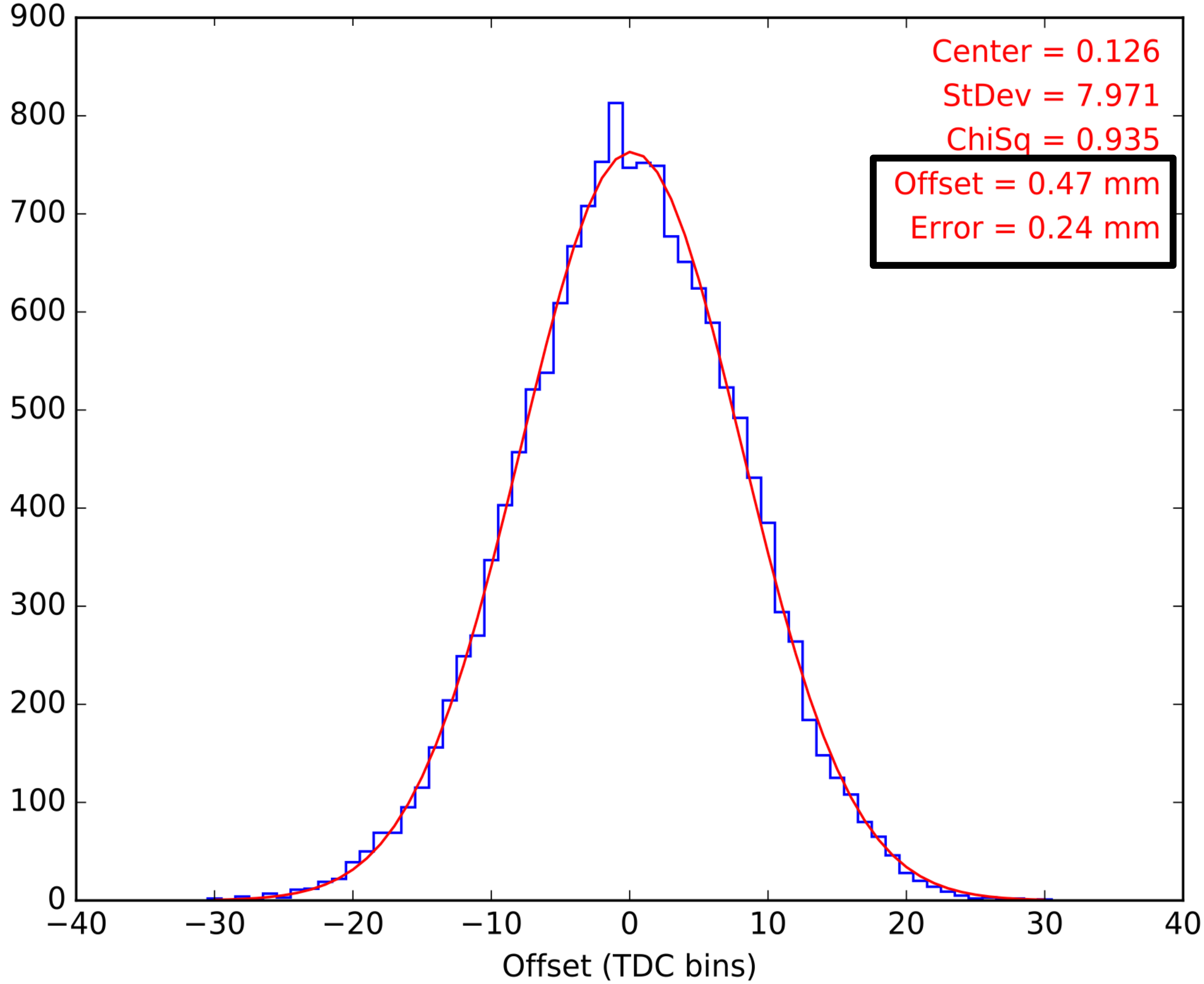
ACS Observations atop Lunar Returns 2016.09.12



All events
Lunar returns
Neither (bkg)

Clear Lunar signal (3k photons in 10k shots), even amid heavy ACS rate (11k photons in 10k shots)

Measure Δt of ACS for "transmit" and "receive" gates. Compare with N*12.500000 ns



Find ~mm timing accuracy (in-situ, simultaneous with LLR observations)

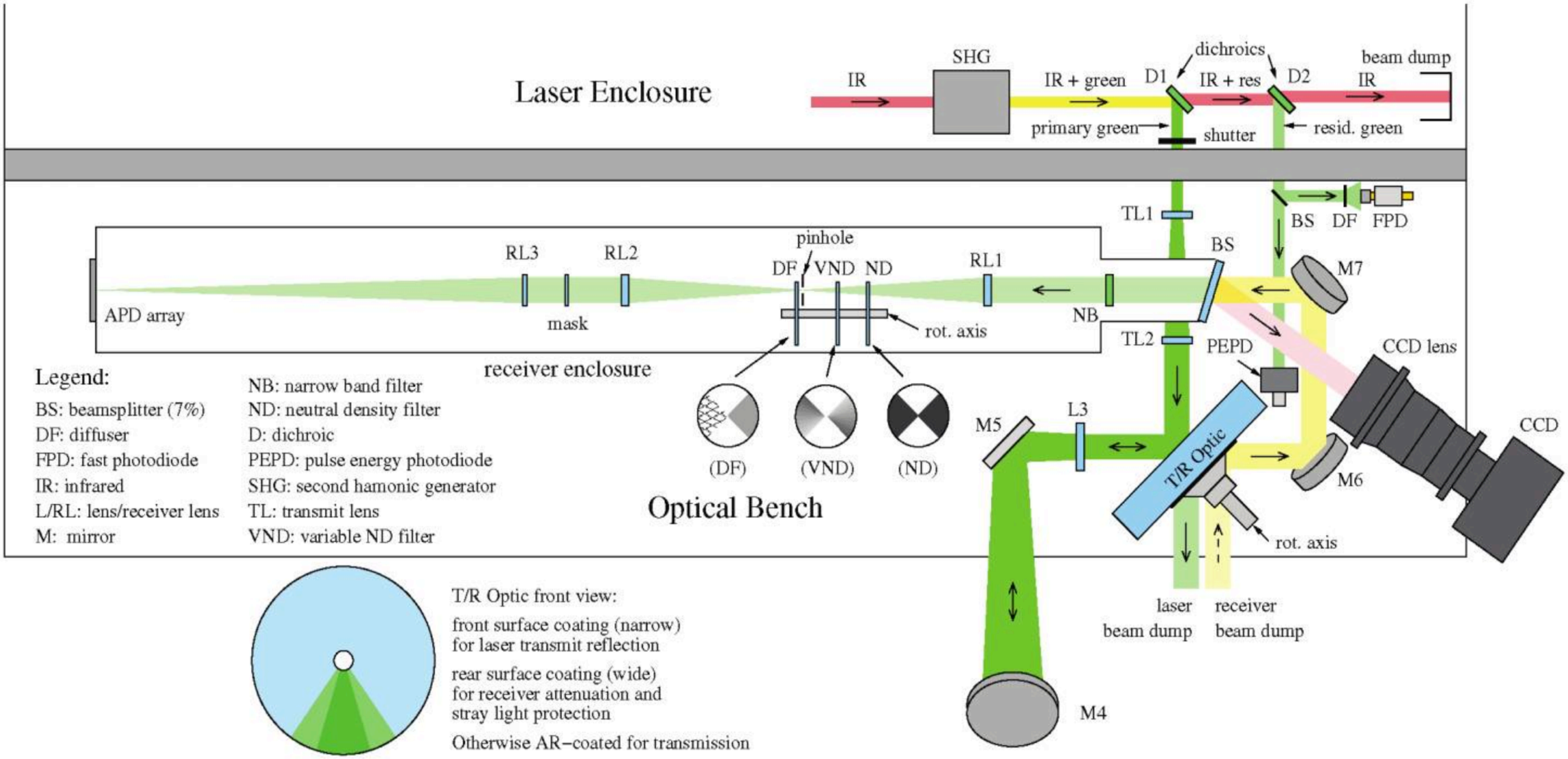
Many possibilities with such a system… Still the early days. For now:

- Clock comparison (Cs vs. GPS) reveal that GPS clock offsets cause ~2.5mm range error
- Can likely correct for ~75% of this over our *entire* 10-year data archive using logged GPS clock reports (10s)
- Can separate ACS photons from Lunar returns
- ACS overlaid on LLR data reveal no unexpected anomalies in our timing accuracy (~mm as expected)
- Next up:
  - measure channel-to-channel offsets, and time evolution, for each of the 16 APD channels
  - Probe/characterize time offsets induced by EM noise from laser fire (cavity dumped by switching 4kV in 1ns)
  - Use Cs as the APOLLO system clock?

Thank you!

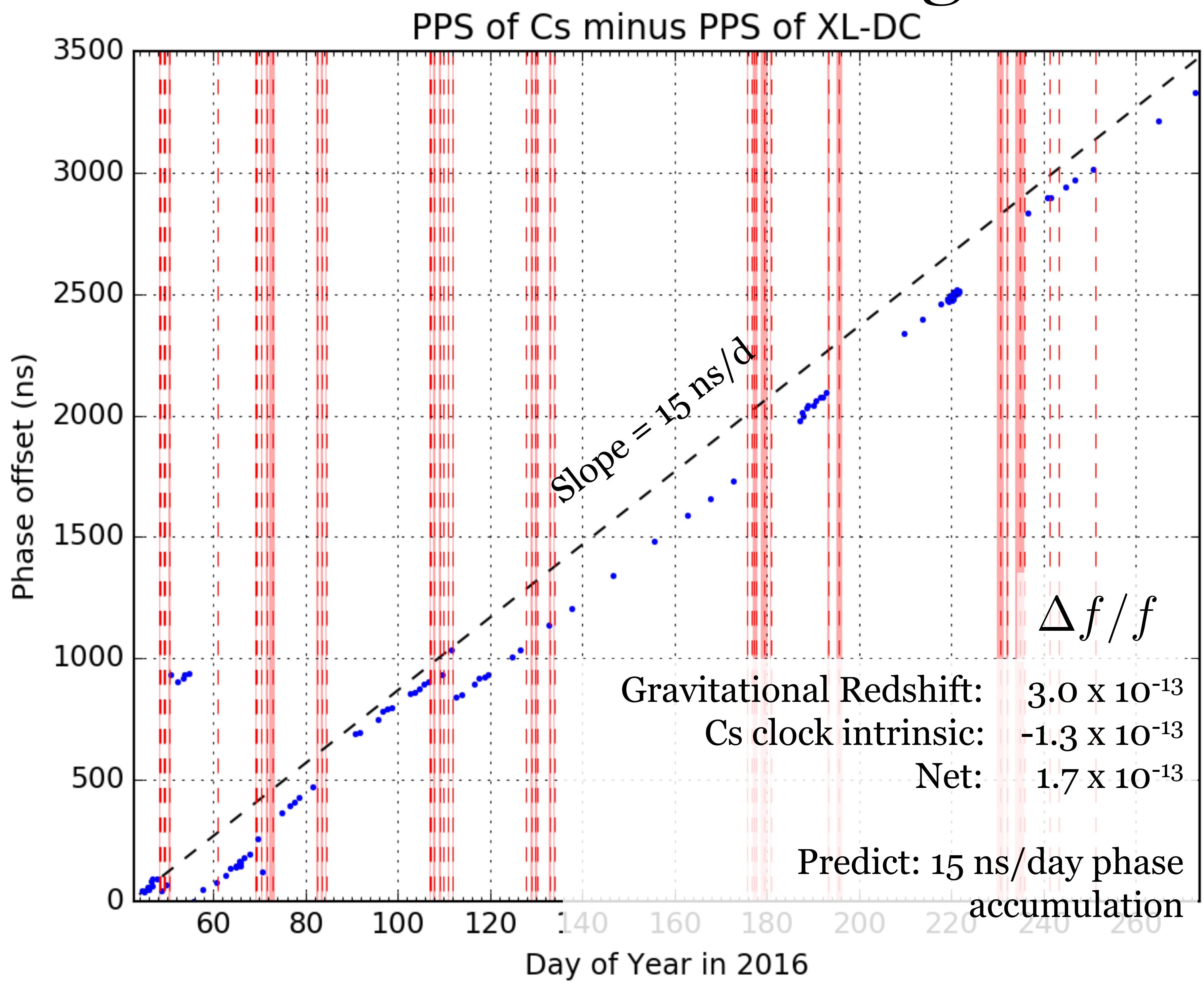
Extras

APOLLO Optical System



T. Murphy et al. PASP 120:20-37 (2008) [arXiv:0710.0890]

Gravitational Redshift Signature



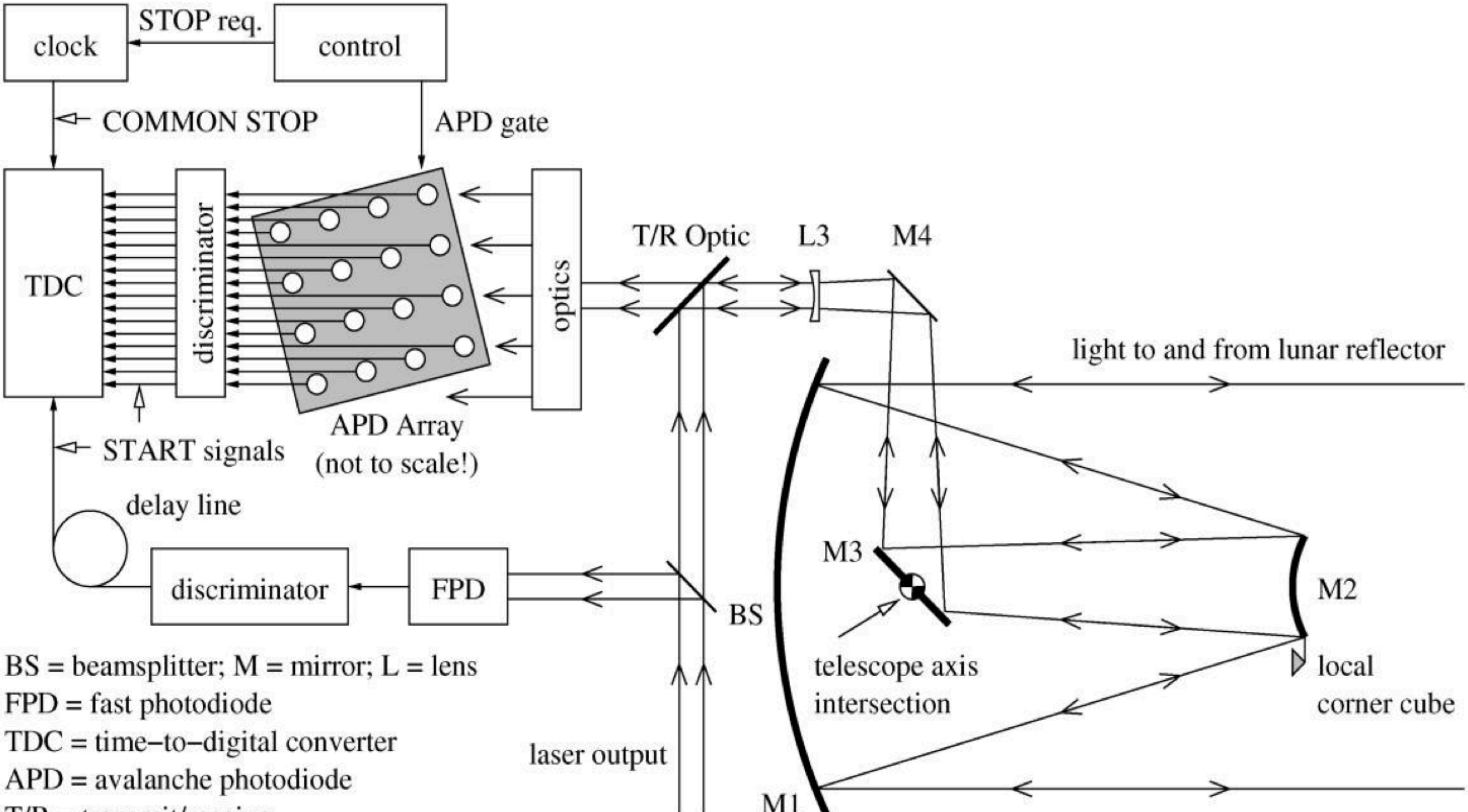
$\Delta f / f$

Gravitational Redshift: 3.0×10^{-13}

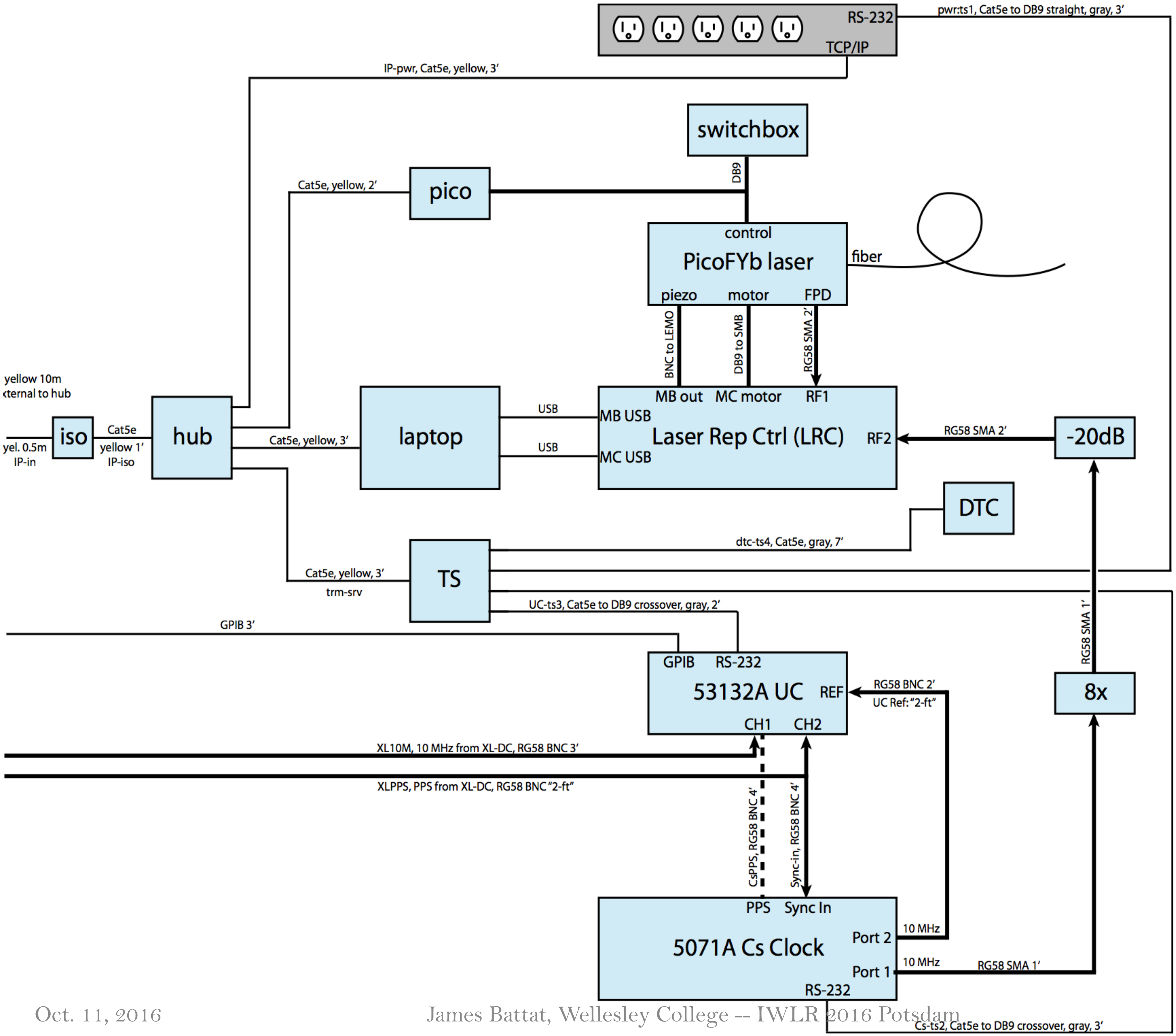
Cs clock intrinsic: -1.3×10^{-13}

Net: 1.7×10^{-13}

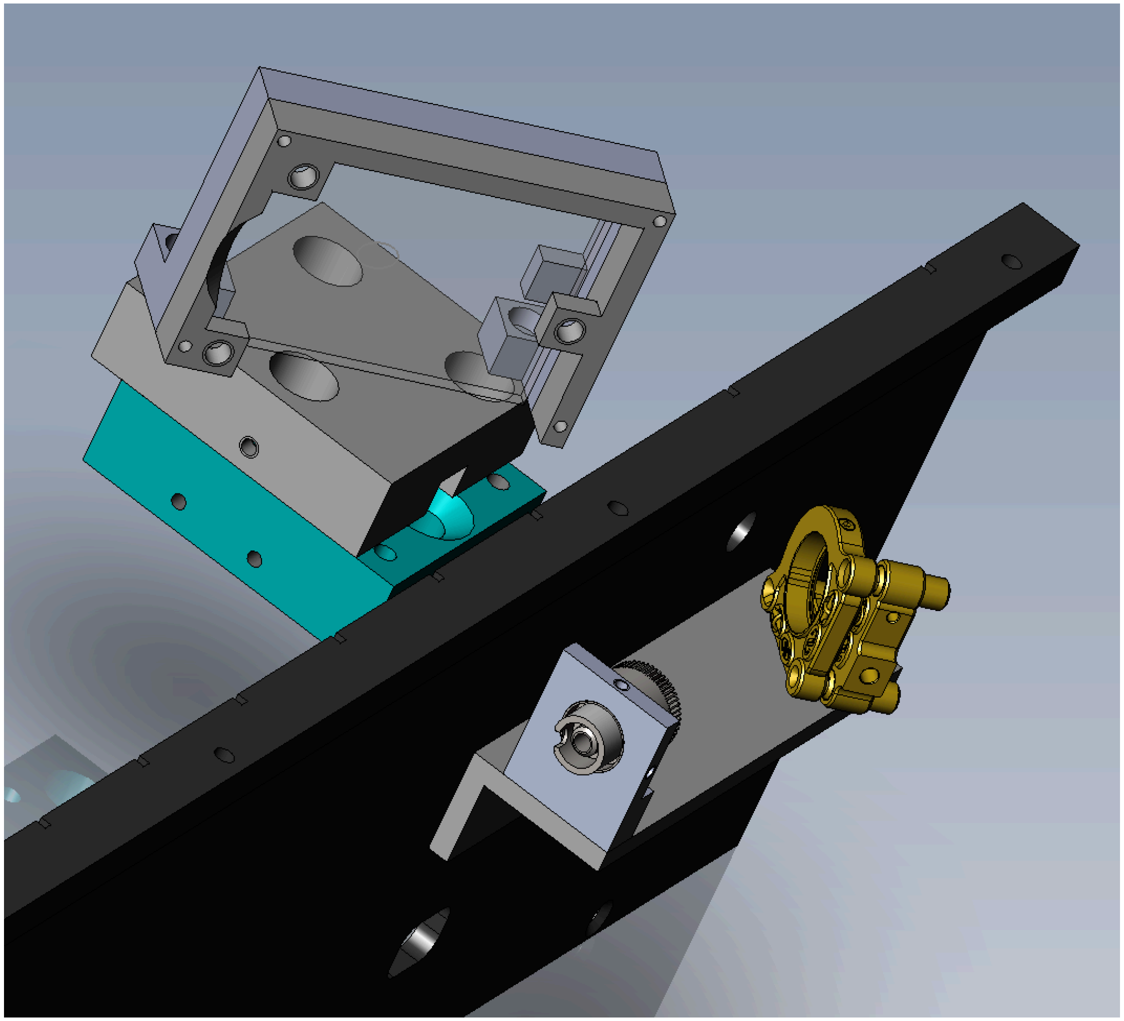
Predict: 15 ns/day phase accumulation

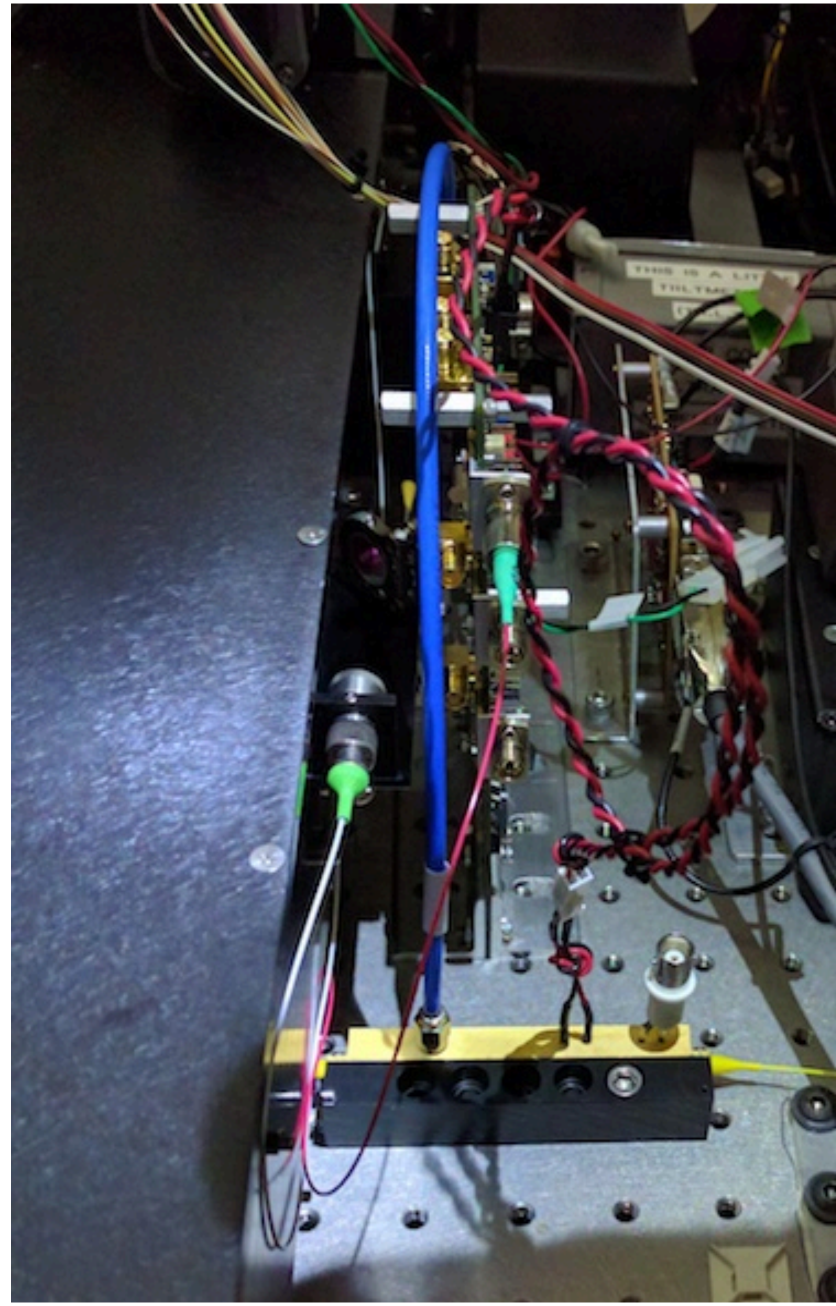


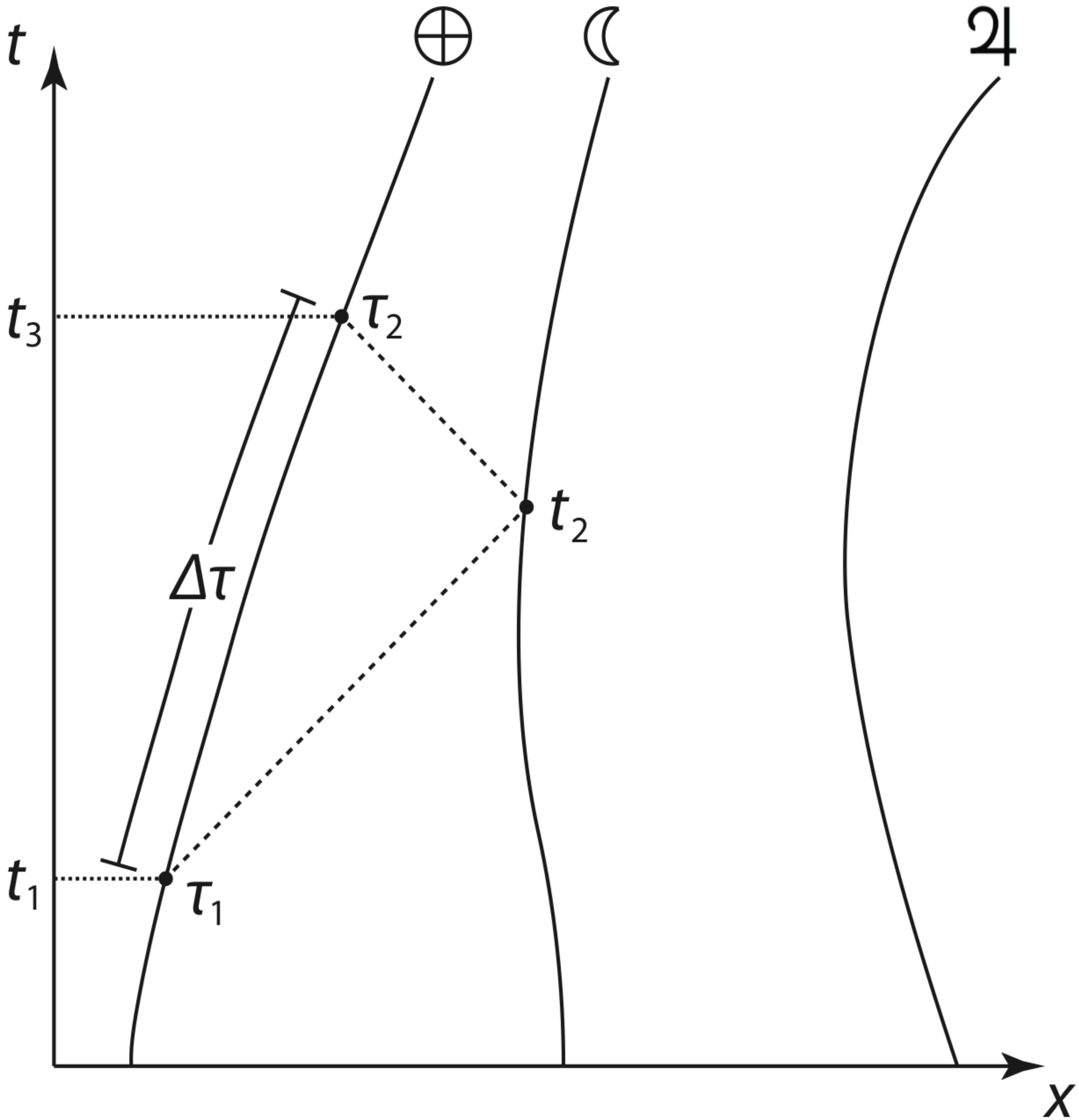
BS = beamsplitter; M = mirror; L = lens
FPD = fast photodiode
TDC = time−to−digital converter
APD = avalanche photodiode
T/R = transmit/receive


RS-232
TCP/IP
pwr:ts1, Cat5e to DB9 straight, gray, 3′
IP-pwr, Cat5e, yellow, 3′
switchbox
DB9
pico
Cat5e, yellow, 2′
control
PicoFYb laser
fiber
piezo
motor
FPD
BNC to LEMO
DB9 to SMB
RG58 SMA 2′
yellow 10m
xternal to hub
iso
yel. 0.5m
IP-in
Cat5e
yellow 1′
IP-iso
hub
Cat5e, yellow, 3′
laptop
USB
USB
MB out
MC motor
RF1
MB USB
Laser Rep Ctrl (LRC)
RF2
MC USB
RG58 SMA 2′
-20dB
DTC
dtc-ts4, Cat5e, gray, 7′
TS
Cat5e, yellow, 3′
trm-srv
UC-ts3, Cat5e to DB9 crossover, gray, 2′
GPIB 3′
RG58 SMA 1′
GPIB
RS-232
53132A UC
REF
RG58 BNC 2′
UC Ref: "2-ft"
8x
CH1
CH2
XL10M, 10 MHz from XL-DC, RG58 BNC 3′
XLPPS, PPS from XL-DC, RG58 BNC "2-ft"
CsPPS, RG58 BNC 4′
Sync-in, RG58 BNC 4′
PPS
Sync In
5071A Cs Clock
Port 2
10 MHz
Port 1
10 MHz
RG58 SMA 1′
RS-232
Cs-ts2, Cat5e to DB9 crossover, gray, 3′

Coupling calibration light into receiver box

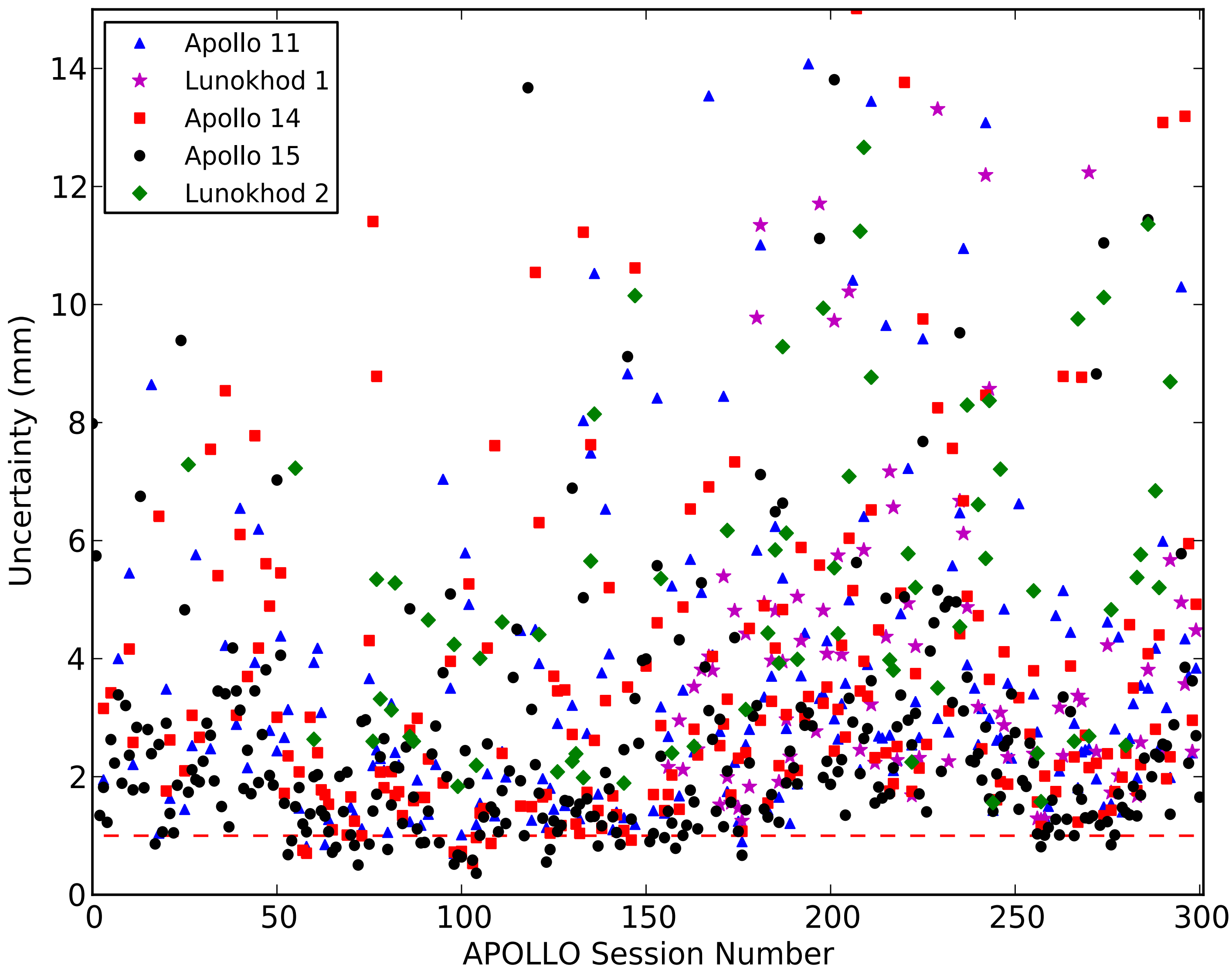






t
⊕
☾
♃
t_3
τ_2
t_2
$\Delta\tau$
t_1
τ_1
x

APOLLO Data & Precision



Uncertainties are per night, per reflector

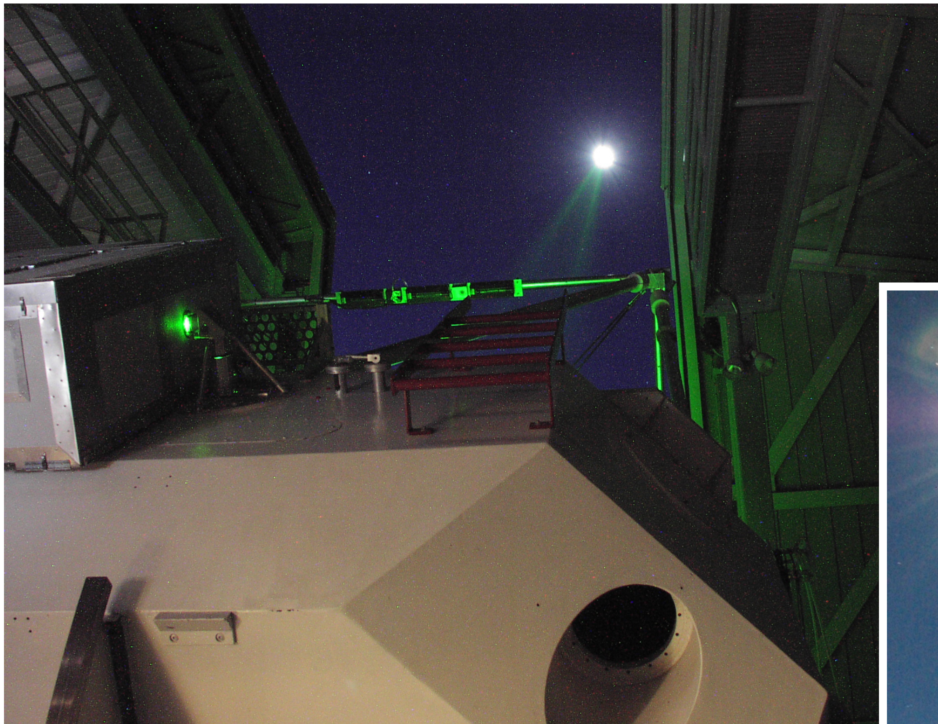
Medians are 2.4, 2.7, 2.4, 1.8, 3.3 mm for A11, L1, A14, A15, L2, respectively

Combined nightly median range error is 1.4 mm

APOLLO random error budget per photon.

Error Source	rms Error (ps)	rms Error (mm)
APD illumination	60	9
APD intrinsic	<50	<7.5
Laser pulse	45	7
Timing electronics	20	3
GPS clock	7	1
Total APOLLO	93	14
Retroreflector array	100–300	15–45
Total random uncertainty	136–314	20–47

APOLLO in action



Credit: Dan Long