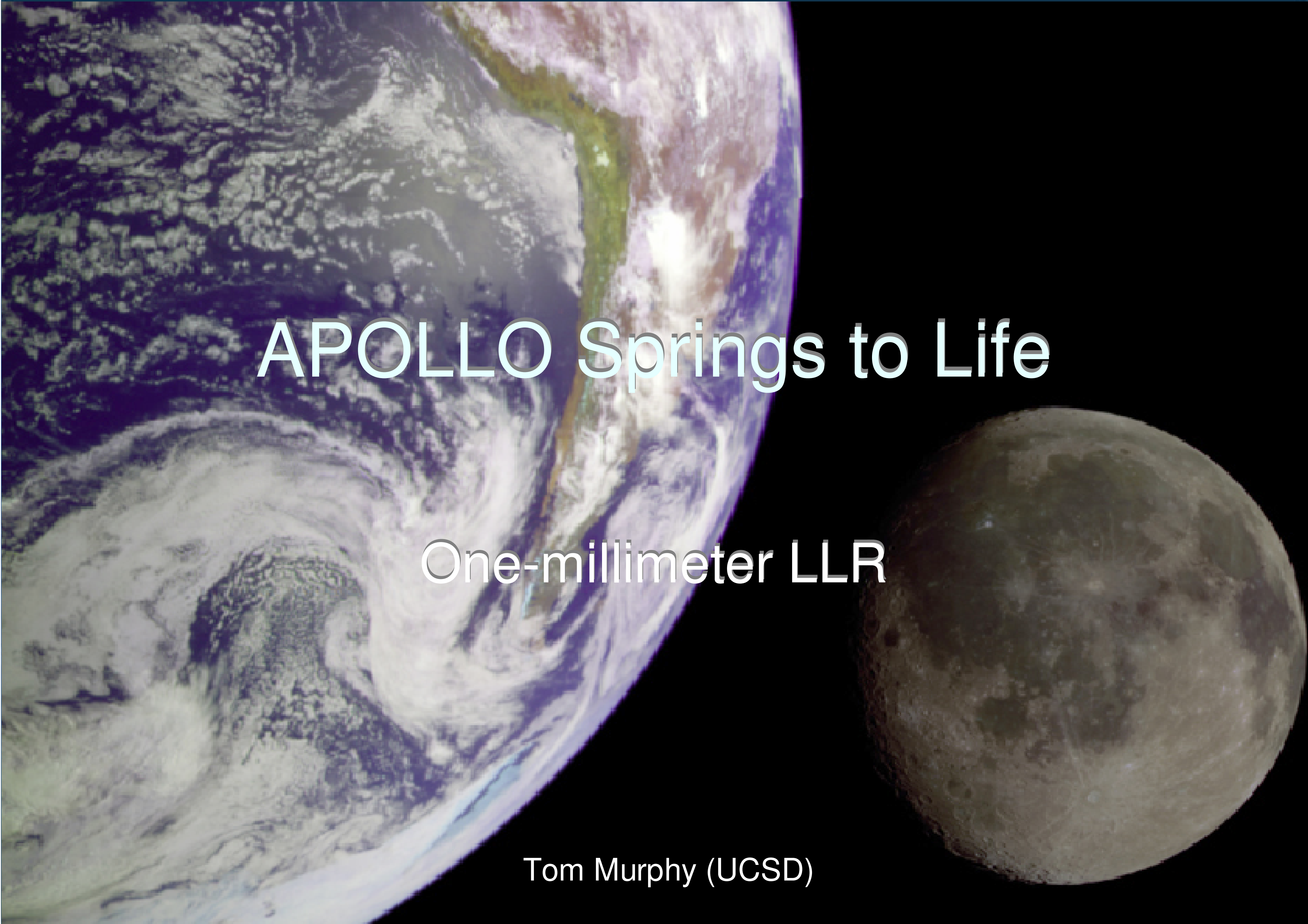

APOLLO Springs to Life

One-millimeter LLR

Tom Murphy (UCSD)

The APOLLO Collaboration

UCSD:
Tom Murphy (PI)
Eric Michelsen
Adam Orin
Eric Williams

U Washington:
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Erik Swanson

Harvard:
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James Battat

JPL:
Jim Williams
Slava Turyshev
Dale Boggs
Jean Dickey

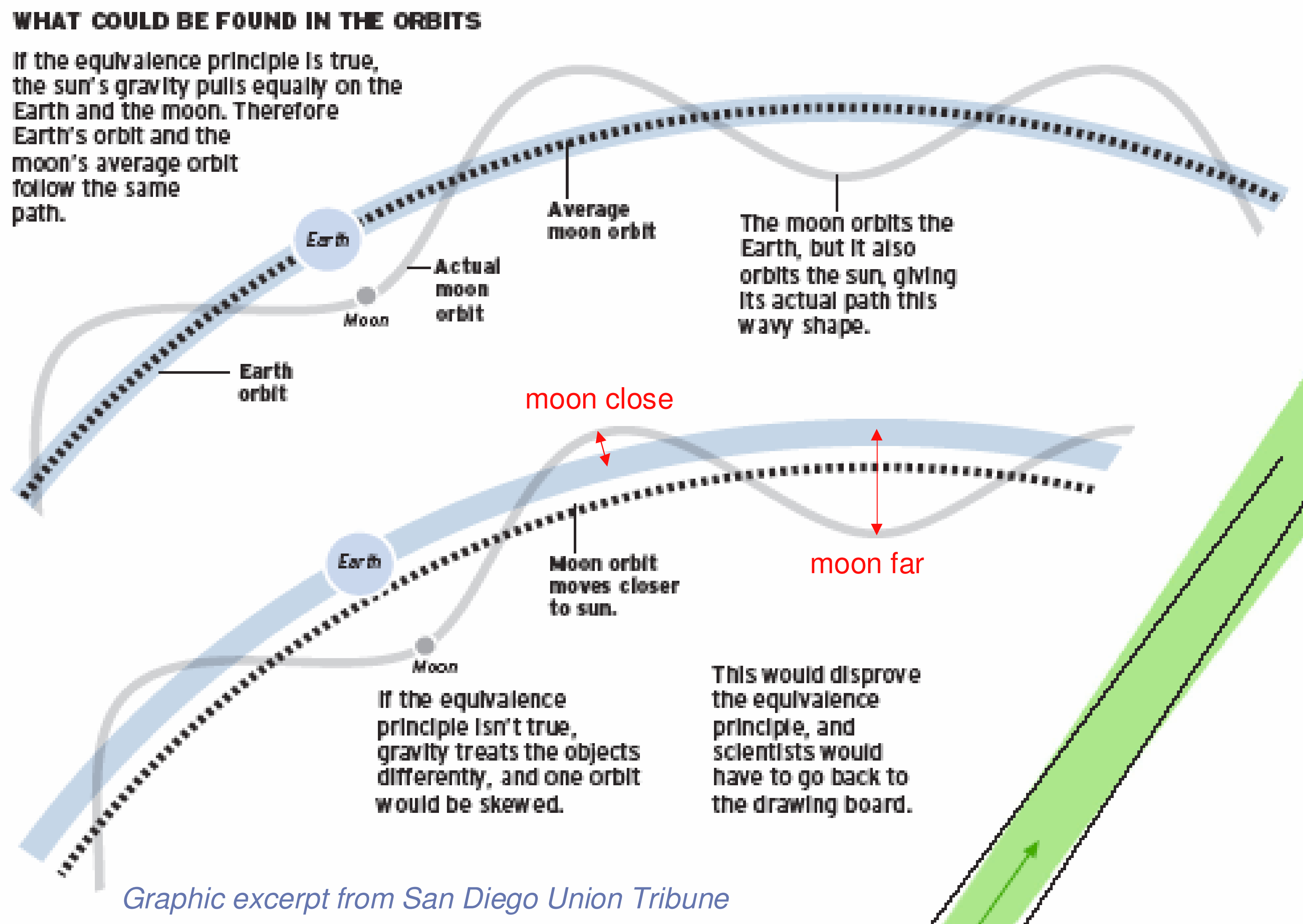
Northwest Analysis:
Ken Nordtvedt

Lincoln Lab:
Brian Aull
Bob Reich

Relativistic Observables in the Lunar Range

- Lunar Laser Ranging currently provides a comprehensive probe of gravity, boasting the best tests of:
  - Equivalence Principle (two flavors)
    - WEP to $\Delta a/a < 10^{-13}$; SEP to $< 4\times10^{-4}$
  - time-rate-of-change of G: $< 10^{-12}$ per year
  - geodetic precession: to $< 0.35\%$
  - $1/r^2$ force law: to $< 10^{-10}$ times the strength of gravity
  - gravitomagnetism (frame-dragging) to $< 0.1\%$
- Equivalence Principle (EP) Violation
  - Happens if gravitational mass and inertial mass are not equal
  - Earth and Moon would fall at different rates toward the sun
  - Would appear as a *polarization* of the lunar orbit
  - Range signal has form of $\cos D$ (D is lunar phase angle)

EP Signal, Illustrated



Graphic excerpt from San Diego Union Tribune

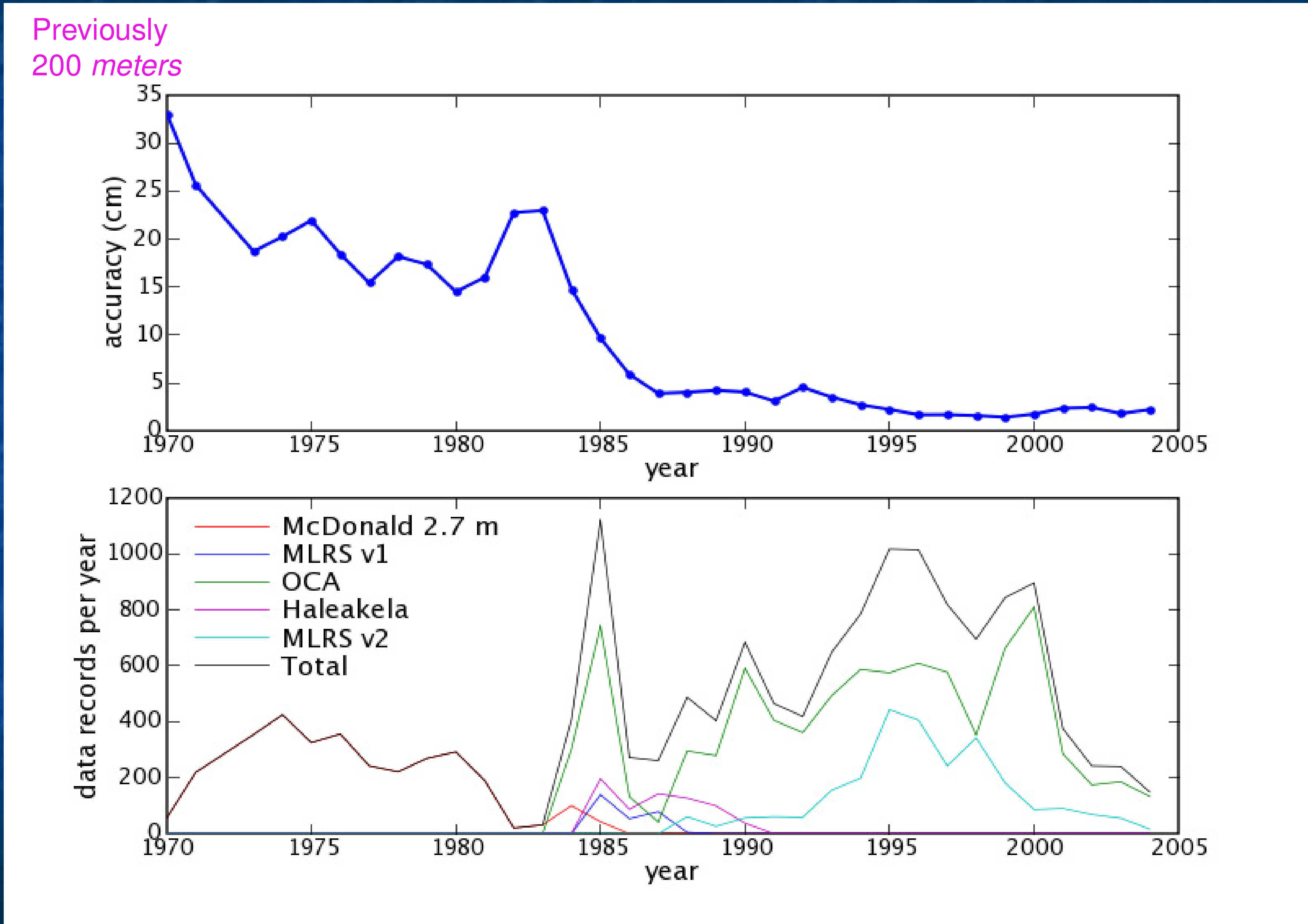
Aside on Gravitomagnetism

- Stems from “motional” term in equation of motion:

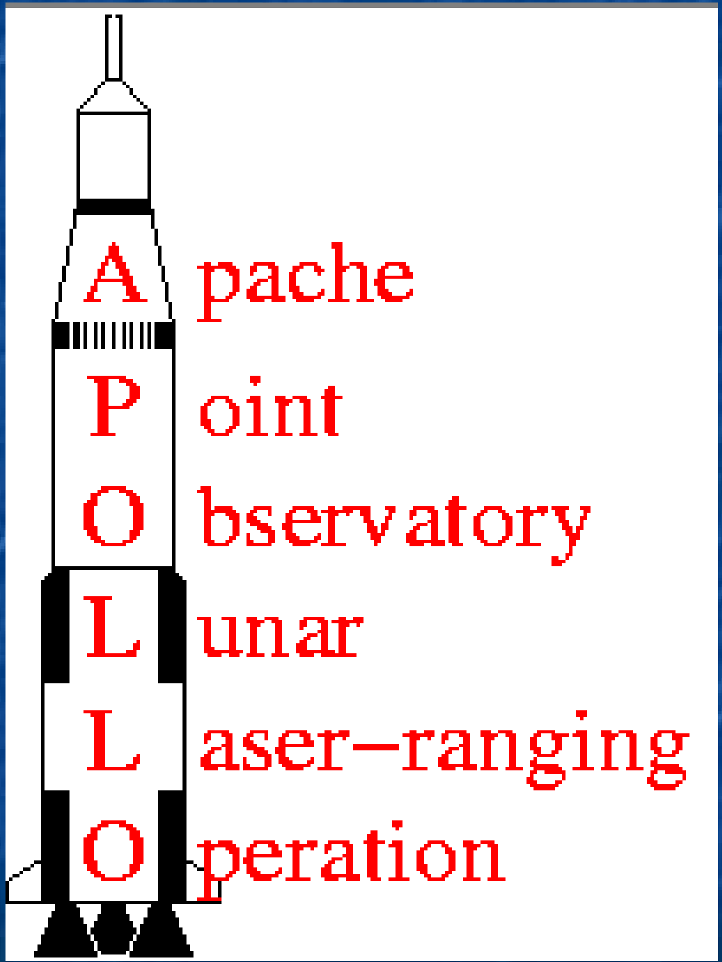
$$\mathbf{a}_i = -\frac{\mu_j(2+2\gamma)}{c^2 r_{ij}^3}\mathbf{v}_i \times (\mathbf{v}_j \times \mathbf{r}_{ij})$$

- If earth has velocity **V**, and moon is **V**+**u**, two terms of consequence emerge:
  - One proportional to V^2 with 6.50 meter cos2*D* signal
  - One proportional to *Vu* with 6.1 meter cos*D* signal
- LLR determines cos*D* to 4 mm precision and cos2*D* to < 8 mm
  - Constitutes a ≈ 0.1% measurement of effect
- The same exact *v*×*v*×*g* term can be used to derive the precession of a gyroscope in the presence of a spinning mass
  - recovers the full effect sought by GPB

LLR through the decades



APOLLO: recipe for success



- APOLLO offers order-of-magnitude improvements to LLR by:
  - Using a 3.5 meter telescope
  - Gathering multiple photons/shot
  - Operating at 20 pulses/sec
  - Using advanced detector technology
  - Achieving millimeter range precision
  - Tightly integrating experiment and analysis
  - Having the best acronym

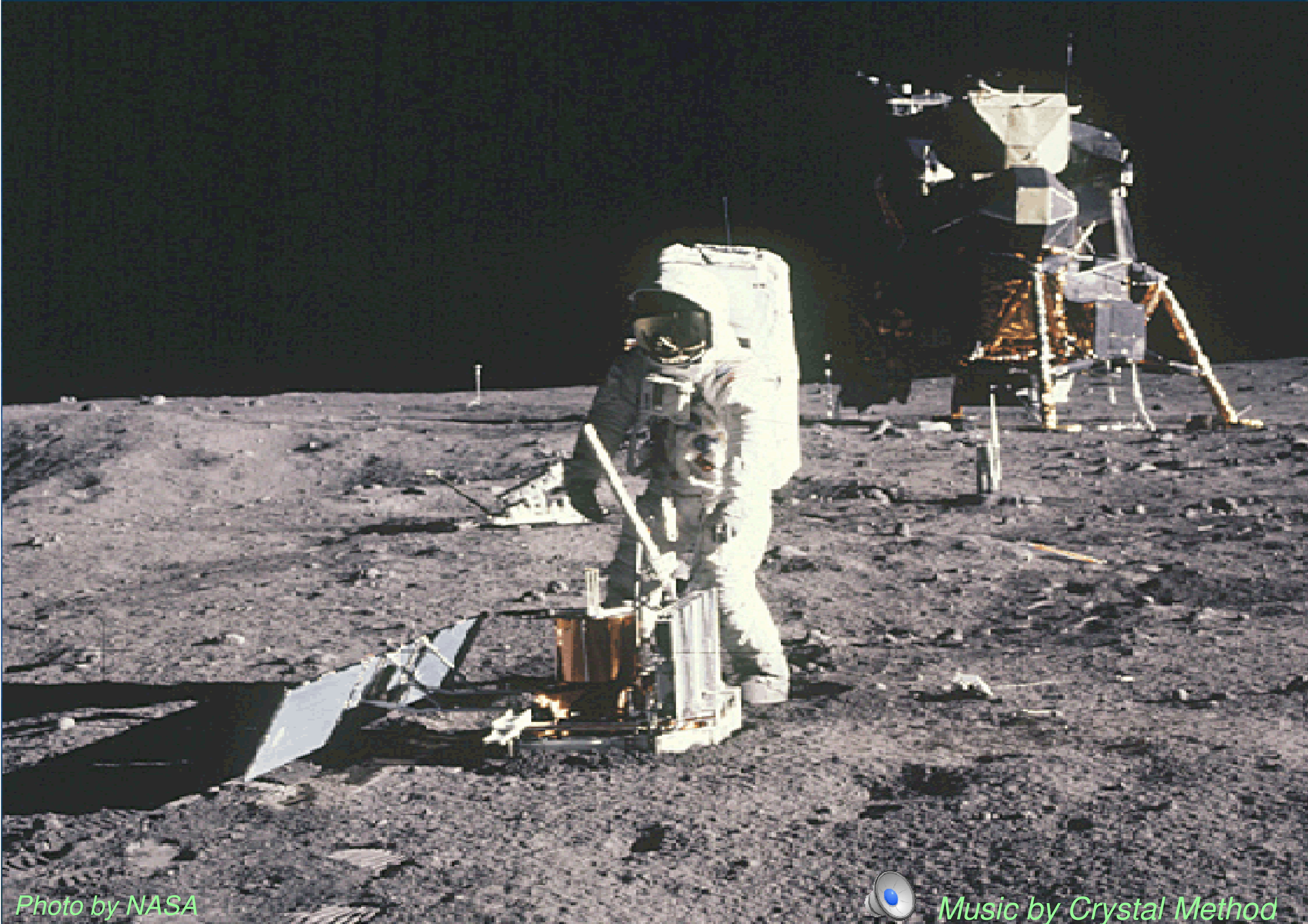
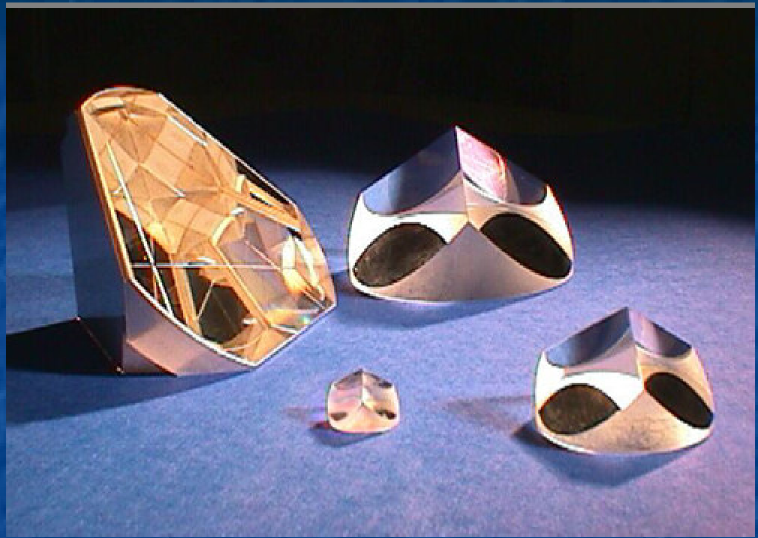
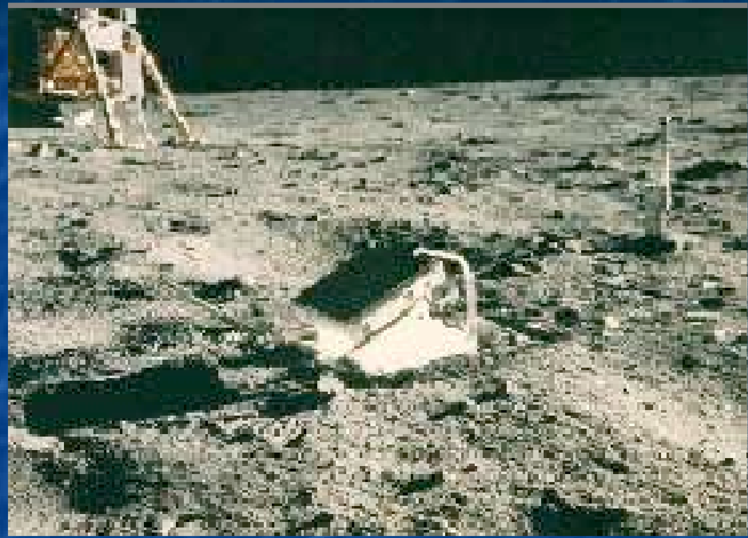


Photo by NASA
Music by Crystal Method

Lunar Retroreflector Arrays

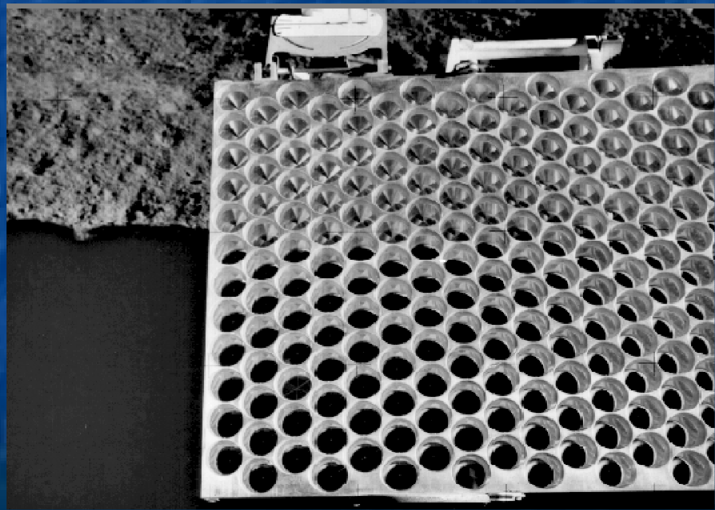


Corner cubes



Apollo 11 retroreflector array

Apollo 14 retroreflector array



Apollo 15 retroreflector array

APOLLO's Secret Weapon: Aperture

- The Apache Point Observatory's 3.5 meter telescope
  - Southern NM (Sunspot)
  - 9,200 ft (2800 m) elevation
  - Great "seeing": 1 arcsec
  - Flexibly scheduled, high-class research telescope
  - 7-university consortium (UW, U Chicago, Princeton, Johns Hopkins, Colorado, NMSU, Virginia)

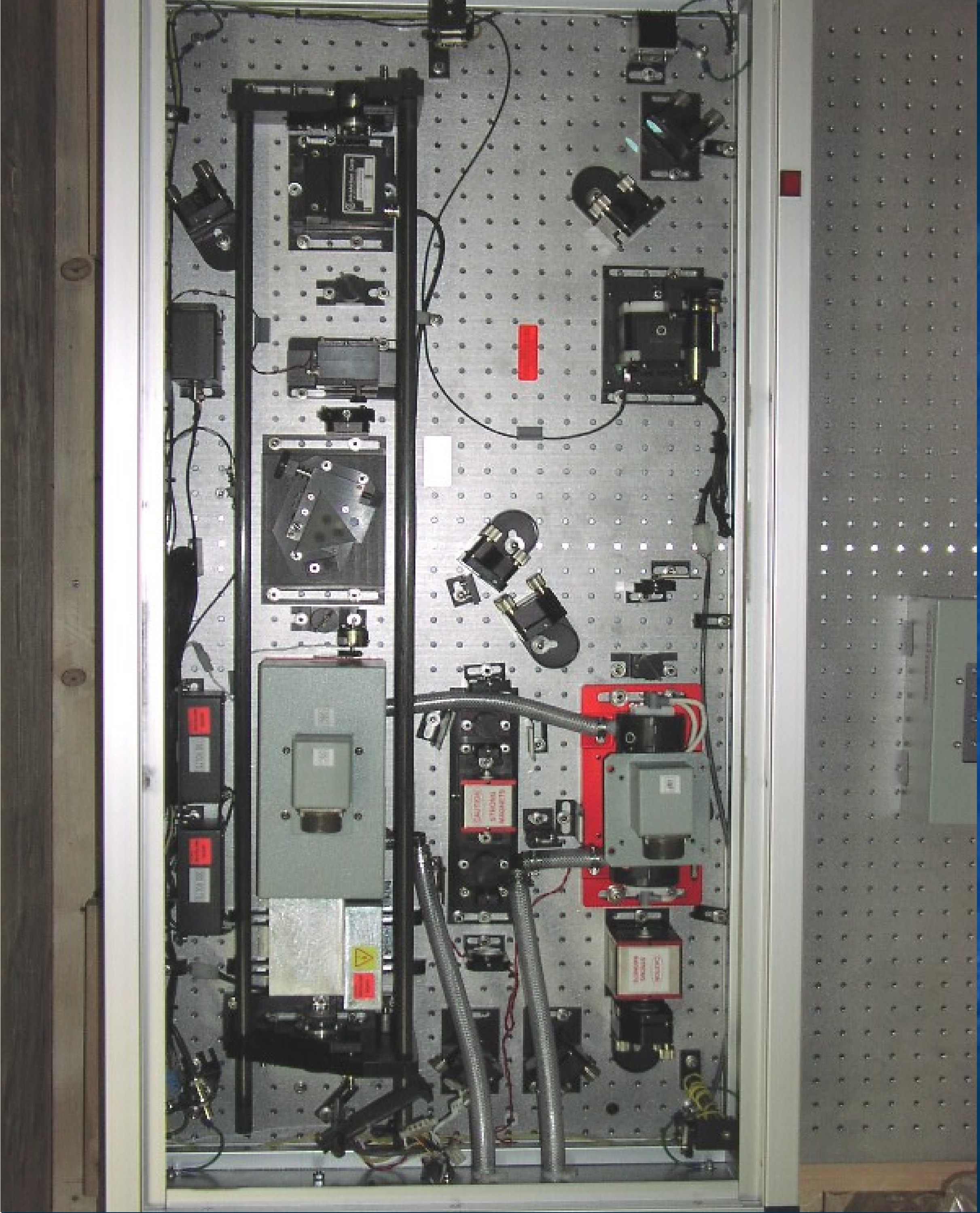
The Link Equation

$$N_{\mathrm{rx}} = N_{\mathrm{tx}}\eta^2 f Q n_{\mathrm{refl}} \left(\frac{d}{\phi r}\right)^2 \left(\frac{D}{\Phi r}\right)^2$$

η = one-way optical throughput (encountered twice)
f = receiver narrow-band filter throughput
Q = detector quantum efficiency
n_{refl} = number of corner cubes in array (100 or 300)
d = diameter of corner cubes (3.8 cm)
ϕ = outgoing beam divergence (atmospheric “seeing”)
r = distance to moon
Φ = return beam divergence (diffraction from cubes)
D = telescope aperture (diameter; 3.5 m)

$$N_{\mathrm{rx}} = 5.4 \left(\frac{E_{\mathrm{pulse}}}{115\ \mathrm{mJ}}\right) \left(\frac{\eta}{0.4}\right)^2 \left(\frac{f}{0.25}\right) \left(\frac{Q}{0.3}\right) \left(\frac{n_{\mathrm{refl}}}{100}\right) \left(\frac{1\ \mathrm{arcsec}}{\phi}\right)^2 \left(\frac{10\ \mathrm{arcsec}}{\Phi}\right)^2 \left(\frac{385000\ \mathrm{km}}{r}\right)^4$$

- APOLLO lands safely in the multi-photon regime
- Other LLR stations get < 1 photon per 100 pulses
- Even at 1% of expected rate, 1 photon/sec good enough for feedback

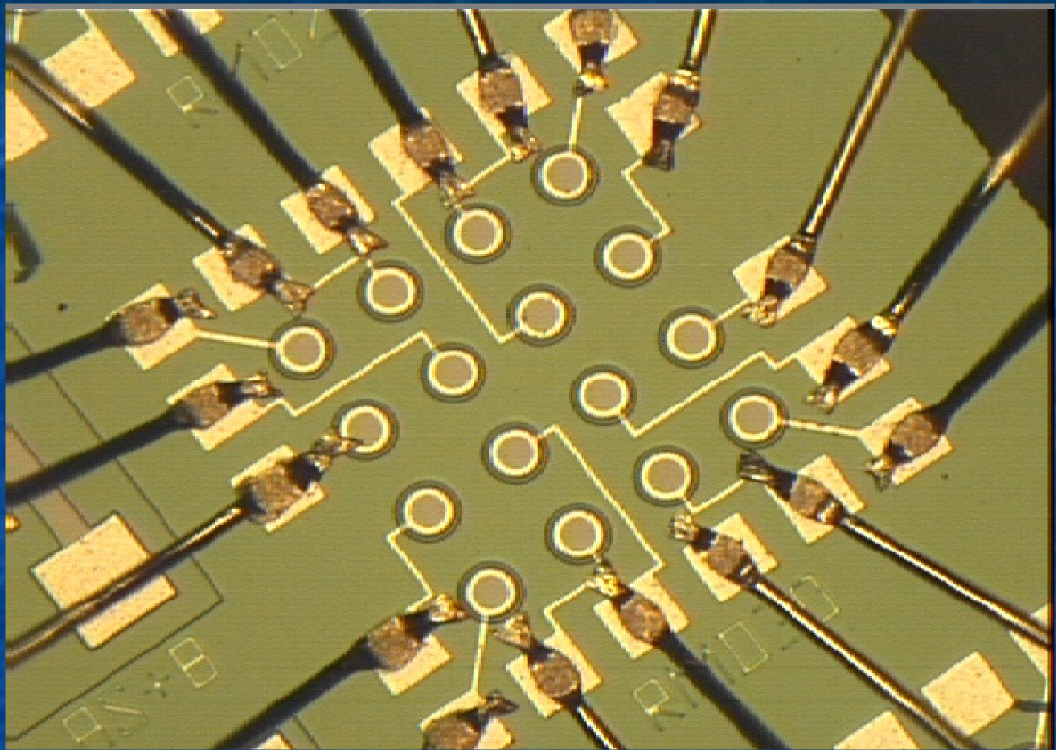


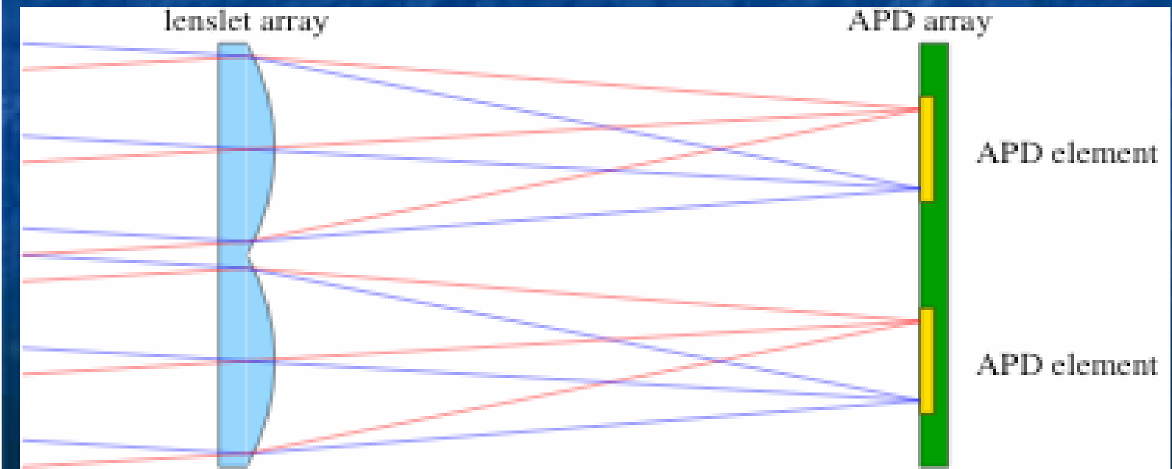
APOLLO Laser

- Nd:YAG mode-locked, cavity-dumped
- Frequency-doubled to 532 nm (green)
- 90 ps pulse width (FWHM)
- 115 mJ per pulse
- 20 Hz repetition rate
- 2.3 Watt average power
- GW peak power!!

- Beam is expanded to 3.5 meter aperture
  - Less of an eye hazard
  - Less damaging to optics

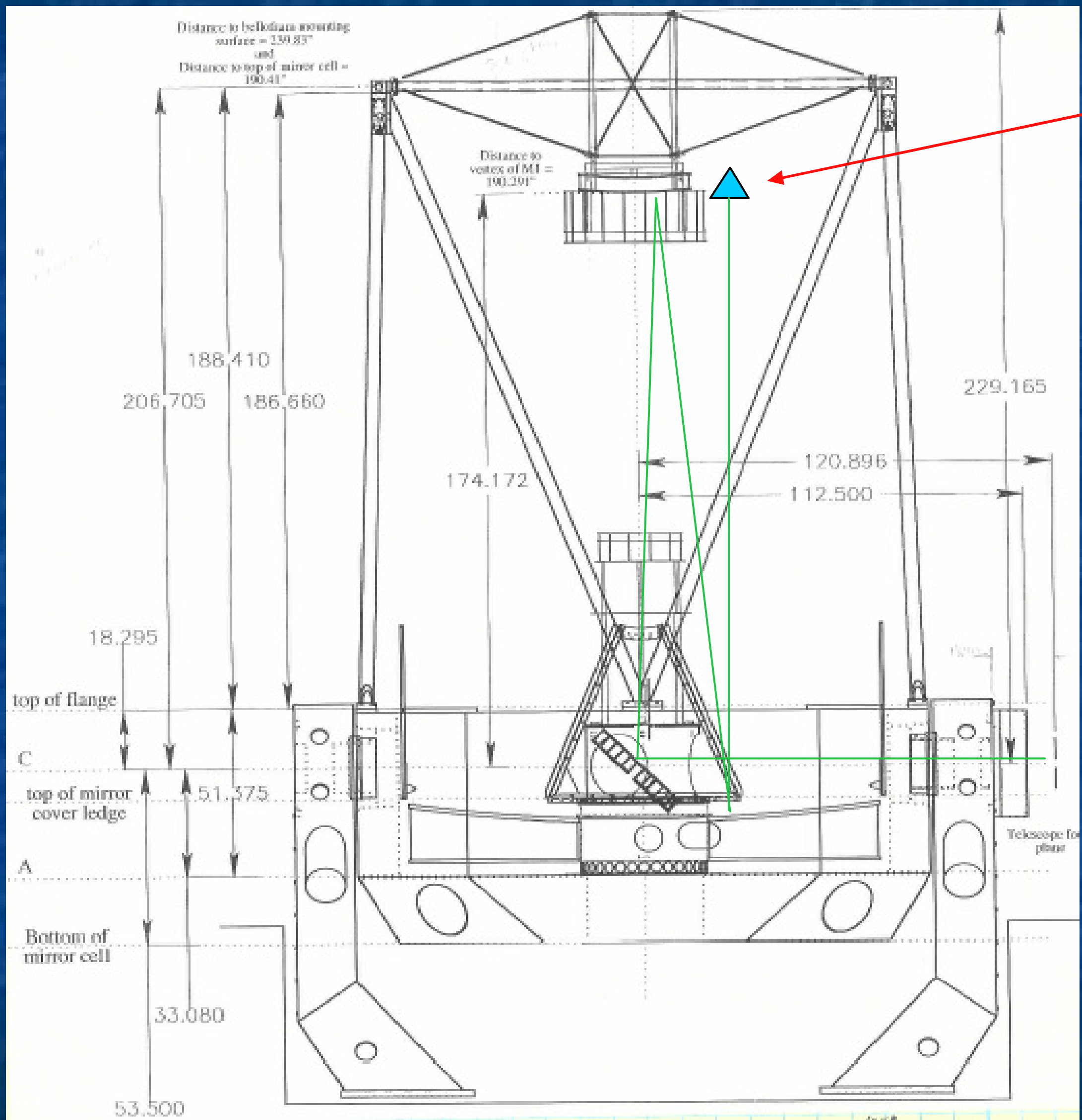
Catching All the Photons





- Several photons per pulse necessitates multiple "buckets" to time-tag each one
  - Avalanche Photodiodes (APDs) respond only to *first* photon
- Lincoln Lab prototype APD arrays are perfect for APOLLO
  - 4×4 array of 30 μm elements on 100 μm centers
- Lenslet array in front recovers full fill factor
  - Resultant field is 1.4 arcsec on a side
  - Focused image is formed at lenslet
  - 2-D tracking capability facilitates optimal efficiency

Differential Measurement Scheme



- Corner Cube at telescope exit returns fiducial pulse
- Same optical path, attenuated by 10 O.D.
- Same APD detector, electronics, TDC range
- Diffused to present identical illumination on detector elements
- Result is differential over 2.5 seconds
- Must correct for distance between telescope axis intersection and corner cube

APOLLO Random Error Budget

Error Source	Time Uncert. (ps) (round trip)	Range error (mm) (one way)
Retro Array Orient.	100–300	15–45
APD Illumination	60	9
APD Intrinsic	<50	< 7
Laser Pulse Width	45	6.5
Timing Electronics	20	3
GPS-slaved Clock	7	1
Total Random Uncert	136–314	20–47

Ignoring retro array, APOLLO system has 93 ps (14 mm) error *per photon*

Systematic Error Sources

- We can cut the 50 mm (worst-case) random uncertainty down to 1 mm with 2500 photons
  - 2 minutes at 20 Hz and 1 photon per pulse
- Systematic uncertainties are more worrisome
  - Atmospheric delay (2 meter effective path delay)
  - Deflection of earth's crust by:
    - Ocean: even in NM, tidal buildup on CA coast → few mm deflection
    - Atmosphere: 0.35 mm per millibar pressure differential
    - ground water: ????
  - Thermal expansion of telescope and retroreflector arrays
  - Radiation pressure (3.85 mm differential signal)
  - Implementation systematics
    - Detector illumination
    - Strong signal bias
    - Temperature-dependent electronic timing
    - Observation schedule/sampling: danger of aliasing

Beating the Systematics

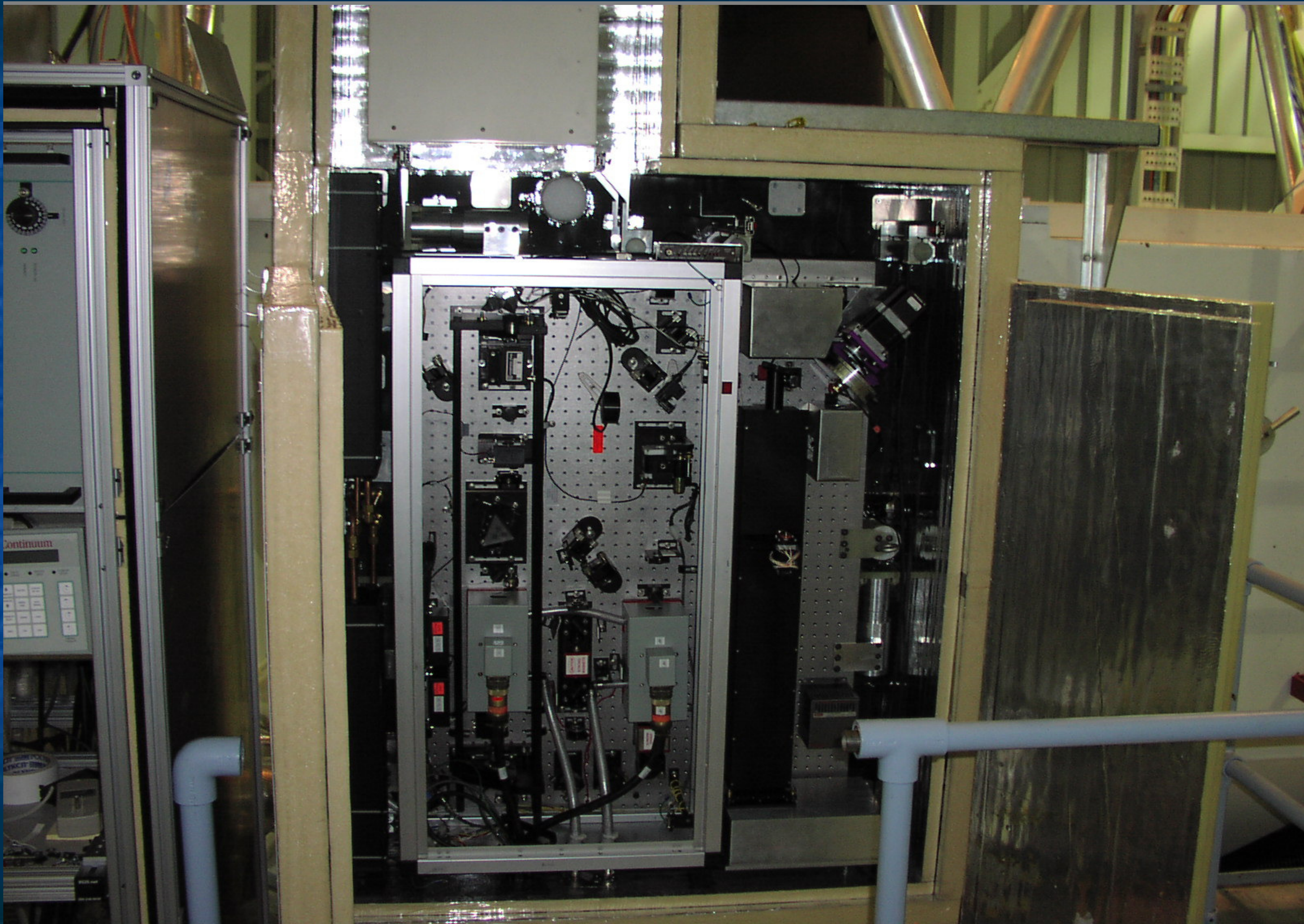
- Precision barometry for atmospheric delay (0.2 mbar)
- Precision GPS installation
  - 0.5 mm horizontal
  - 2.5 mm vertical
- Superconducting gravimeter
  - Invented at UCSD by John Goodkind
  - Can sense sub-mm vertical offsets by change in *g*!
  - Refurbishing Goodkind sensor for use in NM
- Tight feedback between data collection and analysis
  - Sensitive to alias, bias, etc.

Periodicity: Our Saving Grace

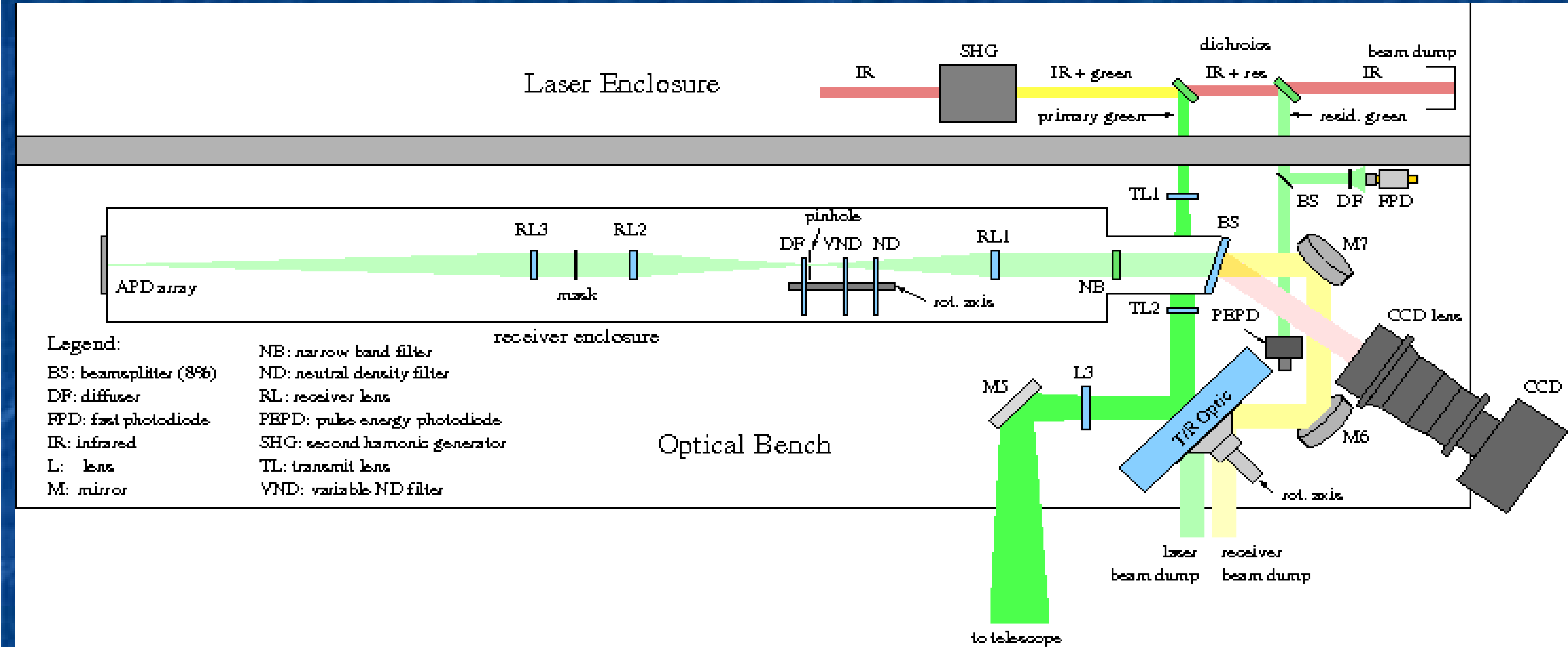
- If we don’t get all this supplemental metrology *right*, we’re still okay:
  - Our science signals are at discrete, well-defined frequencies
  - Equivalence Principle signal at 29.53 days
  - Other science via 27.55 day signal (eccentricity)
- Meteorological influences are *broadband*
  - Atmospheric, ground-water loading are random
  - Even tides, ocean loading don’t have power at EP period
  - Thermal effects are seasonal

Laser Mounted on Telescope

Optical System

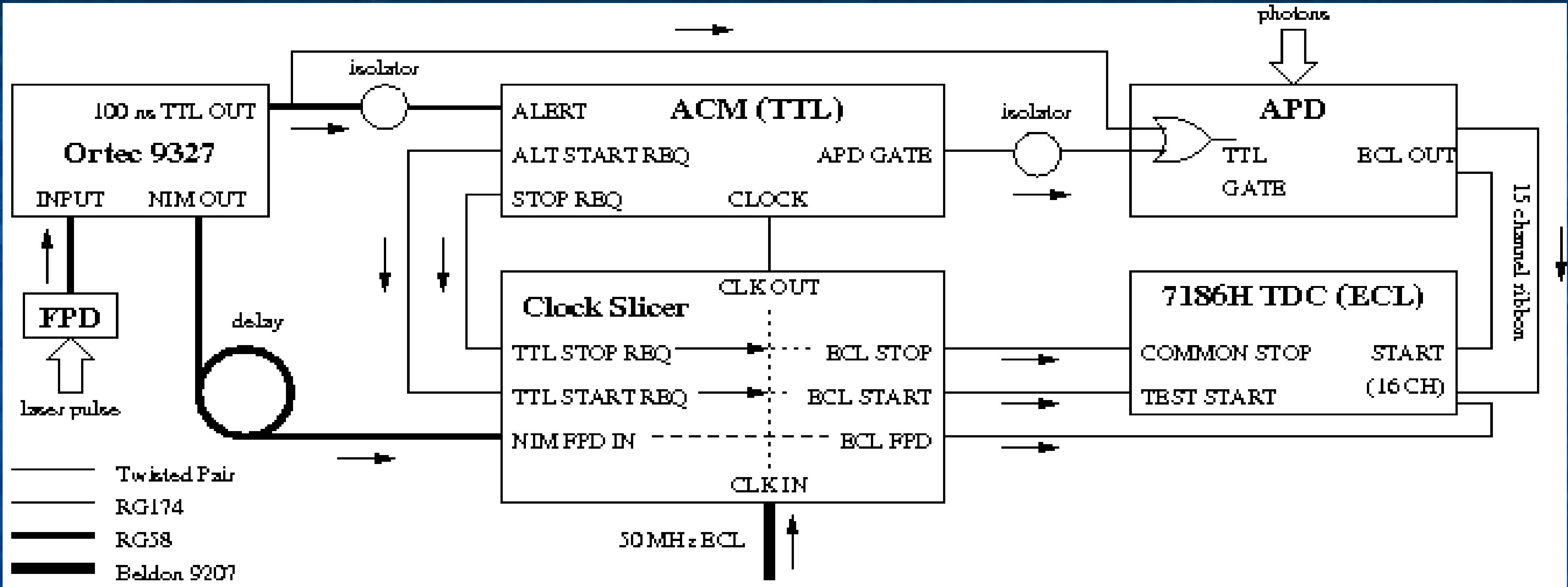


Optical Layout



Electronics Cabinet

Timing System



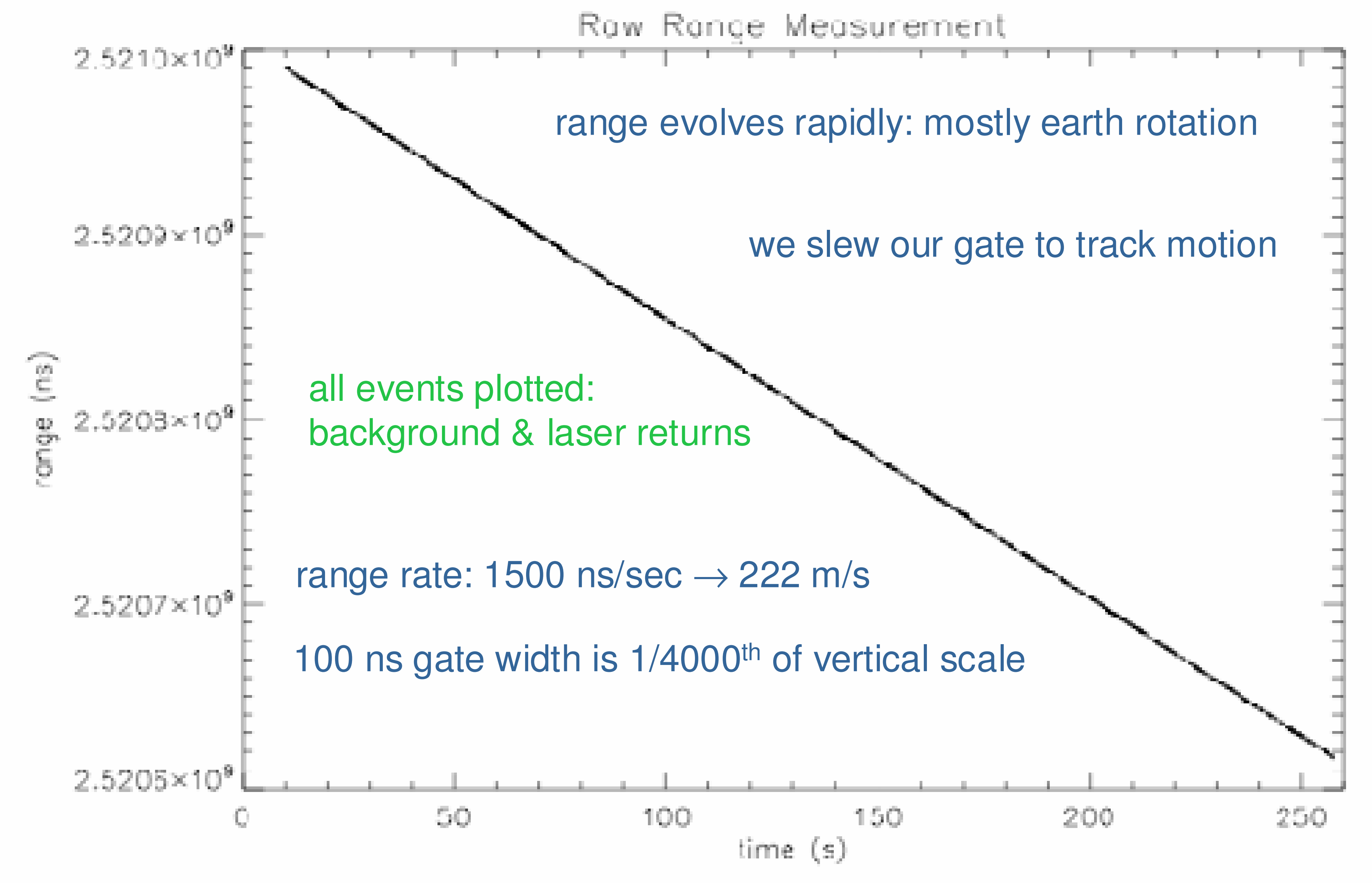
- Custom timing system uses 16-channel TDC (100 ns range; 25 ps resolution; 13 ps jitter) plus custom CAMAC state machine to get multiplexed 15 ps timing (up to 4 kHz rate)
- Common STOP sliced from 50 MHz ECL clock train (Truetime XL-DC base)
- Each APD channel produces independent START
- Clock Slicer can also produce STARTs based on 50 MHz
  - calibration via 20.00, 40.00, 60.00, 80.00, 100.00 ns START/STOP pairs

First Light: July 24, 2005

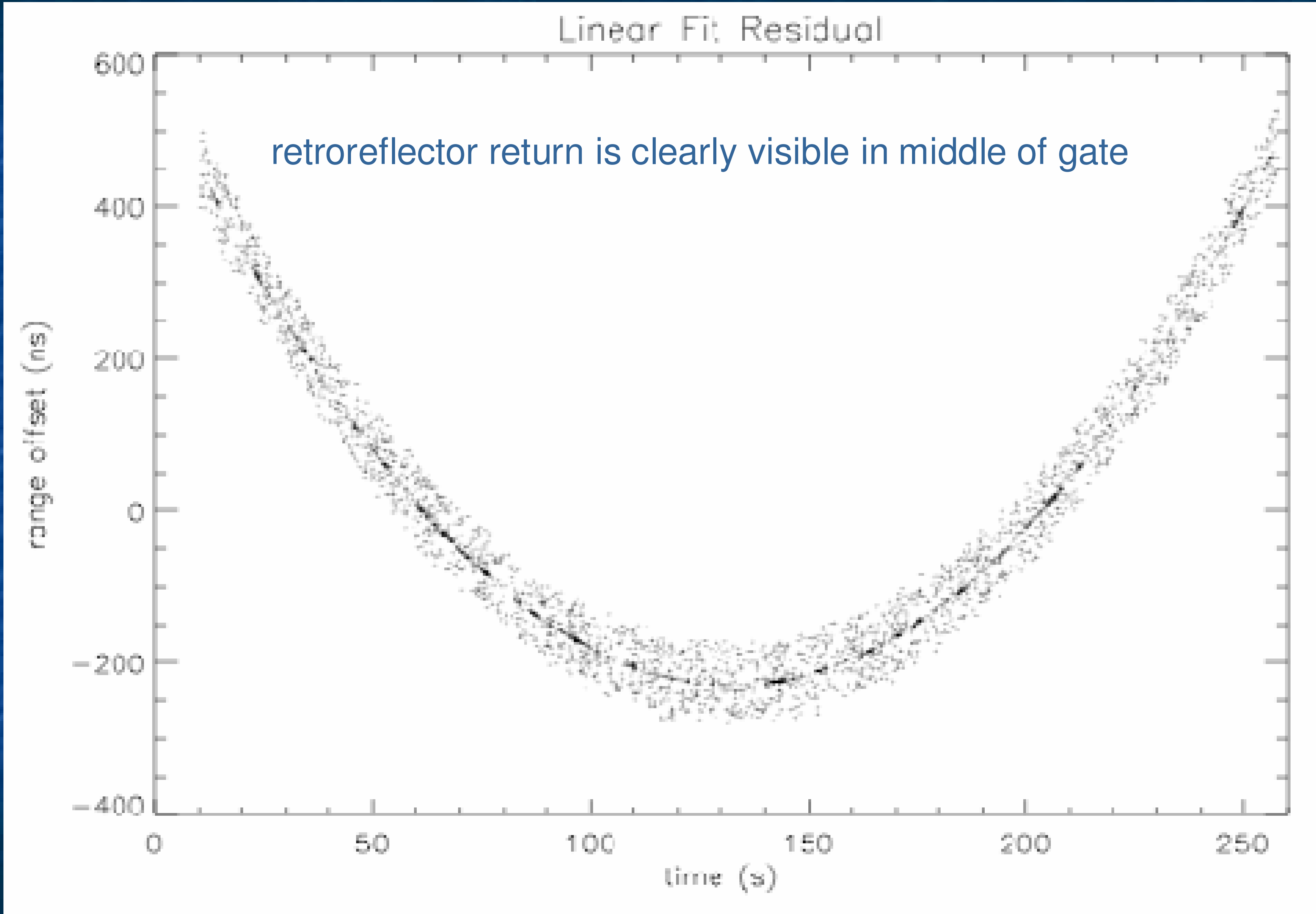
First Light: July 24, 2005

Blasting the Moon

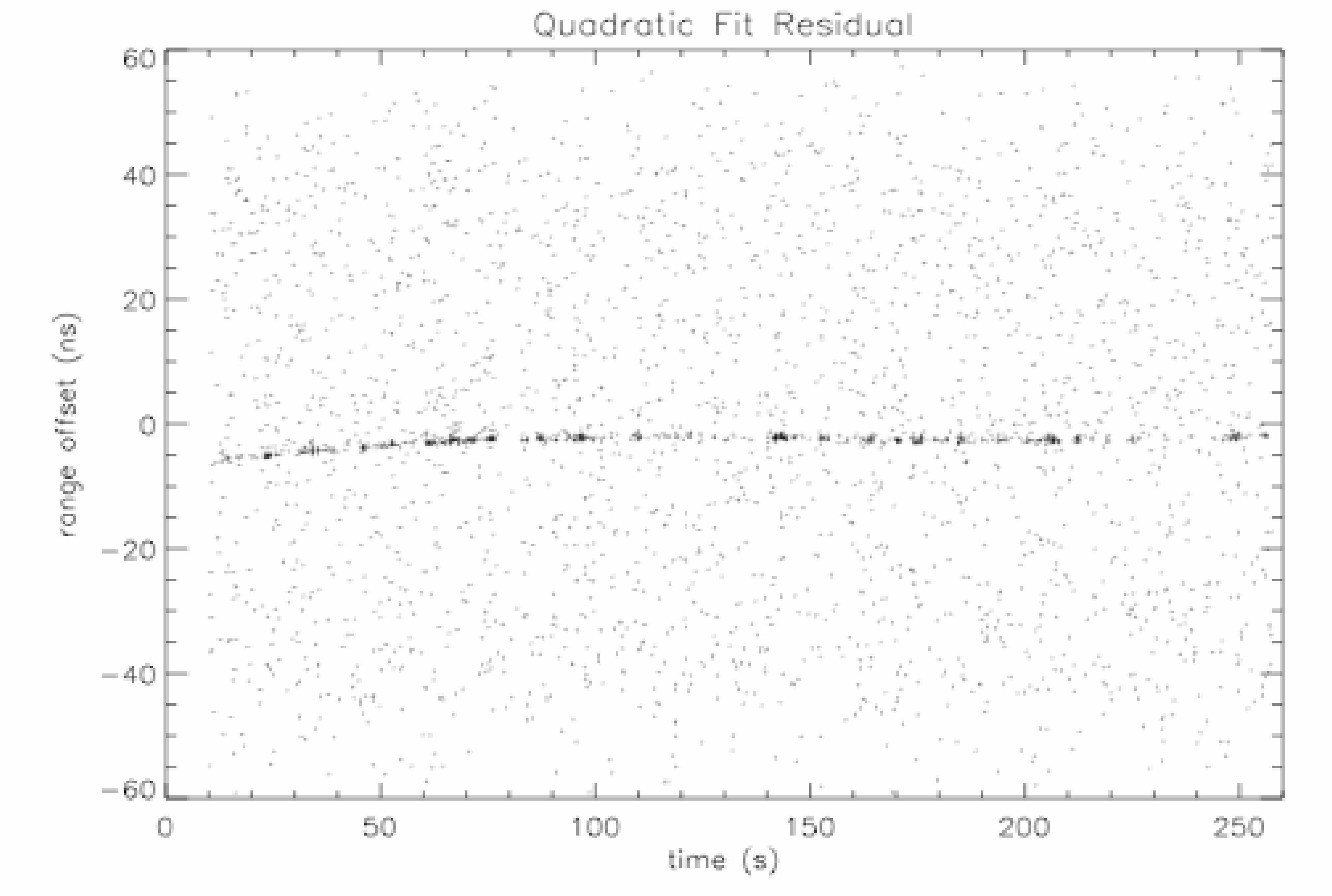
The Raw Data


Raw Range Measurement
range evolves rapidly: mostly earth rotation
we slew our gate to track motion
all events plotted:
background & laser returns
range rate: 1500 ns/sec → 222 m/s
100 ns gate width is 1/4000th of vertical scale
2.5210×10⁹
2.5209×10⁹
2.5208×10⁹
2.5207×10⁹
2.5205×10⁹
range (ns)
0
50
100
150
200
250
time (s)

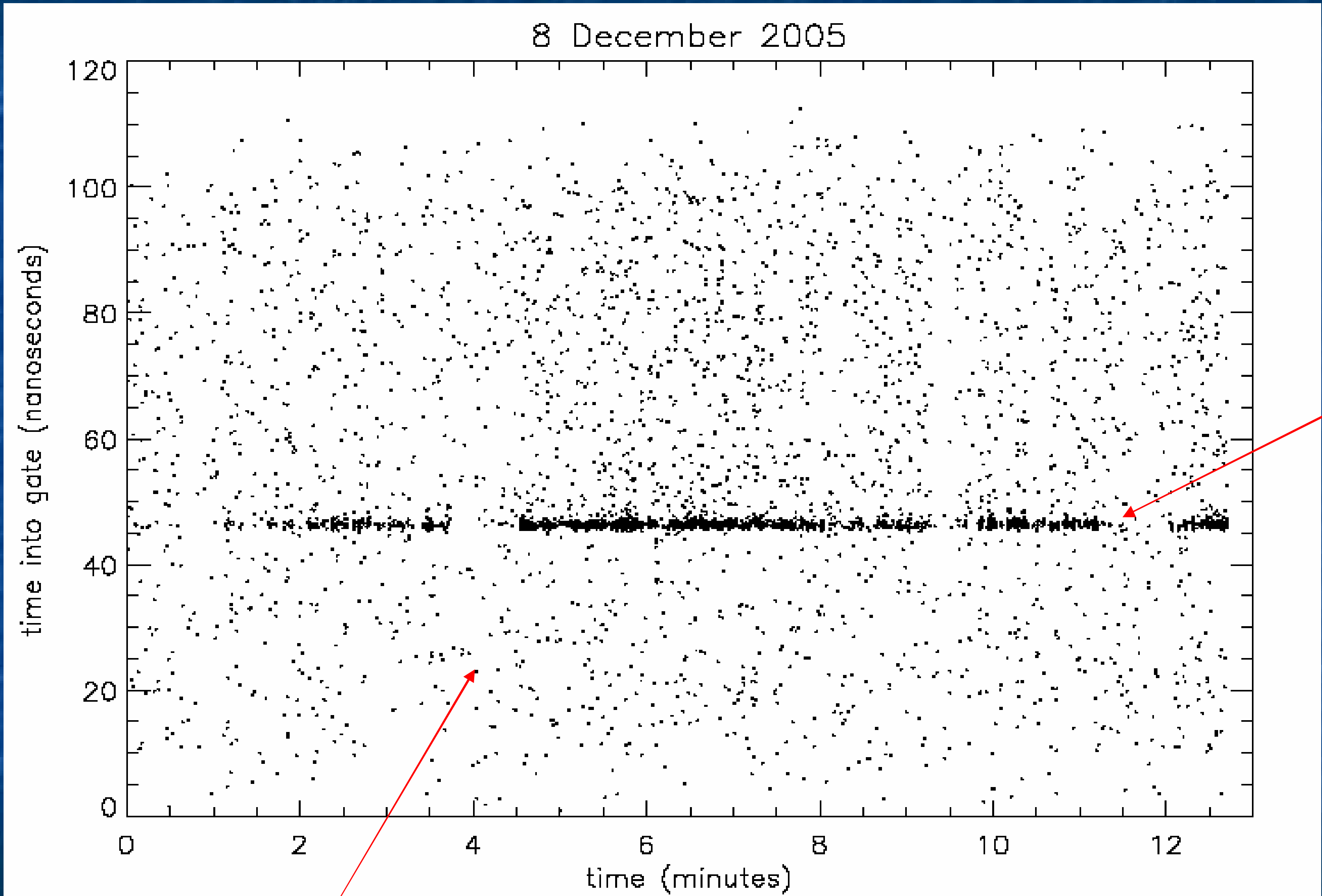
Subtracting Linear Fit…



Subtracting Quadratic Fit…



Example Data



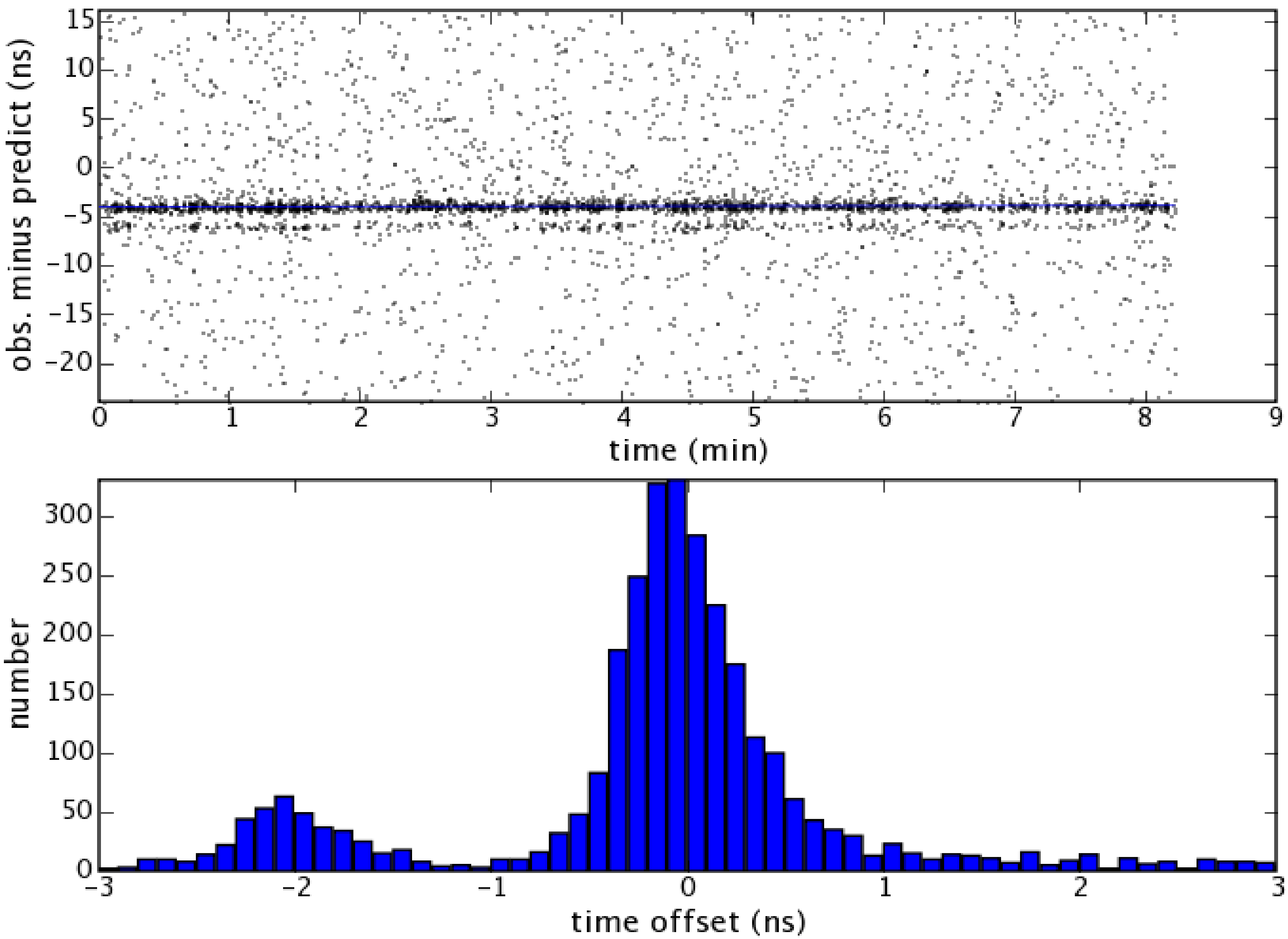
Return photons from reflector

width is < 1 foot (finite array size)

2150 photons in 14,000 shots

Randomly-timed background photons (bright moon)

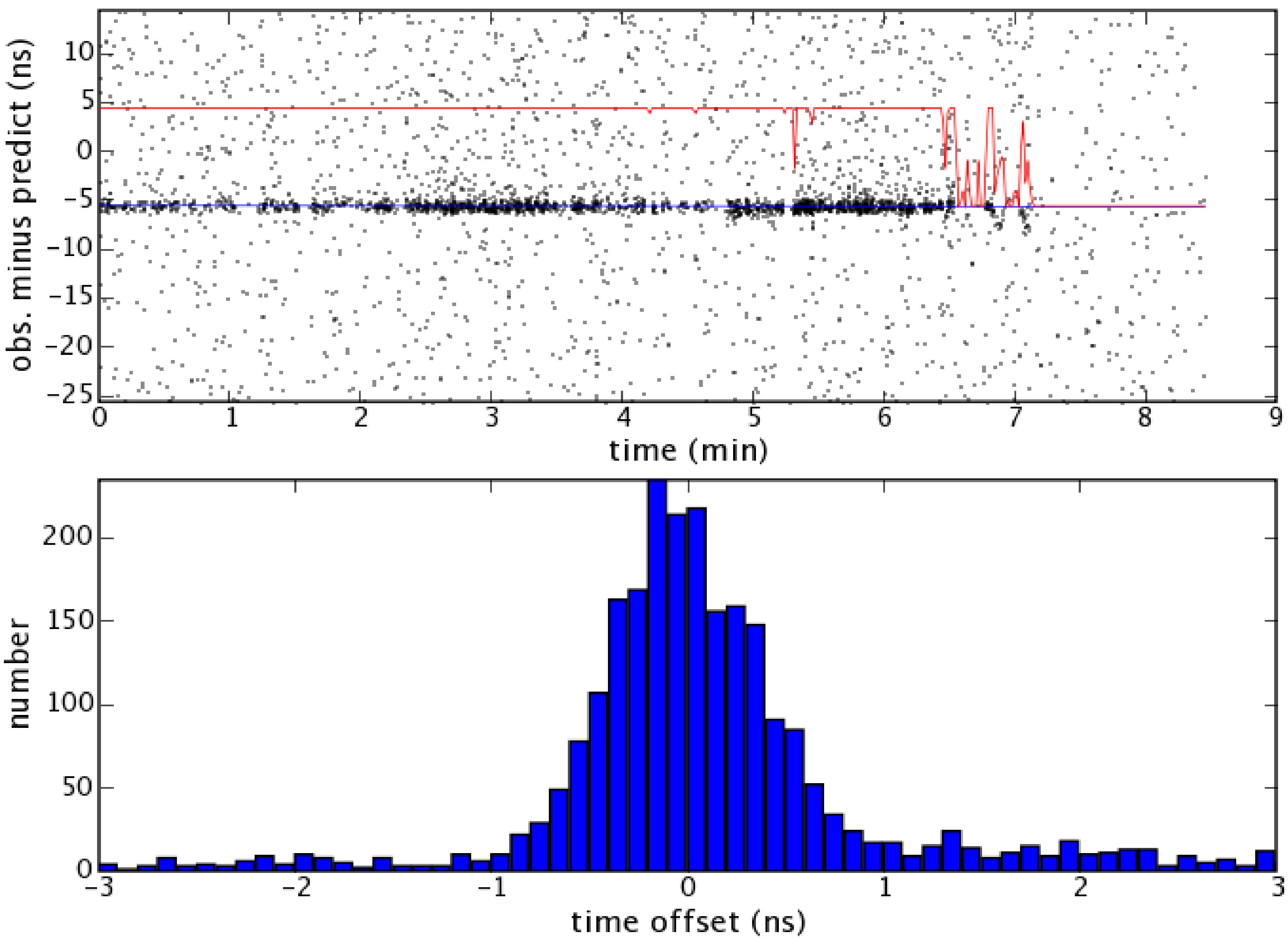
Hands-off run



2500 photons in
10000 shots

mild double-pulse
behavior of laser

Another example

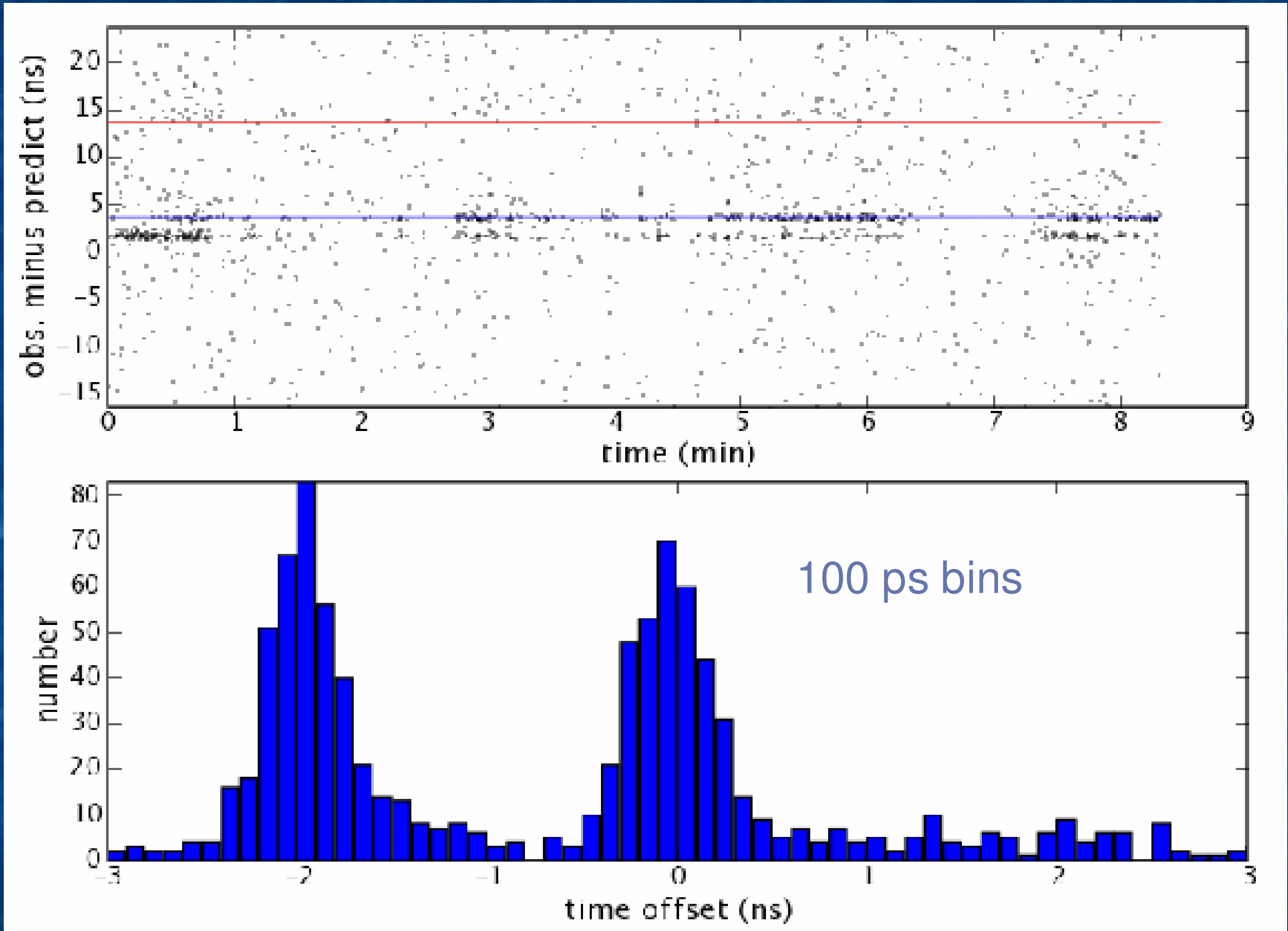


2000 photons in 8000 shots

no more double pulse

Millimeter Accomplished

June 4, 2006 run



600-photon run
(laser double-pulsing)

< 500 ps FWHM
→ 200 ps RMS

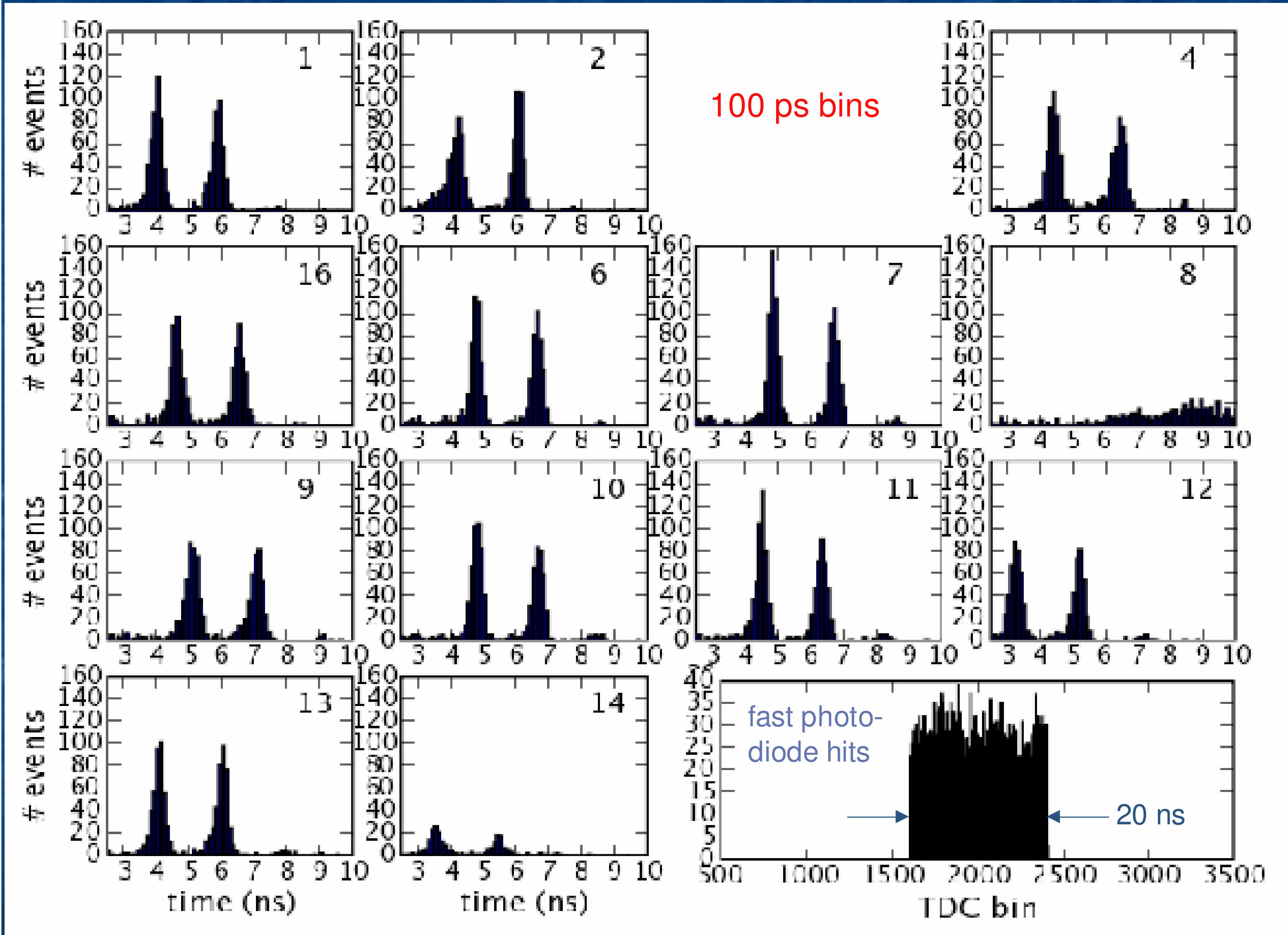
centroid error:
200/sqrt(600) → 8 ps →
1.2 mm one way error

well-separated double pulse is okay, but has been fixed nonetheless

prediction offset is a few nanoseconds

Channel-by-Channel Fiducial Measurement

June 4, 2006 run



The fiducial corner-cube provides local time-of-departure measurement

Each APD channel is separately "calibrated" for time offset, timing performance, detection effficiency, etc.

250 ps FHWM → 100 ps RMS → 15 mm single-photon time error (matches error budget predictions)

1 mm in 225 photons ignoring libration error

APOLLO Superlatives

- More lunar return photons in 10 minutes than other LLR stations get in months to years
  - best single run: >2500 photons in 10,000 shots (8 minutes)
- Peak rates of >0.5 photons per shot (10 per second)
  - and steady rates at 1/4 photons per shot
  - compare to typical 1/500 for McDonald, 1/100 for France
- Range with ease at full moon
  - APOLLO's *very first* returns were at full moon
  - other stations can't fight the high background
- As many as 8 photons detected in a single pulse!
  - In best runs, *half* of detected photons in multi-photon clumps
  - APD **array** is *essential*

Project Timeline

- First acquisition in fall 2005
  - Lenslet installed in October; photons followed
- First "science-quality" data April 6, 2006
  - following fix of known systematic error sources and proper interleaving of fiducial returns
- Acquisition puzzle solved June 2006
- Entered campaign mode: Oct. 1, 2006
- Sufficient data for order-of-magnitude EP in ~1 year
  - expect first results in spring/summer 2007
- Now pushing on data reduction → normal points
- Model refinement/improvement campaign in parallel
  - in conjunction with JPL/Jim Williams
- Continued data collection/analysis for years to come