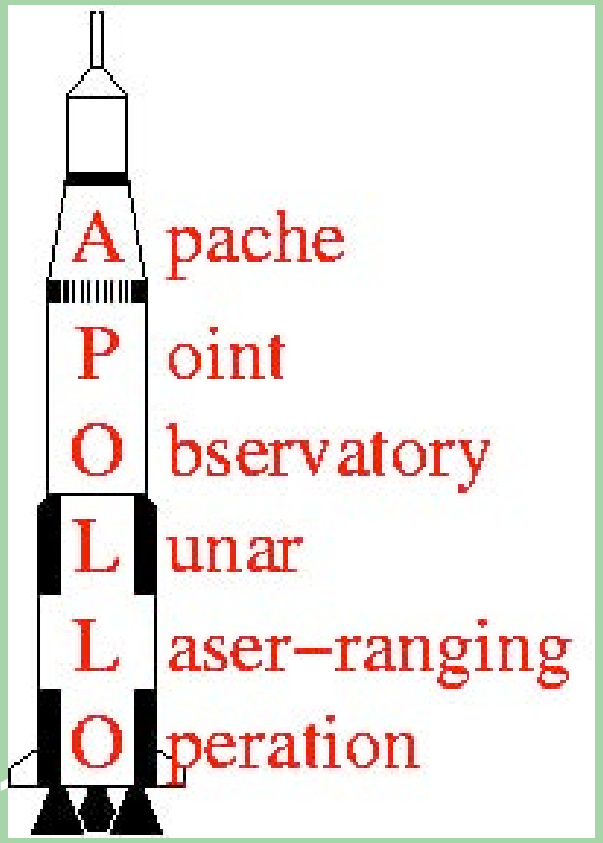
Next-Generation Lunar Laser Ranging



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APOLLO Collaboration

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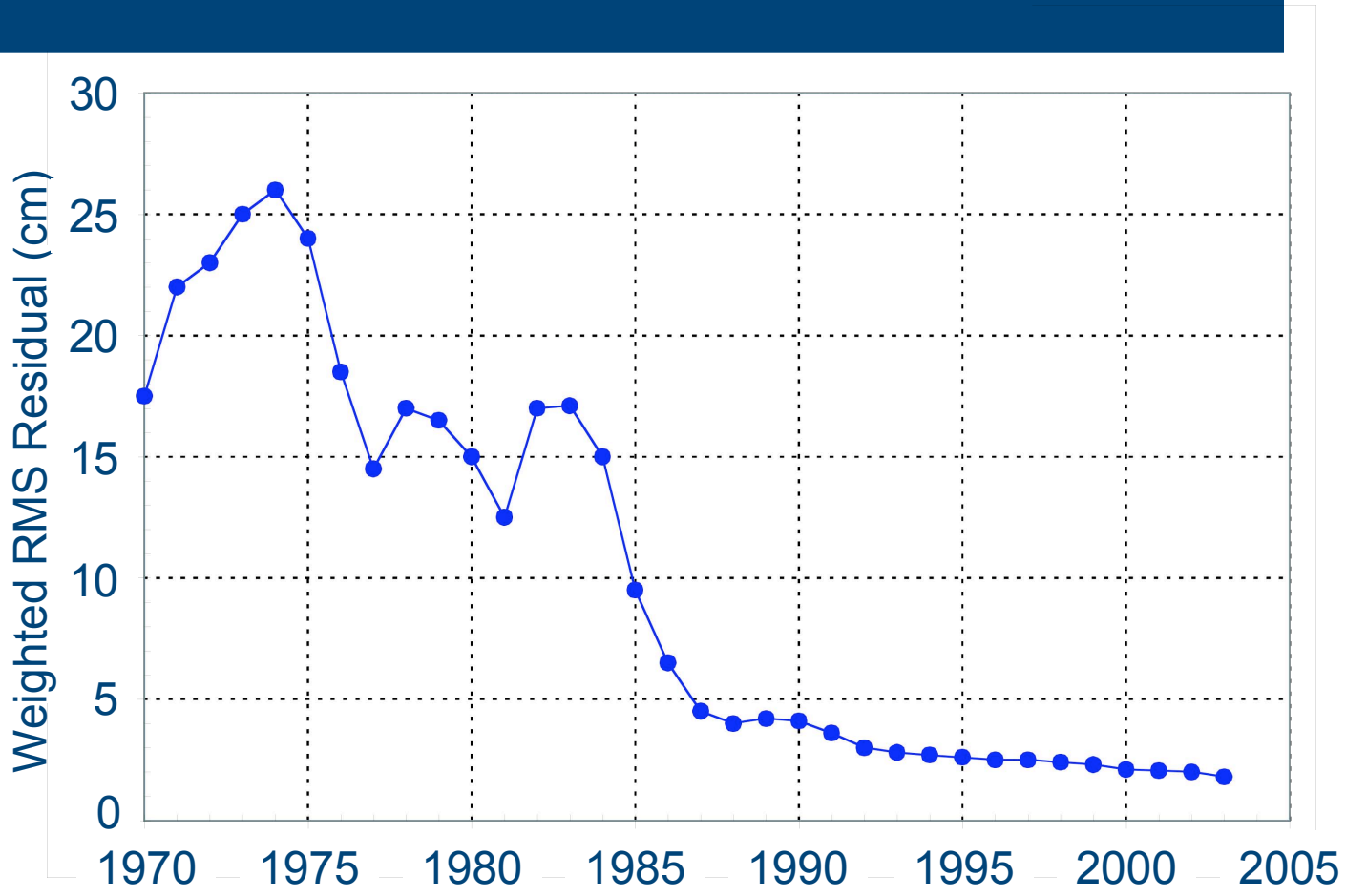
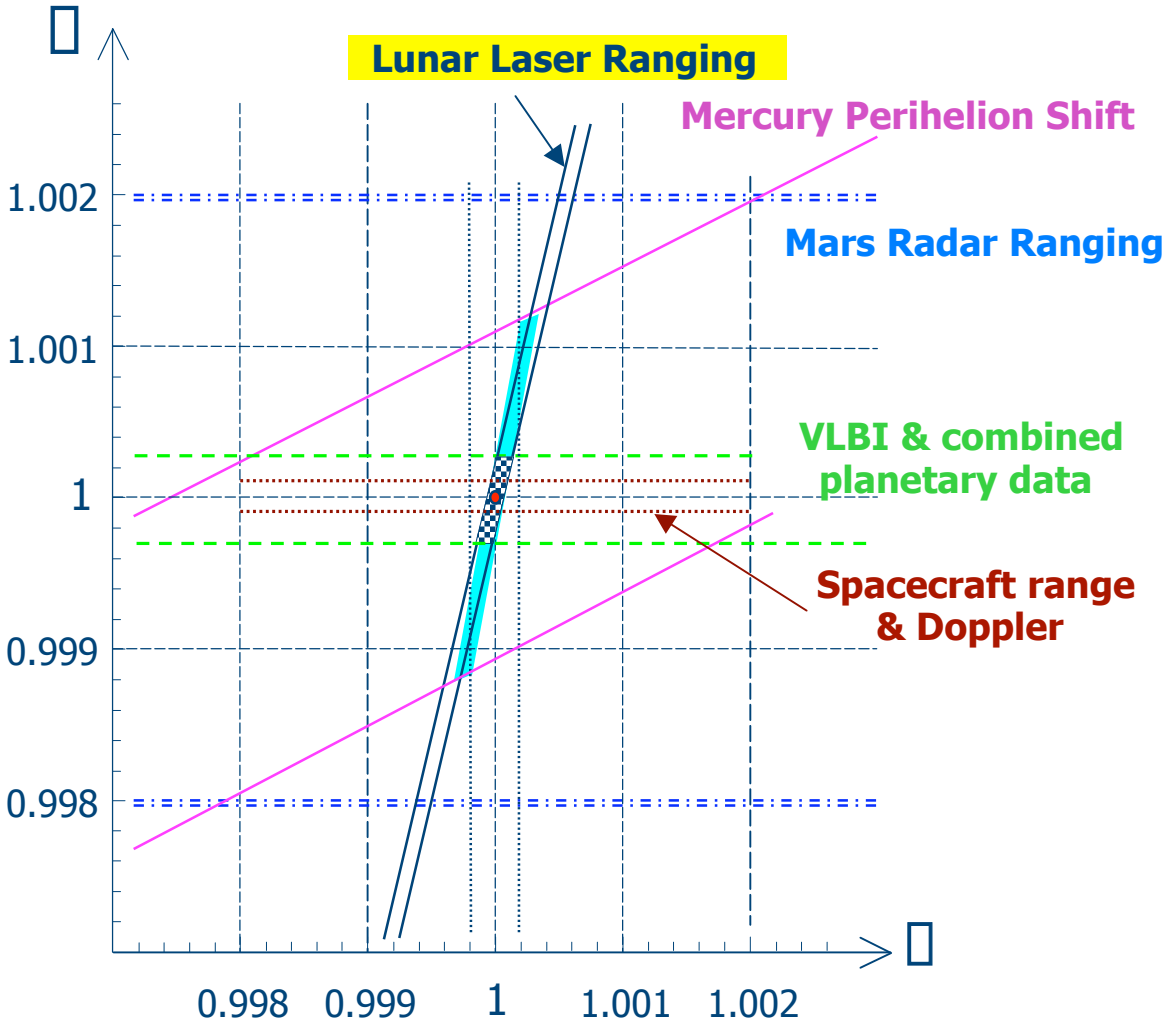
Historical Accuracy of Lunar Ranging



The APOLLO goal is to reduce the range error to ***one millimeter***

Current PPN Constraints on GR



- Is the Parameterized Post-Newtonian (PPN) formalism still relevant?

  Basic phenomenology:

  measures curvature of spacetime

  measures nonlinearity of gravity

- What fool would want to push this further? Isn't GR obviously right?

“Real” Rationale for Pushing Further

- Cosmological departures from old GR model
  - Acceleration of expansion of Universe
- Fine structure constant, □, possibly varying?
  - What about gravitational constant, Equivalence Principle
- Scalar Field modifications to GR
  - Predictions of PPN departures from GR
- Brane-world cosmological models
  - Gravitons leaking into bulk, modifying gravity at large scales

APOLLO: Next-Generation LLR

recipe for success:

- Move LLR back to a large-aperture telescope
  - 3.5-meter: more photons!
- Incorporate modern technology
  - Detectors, precision timing, laser
- Focus attention on fundamental gravity
- Devise brilliant acronym:
  - Apache Point Observatory Lunar Laser-ranging Operation

APOLLO Goals*:

- One millimeter range precision
- Weak Equivalence Principle (WEP) to $\Delta a/a \approx 10^{-14}$
- Strong Equivalence Principle (SEP) to $\eta \approx 3 \times 10^{-5}$
- Gravitomagnetism (frame dragging) to 10^{-4}
- dG/dt to $10^{-13} \cdot G$ per year
- Geodetic precession (μ) to $\approx 3 \times 10^{-4}$
- Long range forces to 10^{-11} _ the strength of gravity

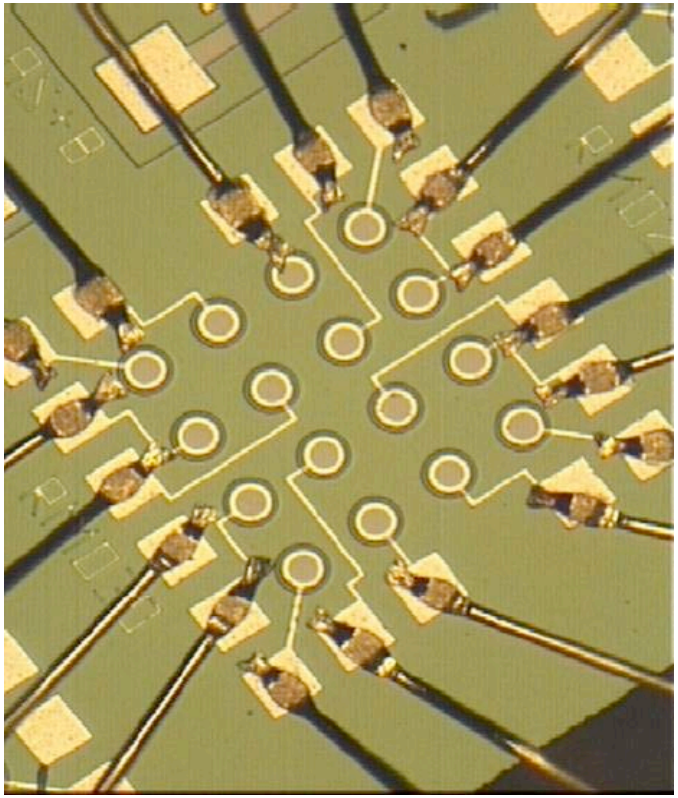
* These 1 errors are simply ~10 times better than current LLR limits. In each case, LLR currently provides *the best* limits. Timescales to achieve stated results vary according to the nature of the signal.

The APOLLO Apparatus

- Uses 3.5-meter telescope at 9200-ft Apache Point, NM
- Excellent atmospheric "seeing"
- 532 nm Nd:YAG, 100 ps, 115 mJ/pulse, 20 Hz laser
- Integrated avalanche photodiode (APD) arrays
- Multi-photon capability
- Daylight/full-moon capability

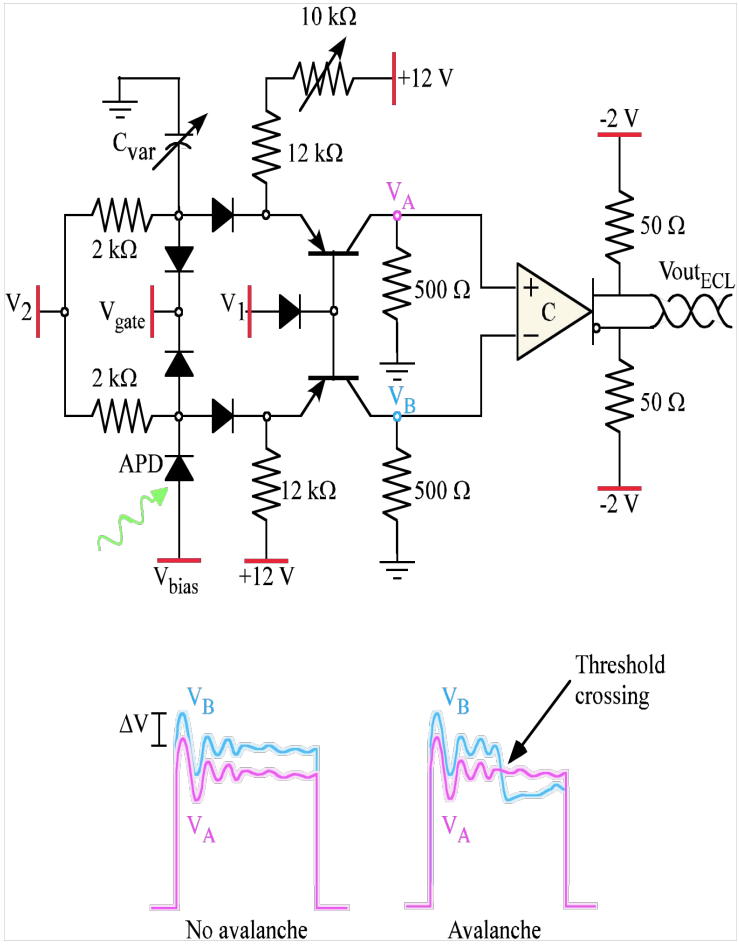
APD Arrays

- We have a working prototype courtesy MIT Lincoln Labs
- 4_4 format (LL has made much larger)
- 30□m diameters on 100□m centers
- Fill-factor recovered by lenslet array
- ~45 ps jitter at 532 nm, ~50% photon detection eff.
- Multiple “buckets” for photon bundle
  - allows simultaneous time-tagging of multiple photons
  - provides spatial/tracking information



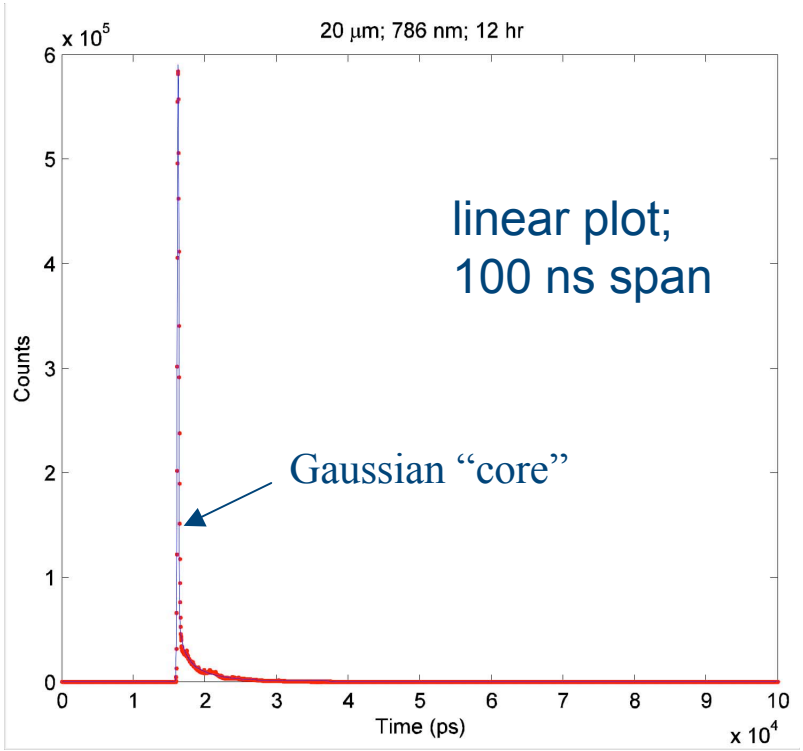
Differential Detection Scheme

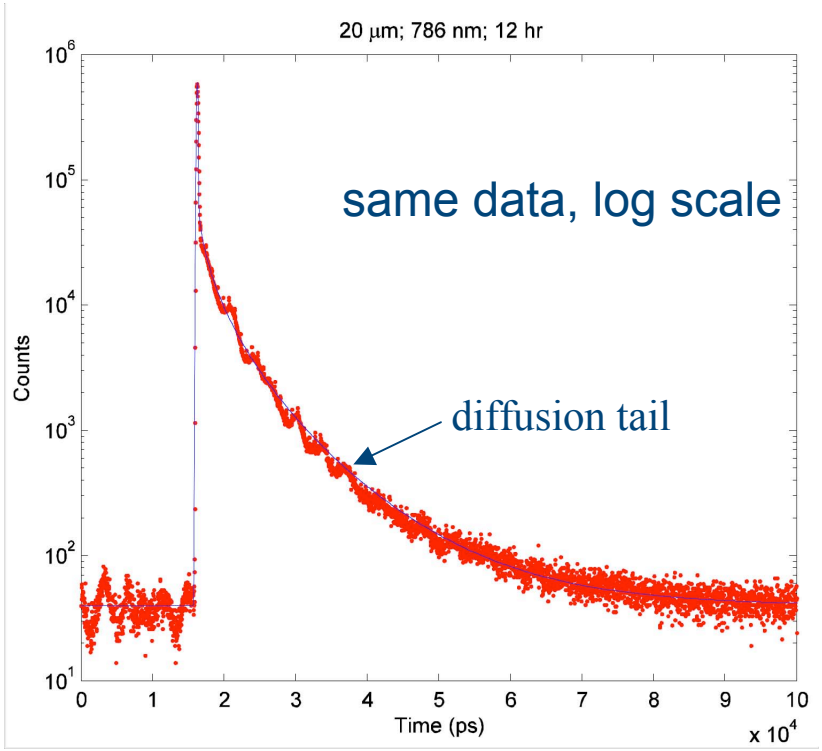
- Follows Lacaita et al. (1995) approach
- Dummy capacitor matched to APD allows differential sensing
- better than 15 ps jitter performance (verified)
- ECL output forms START pulse for Time-to-digital Converter (TDC)



Characterizing APD Performance

- Using fast-pulse 786 nm laser diode, probed APD spatial/temporal response
- Deep (10 □m) penetration of 786 nm light into silicon permitted us to fully explore avalanche and diffusion regions of device in single photon mode





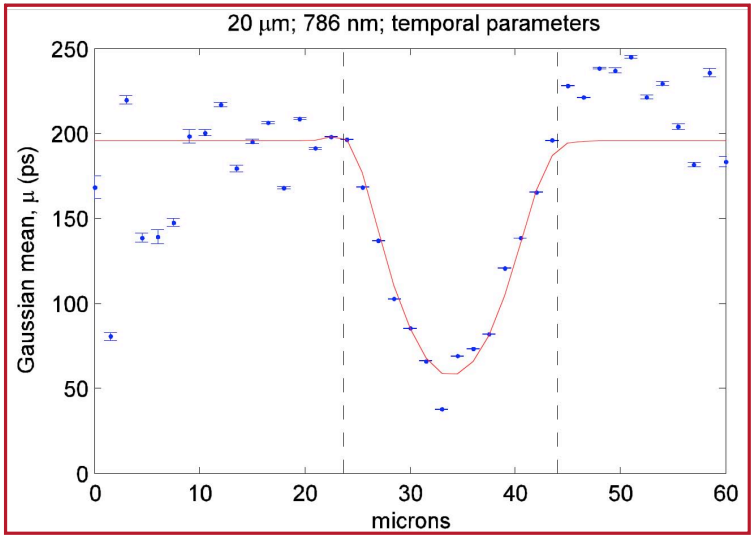
Wavelength Dependence of APD

- In addition to the 786 nm test laser, we used a 668 nm short-pulse laser to test the APDs
- Developed a model of temporal response based on known doping profile of APD device
- Good agreement allows us to *predict* performance at 532 nm:
  - penetration depth is 1 □m
  - Long diffusion tail is virtually eliminated
  - Estimated single-photon timing uncertainty: 50 ps

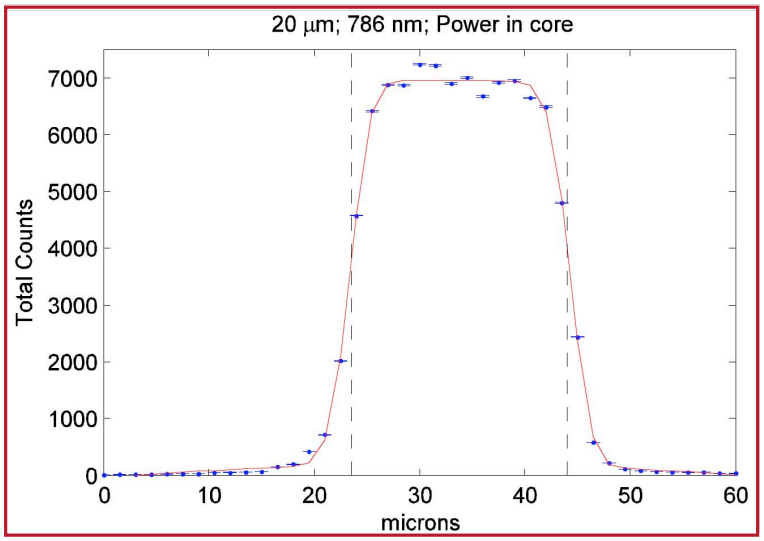
Spatial Response of APD

- By scanning a small laser spot across the detector element (either 20 or 30 □m elements), we were able to determine that:
  - the spatial (flux) response of the element is uniform
  - the flux in the diffusion tail is spatially quadratic, diminishing at the sides due to the guard ring
  - the time-of-report "walks" as a function of photon position within the device
- This last point depends on the details of avalanche propagation

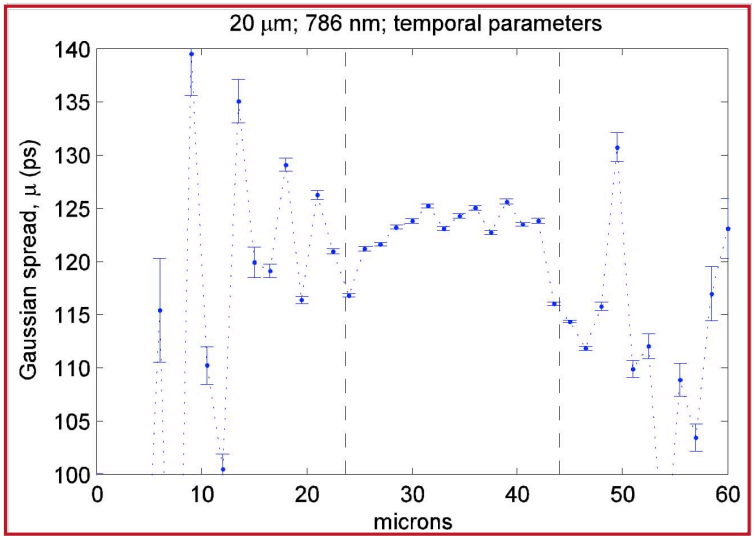
Example results from the 20 μm device



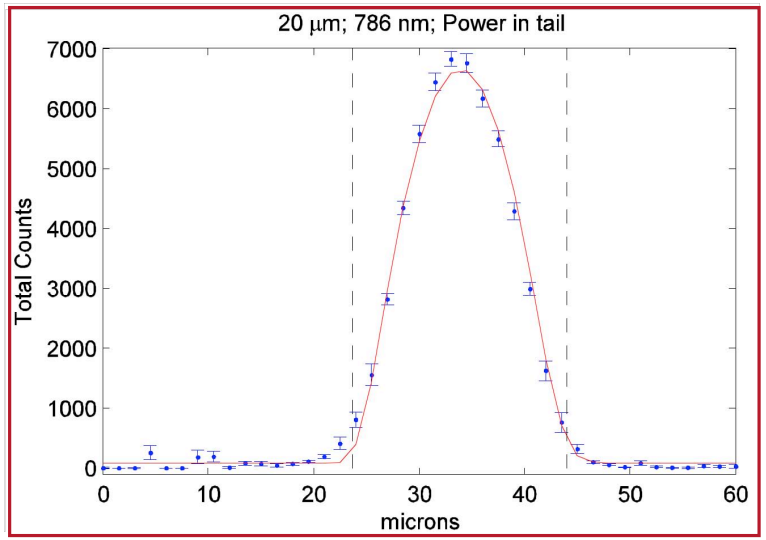
Temporal walk of Gaussian core



Total counts within Gaussian core

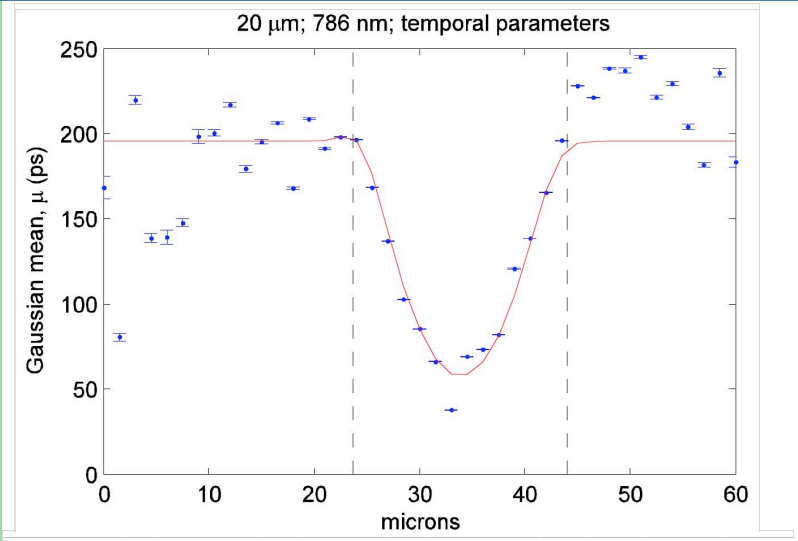


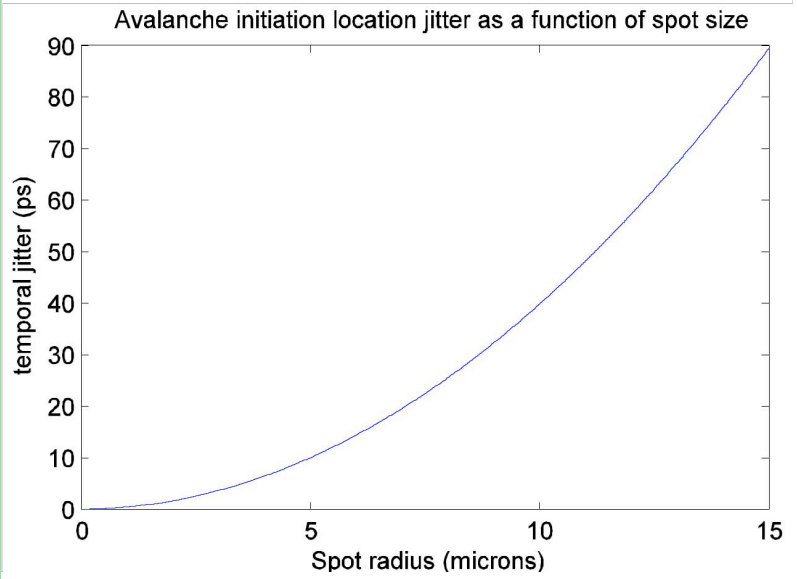
Uniform width of Gaussian core



Total counts within diffusion tail

Implications of Avalanche Walk





- Centrally-initiated avalanche reaches full-scale sooner
- Sluggish at edges
- Informs us about illumination spot size
- A 25 □m spot results in 60 ps of effective jitter
  - will be the dominant effect in these devices

APD Characterization Summarized

- Detailed investigation of detector properties (Jana Strasburg thesis material)
- Connection to understood device physics
- This understanding will allow us to remove potential range biases
  - e.g., illumination of detector is different for lunar vs. internal corner-cube returns; previously discussed “walk” would introduce bias if not understood

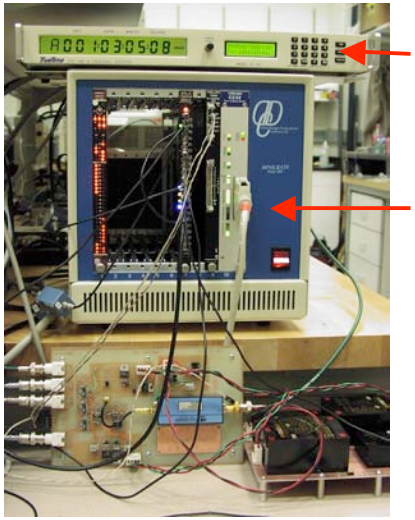
APOLLO Random Error Budget

Expected Statistical Error	RMS Error (ps)	One-way Error (mm)
Laser Pulse (95 ps FWHM)	40	6
APD Jitter (including walk)	75	11
TDC Jitter	15	2.2
50 MHz Freq. Reference	7	1
APOLLO System Total	86	13
Lunar Retroreflector Array	80–230	12–35
Total Error per Photon	115–245	18–37*

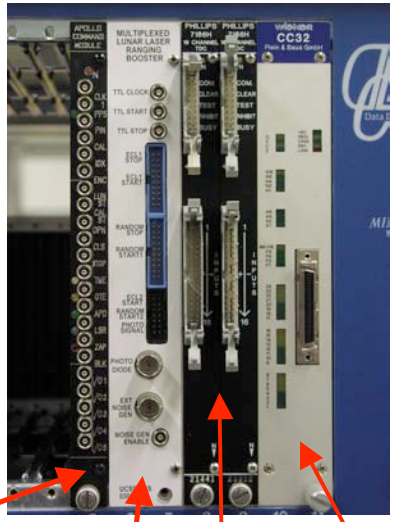
* Need 300–1400 photons for millimeter statistical error; one minute for APOLLO at one photon per pulse, 20 Hz (could see 5 photons/pulse)

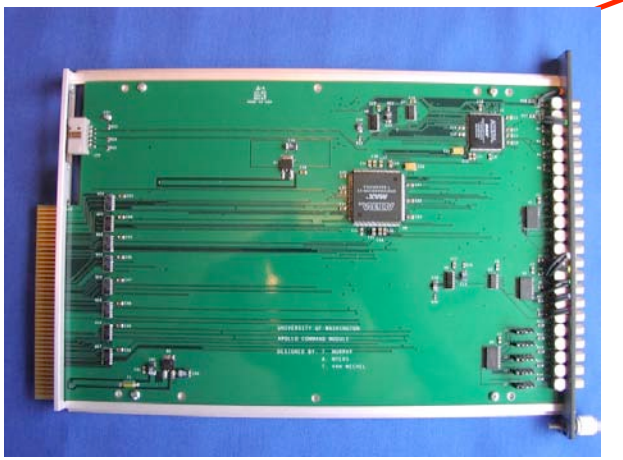
Timing Electronics Built/Verified

Timing System in Operation

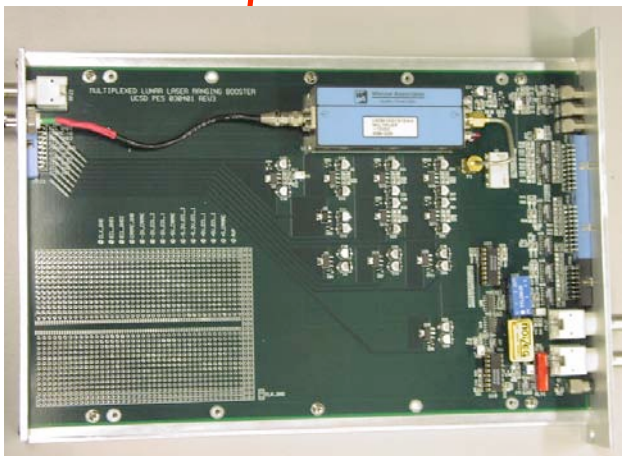


CAMAC Crate Inhabitants





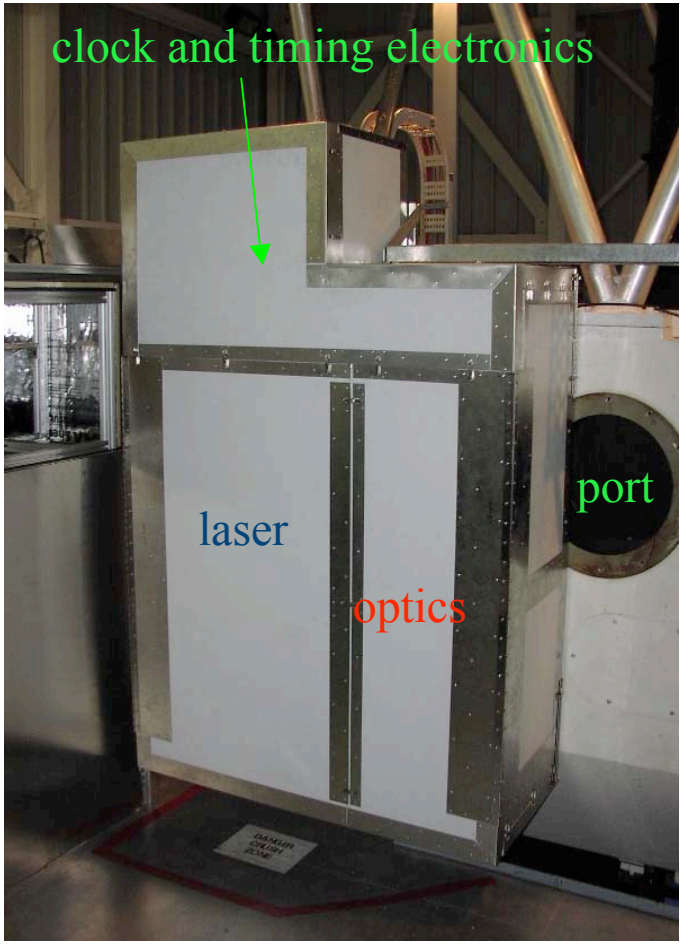
APOLLO Command Module
Timing/APD control, CPU interface



Calibration/Frequency Board

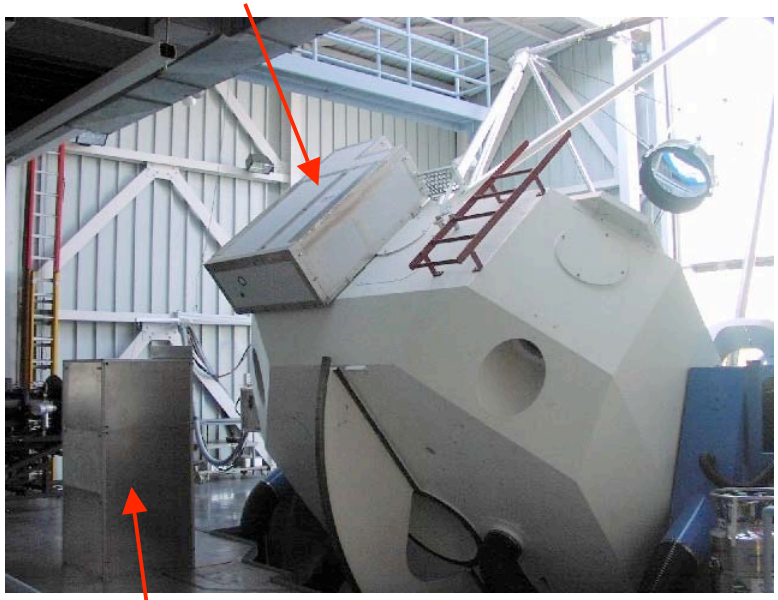
Laser Mounted on Telescope

Laser bench kinematically mounted



In thermal enclosure (“fridge”)
8.6 cm thick

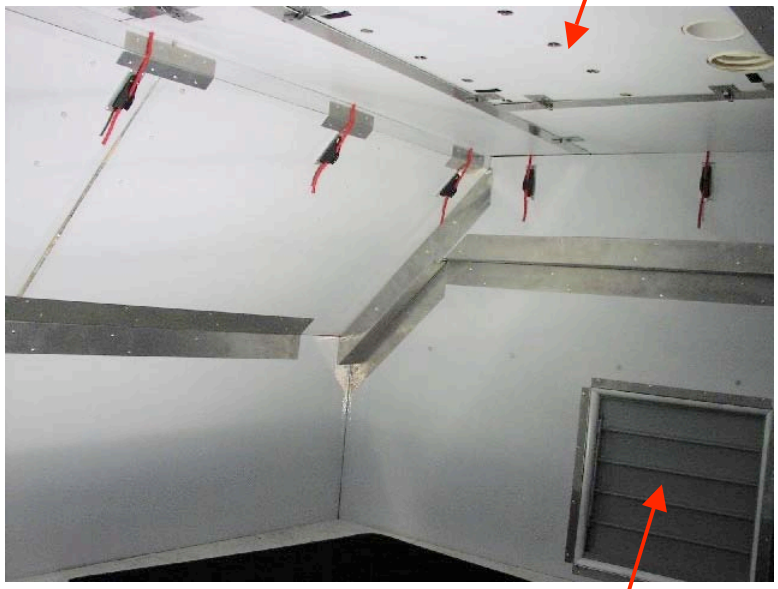
Observing Floor Layout

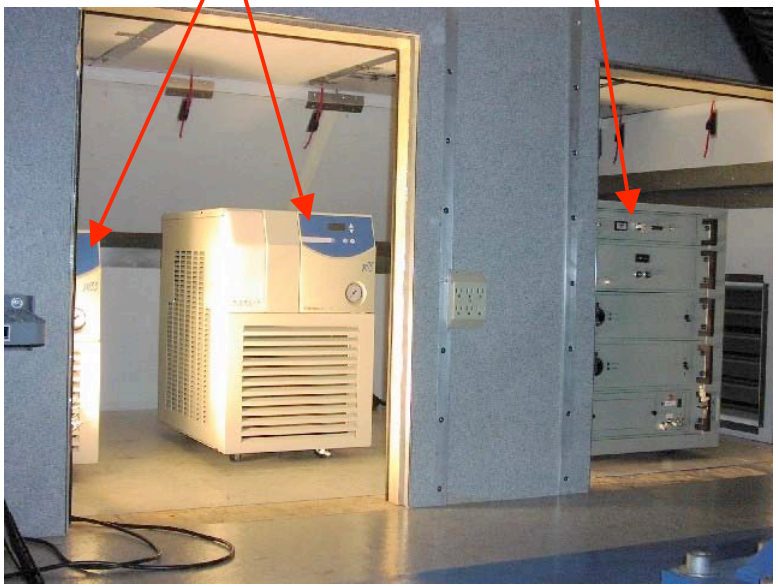


Significant challenge to construction is observatory's demand that we keep thermal emissions < 50 W in dome!

cabinet encloses control computer, laser capacitor banks, and other electronics that must be close to laser-bench components

Insulated Enclosure for Electronics





4–5 kW of power in this custom-built room (walls 6 cm thick), exhausted to lower level of observatory where it is flushed out

Summary of Progress

- Most of infrastructure now in place
- Past months have been dominated by manipulation of foam (sick of it!!)
- *Very* active this summer, anticipate laser fire in the fall
- Science results within a year?
- Virtual tour: http://physics.ucsd.edu/~tmurphy/apollo/tour.html