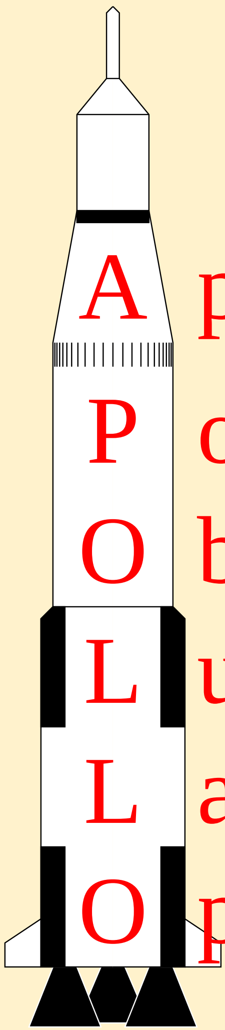
APOLLO: Multiplexed Lunar Laser Ranging



Apache
Point
Observatory
Lunar
Laser–ranging
Operation

Tom Murphy	University of Washington (& UC San Diego)
Eric Adelberger	University of Washington
Jean Dickey	Jet Propulsion Laboratory
Bruce Gillespie	Apache Point Observatory
John Goodkind	UC San Diego
Ken Nordtvedt	Northwest Analysis
Jana Strasburg	University of Washington
Chris Stubbs	University of Washington
Jim Williams	Jet Propulsion Laboratory

LLR Science

Gravitational Physics:

- The *best* test available of the strong equivalence principle (EP)
- A *leading* test of the weak (composition-dependent) EP
- The *best* test of time-variation of Newton's constant, G
- Currently the *best* probe of relativistic geodetic precession

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Other Science:

- Lunar interior
- Coordinate systems
- Geophysics

APOLLO Goals/Expectations

- One-millimeter RMS normal point precision
- Test of the strong equivalence principle to 3×10^{-5}
- Test of the weak equivalence principle with $\Delta a/a \approx 10^{-14}$
- Measurement of $\dot{G}/G$ to 10^{-13} yr^{-1}
- Measurement of geodetic (de Sitter) precession to $\sim 3 \times 10^{-4}$
- Similar order-of-magnitude gains in lunar science, coordinate determinations, etc.

Where Are We Now?

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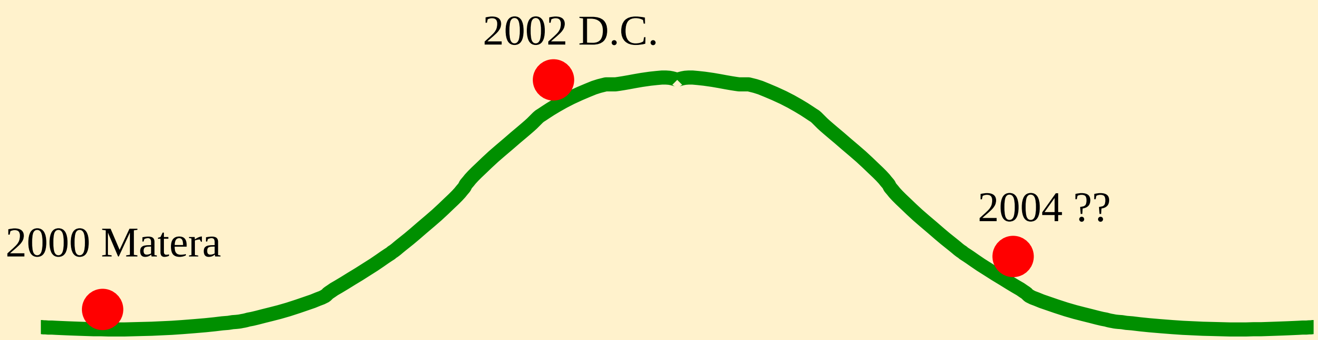
Technological Hump



Science Motivation

Science Results

APOLLO's photon rate expectations

$$N_{detect} = \text{5.4 photons} \times \left(\frac{E}{\text{115 mJ}}\right)\left(\frac{\eta}{0.4}\right)^2\left(\frac{f}{0.25}\right)\left(\frac{Q}{0.30}\right)\times \left(\frac{n}{100}\right)\left(\frac{\text{1 arcsec}}{\Phi}\right)^2\left(\frac{\text{10 arcsec}}{\phi}\right)^2\left(\frac{\text{384,402 km}}{r}\right)^4$$

E = laser pulse energy

η = one-way optical throughput

f = narrow-band filter throughput

Q = photon detection efficiency (APD)

n = number of 3.8 cm corner cubes in array

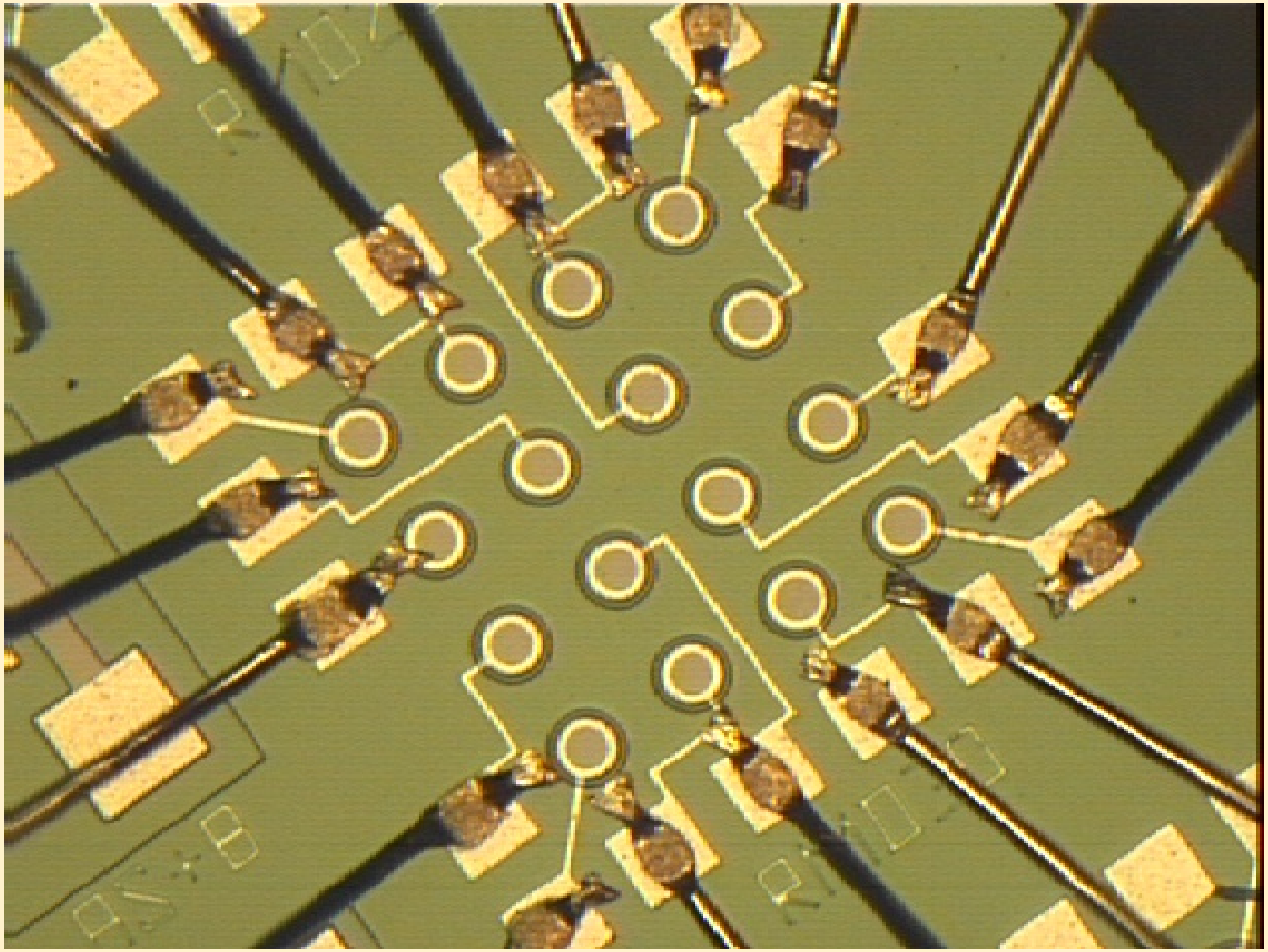
Φ = atmospheric "seeing"

ϕ = corner cube effective divergence

r = earth-moon distance

Avalanche Photodiode Array:

Gateway to multiple photons



Lincoln Labs APD Array

Multi-photon Advantages

- Can arrange for *every* shot to be calibrated, since $\langle N_{\mathrm{cal}} \rangle \sim 5$
- Get a range profile (albeit sparse) of the target array with each shot

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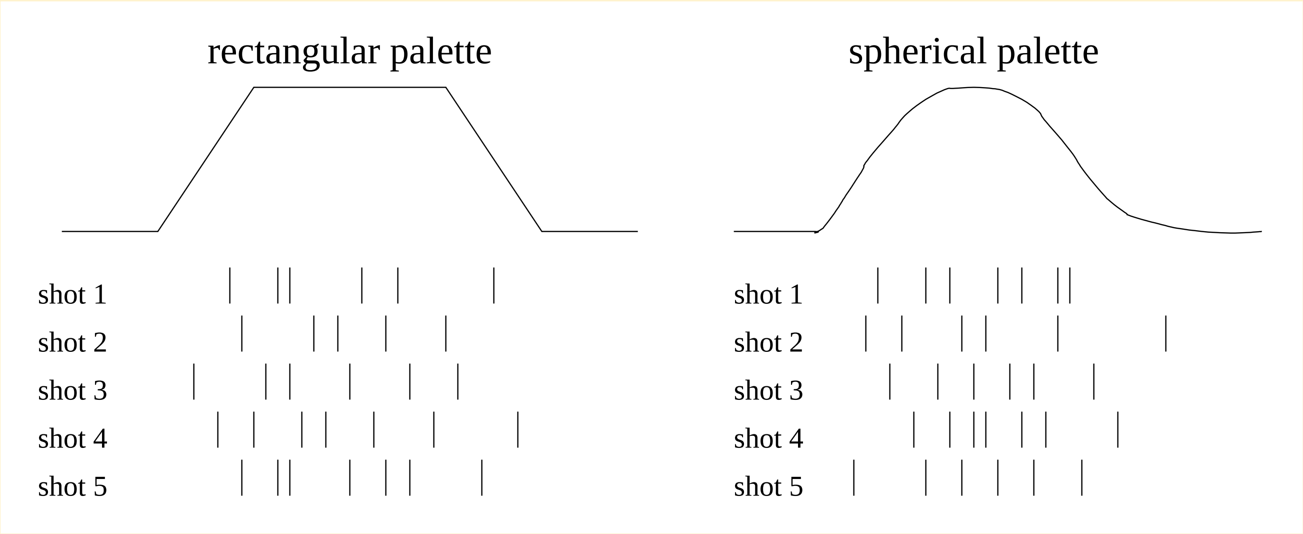
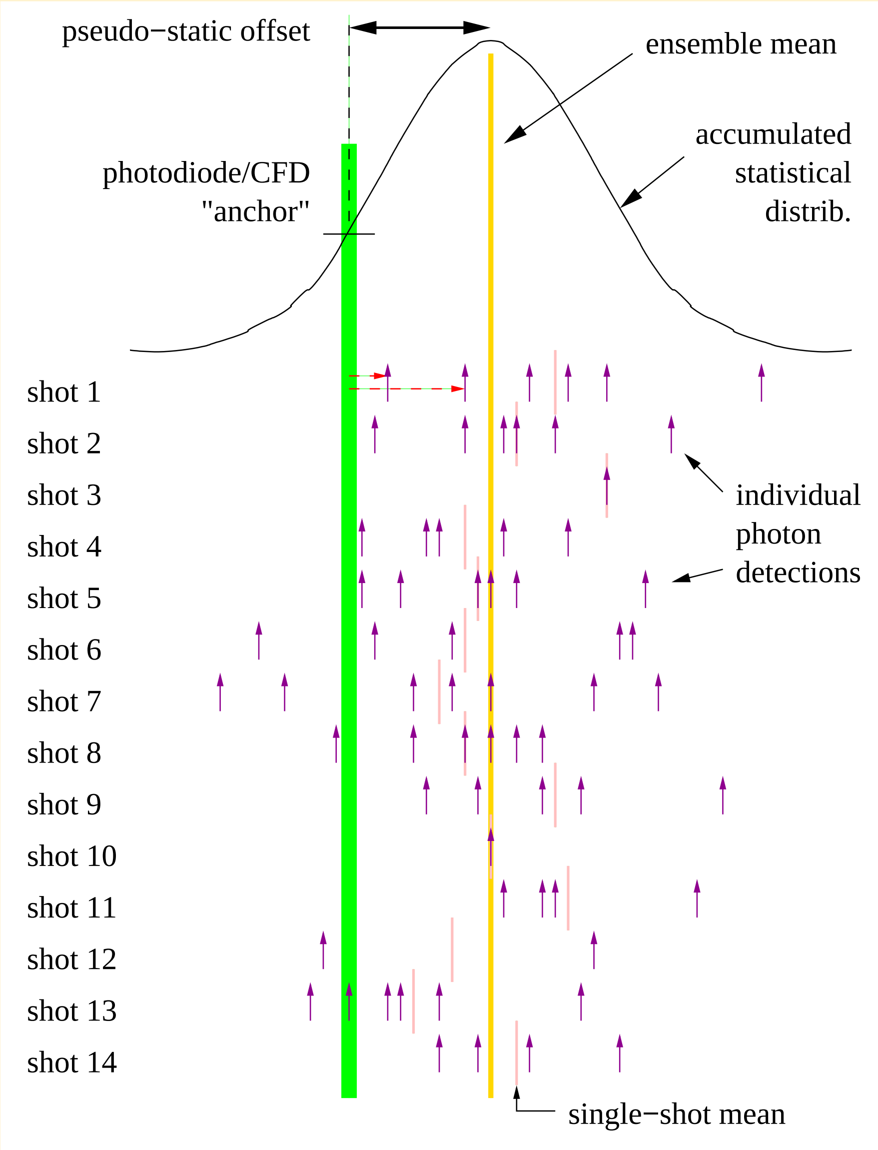


Calibration Scheme



- Fast photodiode plus CFD determines laser pulse time to ± 15 ps
- Each photon is referenced to this time (green line)
- Ensemble yields mean (yellow line) and pulse shape (plus timing electronics contribution)
- Offset is constant over short term ($\sim$ 5 min)
- Running average allows offset to vary with environmental conditions

Multiplexed Timing Scheme

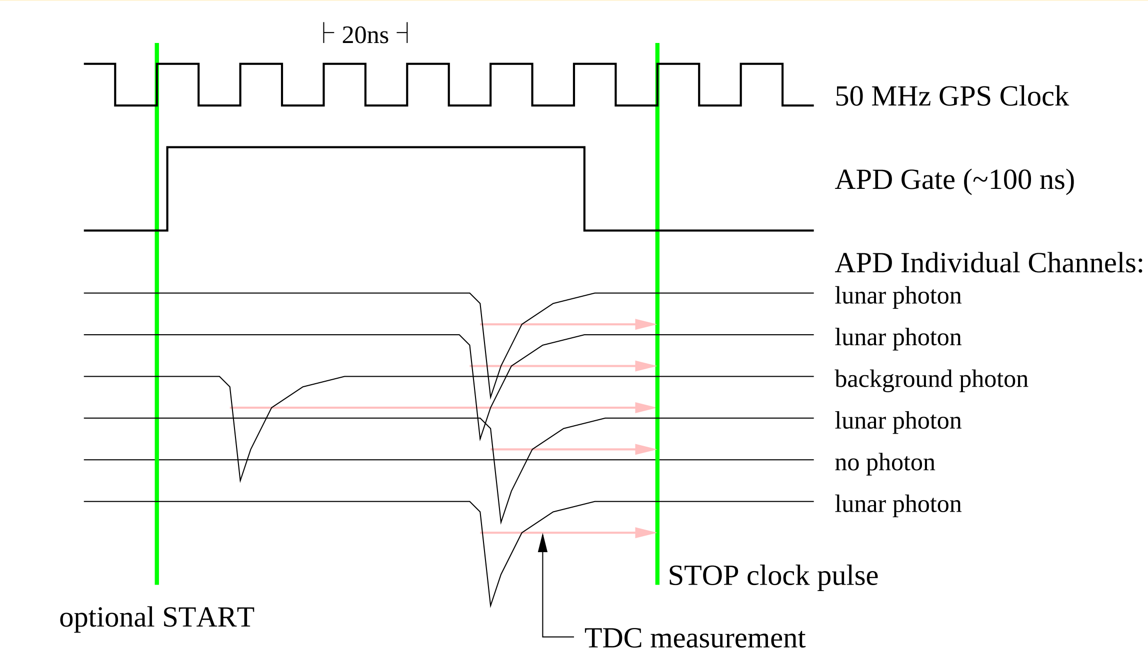
- The usual event timers are not capable of multiplexing a handful of photons within a nanosecond
- The *Phillips Scientific* 7186 Time-to-Digital Converter (TDC) *is* multiplexed with 16 channels per module
- The 7186 is a CAMAC module, and has driven our design accordingly

Phillips Scientific 7186 TDC Properties

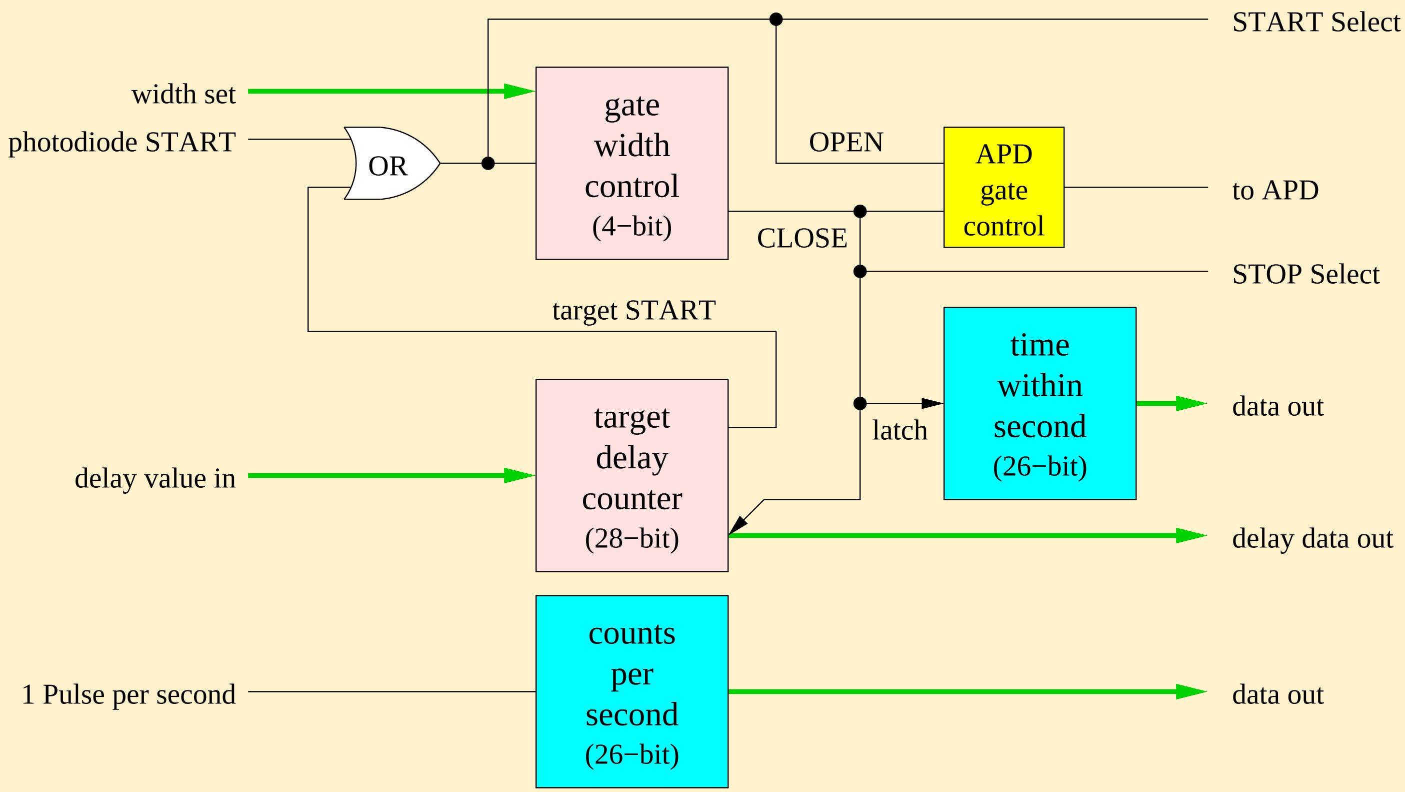
Jitter	13 ps
Range	100 ns
Resolution	12-bit (25 ps)
Differential Linearity	25 ps across range
Thermal Stability	100 ppm per $^\circ$C
Features	Sparse read, Thresholds, Pedestal

Timing Diagram

- GPS-disciplined clock (*TrueTime XL-DC*) at 50 MHz serves as both frequency reference (7 ps RMS jitter over 2.5 sec) and as digital clock
- TDC measures Δt between photon event and *selected* clock pulse, while digital counters keep track of coarse (20 ns) time
- Common STOP clock pulse selection is *synchronized* with clock



Block Diagram of Timing Scheme



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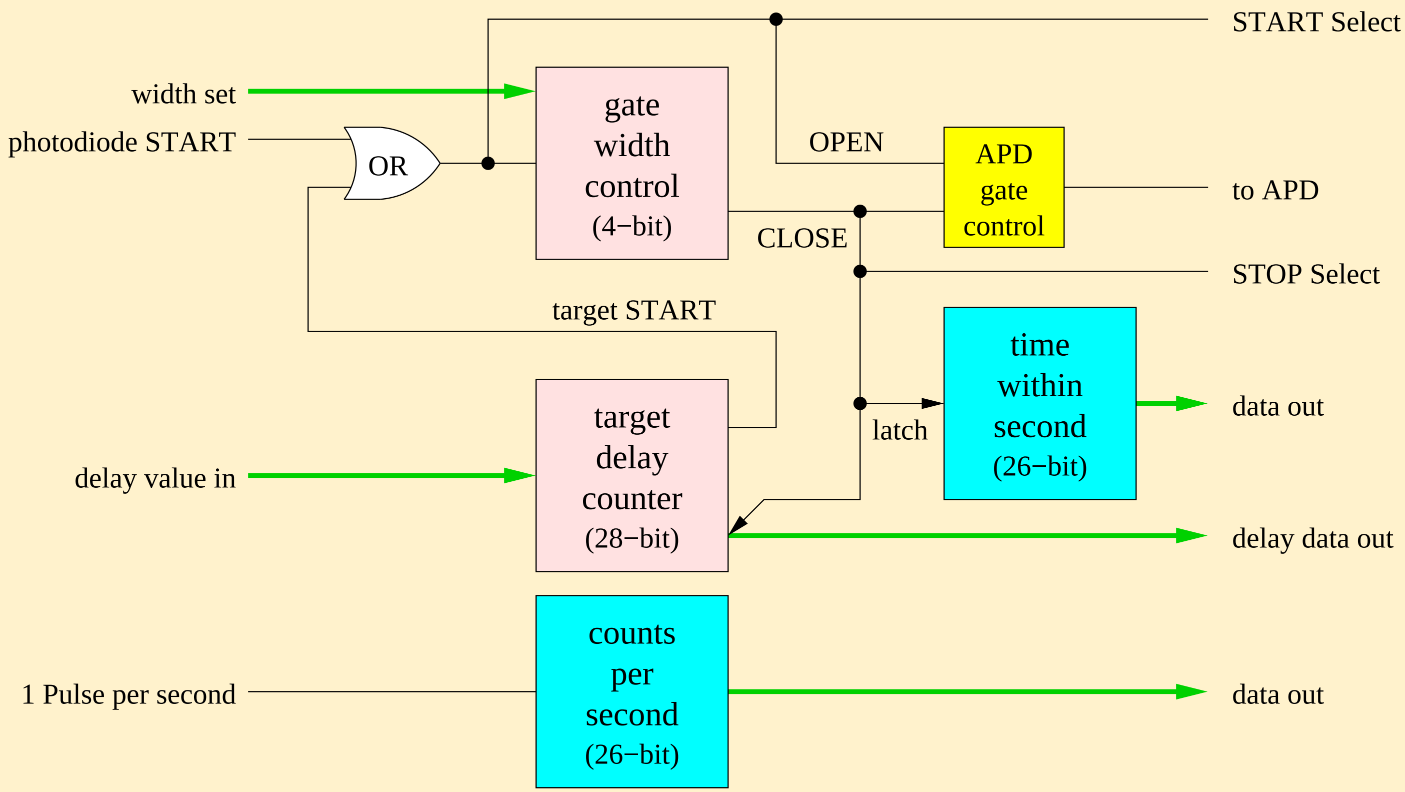
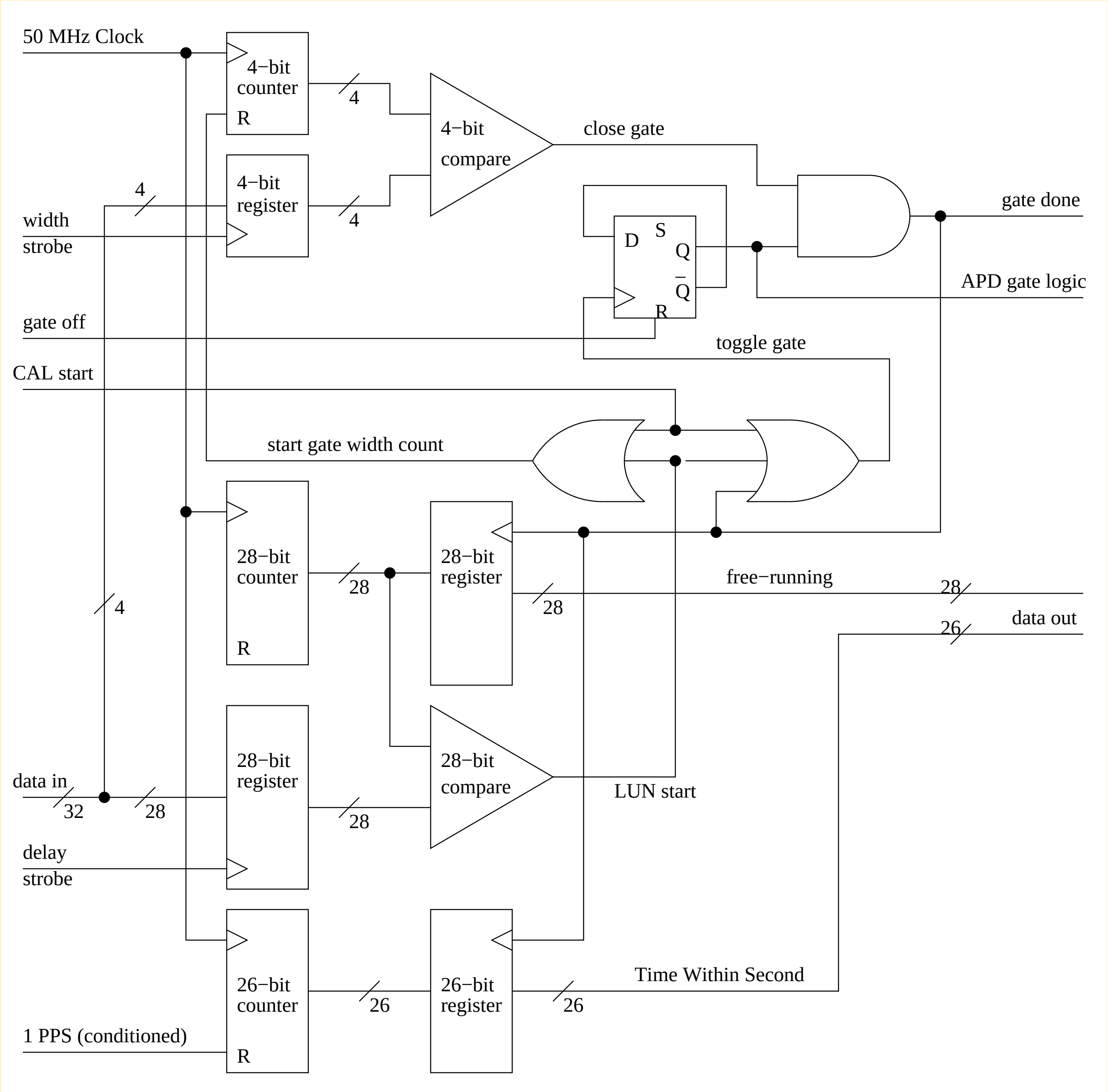
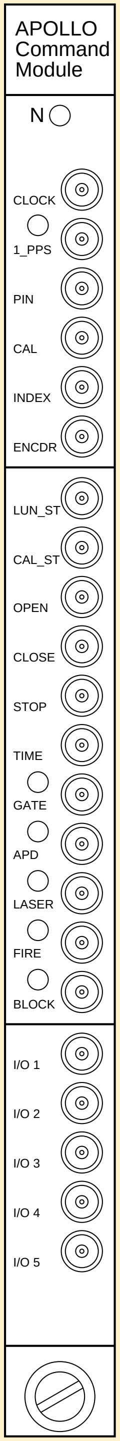


Based on counters at 50 MHz, registers, comparators, standard logic...


50 MHz Clock
4−bit counter
R
4−bit register
4
4
4
4−bit compare
close gate
gate done
width
strobe
D
S
Q
Q
R
APD gate logic
gate off
toggle gate
CAL start
start gate width count
28−bit counter
R
28−bit register
28
28
free−running
28
26
data out
4
28−bit register
28−bit compare
data in
32
28
28
LUN start
delay
strobe
26−bit counter
R
26
26−bit register
26
Time Within Second
1 PPS (conditioned)



APOLLO Command Module

The ACM is a custom CAMAC single-width module based on a pair of *Altera* programmable logic devices, handling the digital logic associated with:

- counting clock pulses and registering significant epochs
- activating the APD gate at the appropriate time, with tunable width
- providing output enable signals for selecting individual clock START/STOP pulses for the TDC
- calibrating the TDC with START/STOP pulses $N \times 20.00$ ns apart, ± 10 ps
- firing the laser in response to the T/R switch encoder
- various safety features associated with laser fire and APD duty-cycle

Project Status

- Laser delivered to APO (Continuum *Leopard*; 532 nm, $<$100 ps pulsewidth, 115 mJ/pulse, 20 Hz)
- Timing/Control Electronics nearing completion of assembly/testing; ACM in production
- Optical design complete, procurement initiated
- Error budget shaping up nicely...

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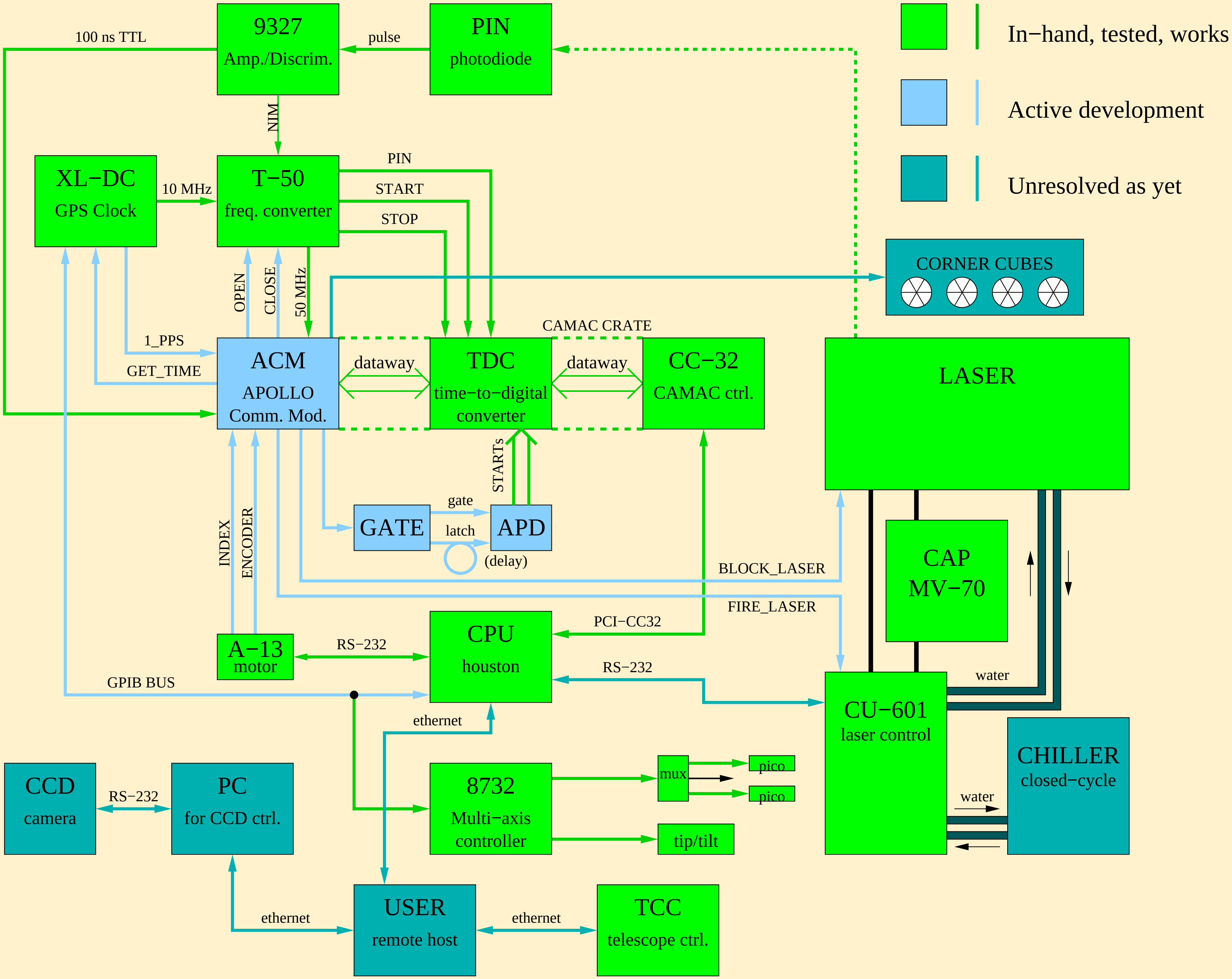
Statistical Error Source	RMS Error (ps)	One-way Error (mm)
Laser Pulse (95 ps FWHM)	40	6
APD Jitter	30	4.5
TDC Jitter	15	2.2
50 MHz Freq. Reference	7	1
APOLLO System Total	52	8
Lunar Retroreflector Array	80–230	12–35
Total Error per Photon	100–240	14–37


9327
Amp./Discrim.
PIN
photodiode
pulse
100 ns TTL
NIM
XL−DC
GPS Clock
10 MHz
T−50
freq. converter
PIN
START
STOP
OPEN
CLOSE
50 MHz
1_PPS
GET_TIME
ACM
APOLLO
Comm. Mod.
dataway
TDC
time−to−digital
converter
dataway
CC−32
CAMAC ctrl.
CAMAC CRATE
CORNER CUBES
LASER
STARTs
GATE
gate
latch
APD
(delay)
INDEX
ENCODER
BLOCK_LASER
FIRE_LASER
CAP
MV−70
A−13
motor
RS−232
CPU
houston
PCI−CC32
RS−232
CU−601
laser control
water
GPIB BUS
ethernet
CHILLER
closed−cycle
water
CCD
camera
RS−232
PC
for CCD ctrl.
8732
Multi−axis
controller
mux
pico
pico
tip/tilt
USER
remote host
ethernet
ethernet
TCC
telescope ctrl.
In−hand, tested, works
Active development
Unresolved as yet