

Science Goals - Nordtvedt Effect

The self-energy of a body is calculated as $M_{SE}c^2 = \iint \frac{G\rho(\vec{r})\rho(\vec{r}')}{|\vec{r}-\vec{r}'|} d^3r d^3r'$

For a rough idea, a uniform density sphere has $M_{SE}c^2 = G\rho^2 \iint \frac{d^3r d^3r'}{|\vec{r}-\vec{r}'|} \sim G\rho^2 \frac{V^2}{R}$

with $V = \text{volume}$, $R = \text{spherical radius} \rightarrow M_{SE}c^2 \sim \frac{GM^2}{R}$

The fractional self energy is then $\frac{M_{SE}}{M} = \frac{GM}{Rc^2} \propto \frac{M}{R}$ earth $\rightarrow 7 \times 10^{-10}$

Real density profile yields $\frac{M_{SE}}{M} = 4.6 \times 10^{-10}$

The moon then has about $\frac{M_E}{R_E} \frac{R_M}{M_M} = \frac{R_M/R_E}{M_M/M_E} = \frac{3.67}{81.3} = \frac{1}{22}$ of earth's $\frac{M_{SE}}{M} \rightarrow 2 \times 10^{-11}$

Assuming for a moment that the moon orbits the sun independent of the earth (nearly true), the earth's orbit is displaced from the moon's according to:

$$\frac{GM_\odot M_j}{r^2} = \frac{M_i v^2}{r} \quad \text{where } M_j \text{ \& } M_i \text{ are gravitational \& inertial masses.}$$

Preserving earth's orbital period $\frac{v}{r} = \omega = \text{const.} \rightarrow \frac{GM_\odot M_j}{r^2} = M_i \omega^2 r$

or $r^3 = \frac{GM_\odot}{\omega^2} \frac{M_j}{M_i}$, Kepler's law. The moon's orbit (and the earth's if $M_j = M_i$) has

$a = \left(\frac{GM_\odot}{\omega^2}\right)^{1/3}$, defining the astronomical unit. But if $M_i \neq M_j$, $r = a \left(\frac{M_j}{M_i}\right)^{1/3}$

If $M_j = M_i + \epsilon$, $r \approx a(1 + \frac{1}{3}\epsilon) \rightarrow \delta r = r - a = \frac{1}{3}\epsilon a$

Under full violation (self energy has no inertial mass), $\epsilon = -\frac{M_{SE}}{M} \sim -4.6 \times 10^{-10}$

$\rightarrow \delta r = -23 \text{ m}$ (full violation $\rightarrow |\eta| = 1$)

"Real" calculations get $\delta r = 13.5 \eta \text{ m}$ (η measures magnitude of violation)

1 cm LLR data establish η to the 10^{-3} level; $1 \text{ mm data pushes to } 10^{-4}$

or 4.6×10^{-15} in total $\frac{M_j}{M_i}$

Science Goals - \dot{G} and the rest of it

Kepler's law, $GM = a^3 \omega^2$ can be used to accurately determine GM as a function of semi-major axis (direct range measurement) and orbital period. Of course it's not so simple in a 3+ body system, but the idea is the same.

A precise measurement of GM allows us to study $\frac{d}{dt} GM \sim \dot{G}M \rightarrow \frac{1}{GM} \frac{d}{dt} GM \sim \frac{\dot{G}}{G}$

Current measurements (over decades) limits $\frac{\dot{G}}{G}$ to $< 10^{-12}$ per year - two orders of magnitude less than a secular effect scaling with the Hubble expansion.

Measurement of \dot{G} requires two things: precise measurement of GM , and time.

One year of mm precision LLR data will do little for \dot{G}/G next to the 2+ decades of lower precision measurements thus far accumulated.

Assuming the past 5-10 years of few-cm level data is largely responsible for the current level of precision on \dot{G} , it will take us at least 5 years to beat this down by another factor of 10.

de Sitter Precession:

This small precession of the lunar orbit can be understood as a dragging of the earth-moon inertial frame as it revolves around the sun. This precession is totally dwarfed by Newtonian effects, amounting to 0.0192 arcsec/yr (compared to 20°/year classical precession).

The measurement of de Sitter precession, like \dot{G}/G (and fine wines), improves with time. Presently the precession is verified to agree with GR to 0.35%.

Long Range Forces:

A Yukawa-like force-law with long-range attributes will effect the rate of perigee precession - a secular effect that, of course, is measured over time.

I'm not too familiar with this topic, and don't know what, if any, significant impact few-mm precision range data may offer in the short term.

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Made in U.S.A.

Sources of Error - Crustal Deformations

The earth & moon both experience relatively predictable crustal motions - mainly due to tides. These bulk motions (30-50 cm on earth, I think) are fairly easy to model & fit.

Additional loading of earth's crust by sea and air are less easy to model, yet are said to exist at the several mm level.

My main questions: Is ocean loading relevant at Apache Point - far inland?
Can we not throw in another term to the fit: $\alpha_{154} P$ to express the unknown atmospheric loading as a simple linear function of pressure (which we measure anyway)?

Barring this, an SLR tie-in may be the most effective means of eliminating these uncertainties.

Hardware - Clock

We need a clock.

Absolute precision necessary: Earth rotates 1mm (at equator) in 2 ns

GPS-slaved Quartz clock provides time accurate to 110 ns, accuracy 95% of time (without selective availability - the current condition - this is probably 20-40 ns).

Quartz has superior short-term stability, on par with the high-performance cesium standard over 1-10s timescales (lunar round-trip is 2.4 sec).

Quartz or cesium clocks have 5×10^{-12} stability over 1-10s \rightarrow a few mm

At first I assumed we could not tolerate a 100 ns absolute time error, but I can't remember now what my specific objection was. The fastest relative motion between earth & moon stations is due to earth rotation. Even the 30 km/s earth orbital motion goes 1 mm in 30 ns, but absolute earth/moon position relative to the sun is irrelevant to this precision

Price difference is extreme - \$6k vs \$70k, both produce 10 MHz output reference.

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200 SHEETS RECYCLED 8 SQUARE
400 SHEETS RECYCLED 8 SQUARE
800 SHEETS RECYCLED WHITE 8 SQUARE
Made in U.S.A.

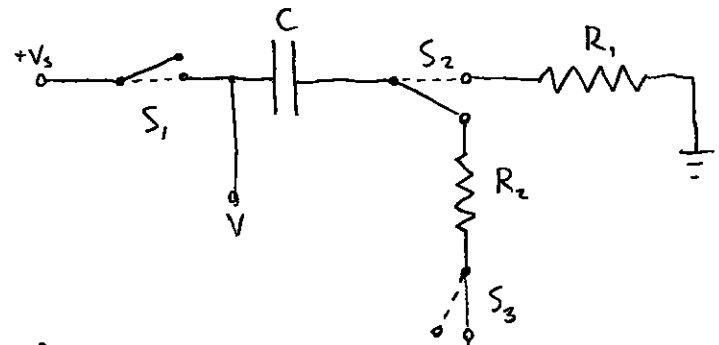


Hardware - Small Interval Counter

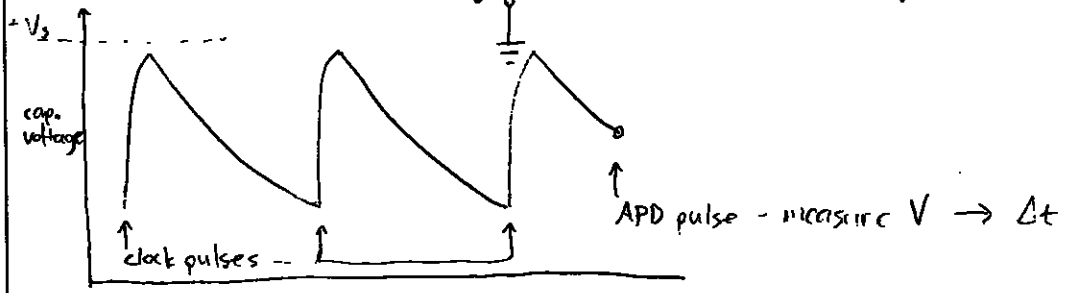
We need to resolve the 10 MHz clock output to $\sim 5 \times 10^{-5}$ (\rightarrow 5 ps) accuracy

The McDonald scheme uses a counter to count 10 MHz intervals, then a vernier to measure the time between the last clock pulse and the stop pulse from the detector.

A schematic vernier is as follows:



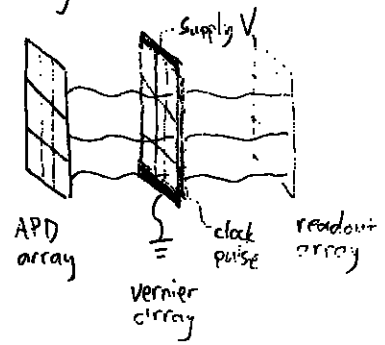
- S_1 : normally open - clock pulse closes temporarily
- S_2 : travels with S_1 - normally points to R_2
- S_3 : normally closed - opened at APD pulse closed again @ clock pulse
- $R_2 C \approx 100$ ns
- $R_1 C \approx$ few ns



Of course the actual verniers are more complex/linear/reliable

As a black box, vernier has 5 inputs: supply voltage, clock pulse, APD pulse, ground, V_{meas} .

The perfect solution would be an array of micro-verniers fabricated on a sheet and placed between APD array and array of FET-based voltage measurement / A/D stage



\Rightarrow output is array of voltages indicating time of signal pulse from APD

How realistic is this scheme? I wish I knew. Probably fabrication is too expensive both in time & money.

What do high energy guys do for timing arrays of detectors? My guess: racks & racks of electronics plus lots of wires.

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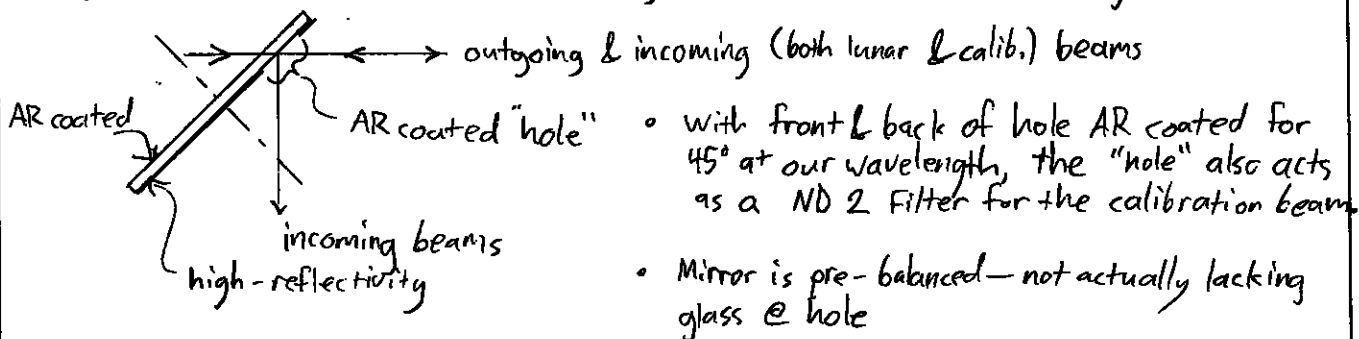
Hardware - Optics & Other Equipment

The simplest part of this system (by-and-large) is the optical system, as we only care about monochromatic light.

It would be most convenient to work with a collimated beam less than 25 mm in diameter, keeping the arrangement compact and the optics small. But with, say, a 20 mm beam, the outgoing pulse will deliver a peak power density of $\sim 300 \text{ MW cm}^{-2}$ — enough that normal AR coatings may be damaged, so that we'll want to have specially coated optics along the power train.

If we want a fully illuminated 3.5 m exit aperture (which leads to an eye-safe beam and an undamaged telescope), then there's no getting around a moving optic — e.g., a mirror with a hole through it, rotating.

The McDonald folks had a calibration path differing from their lunar return path, which we may want to avoid if we require sub-mm metrology. Therefore it may be worth investing in the following arrangement for a rotating mirror:



This type of mirror would need to be made of quality material, with good surfaces, as it must transmit outgoing pulse with immeasurable distortion. Also, the back surface ought to be slightly wedged at the hole location to separate front surface (keeper) from back surface (rejected) reflections. Balance issues can be compensated by symmetric treatment of rear surface. Manufacture of this wedge bit could get pricy, though. Perhaps a better solution is a thicker (self-shielding) mirror.

Narrow band interference filters with 1 nm FWHM, 30-50% throughput, and OD = 4 out-of-band rejection are easy to find. By tilting the filter for calibration pulse, this may act as a variable high-attenuation filter.

We probably also want a PLZT electronically activated filter — if these have high enough transmission. This is for the purpose of knocking out calibration photons

Another useful device to have on the optical bench is a streak camera. These are expensive, but potentially very important in understanding the systematics associated with the pulse width, shape, & stability. On the other hand, if our calibration scheme and APD array timing scheme work well, delivering ~ 10 photons per pulse, we'll have an in situ pulse profile measurement, with the ability to monitor stability over 10-30s (plus) time scales.

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System Performance - Signal

The APO aperture, combined with good seeing/optics offers us the chance to routinely see 2-10 photons per pulse.

The number of detected photons (minus speckle-induced variability) is given by:

$$N_d = N_l \eta^2 f Q \left(\frac{nd^4}{r^2 \Phi^2} \right) \left(\frac{D^2}{r^2 \phi^2} \right)$$

N_l = # photons launched: 100 mJ/pulse \rightarrow 2.7×10^{17} photons @ 532, 5.4×10^{17} @ 1064

η = one way shared optical efficiency (steering/diverging optics, scope, atmosphere) \rightarrow ~ 0.5

f = Narrow-band filter plus PLZT (?) : Worst case ~ 0.25

Q = quantum efficiency of detector in Geiger mode \rightarrow 0.3

d = corner-cube prism aperture : 0.038 m for all Apollo reflectors

n = # of retro-reflectors in array: 100 or 300

D = telescope aperture = 35 m

Φ = outgoing divergence ≈ 1 arcsec

ϕ = retroreflector divergence \rightarrow as bad as 10 arcsec

These numbers range from 7 to 44 (532 nm on 100 element array vs. 1064 on 300) photons detected per pulse.

Speckle structure puts the median return at $\sim \frac{1}{2}$ the average, with average or better about 30% of the time. $\frac{1}{3}$ of average (~ 1 photon) $\sim 70\%$ of time.

Go ahead and knock the estimate down by another factor of two - still in 5 photon regime!

With the above numbers, overall "lab" efficiency is $\eta^2 f Q = 0.019$, which seems modest enough.

At 20 Hz, we'll get ~ 100 photons per second - the content of a typical "normal point".

One throughput variable not considered above is self-shadowing of the retroreflector array, which drops to 60% throughput at a net libration angle of 10°

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System Performance - Background & Noise

The moon is brighter than the daytime sky, so the lunar surface brightness is the dominant source of background photons from natural sources.

The moon, at ^{-12.7}-13 mag, has a surface brightness of 3 mag arcsec⁻²

$$V = 3 \text{ mag} \rightarrow 2.17 \times 10^{-9} \text{ W m}^{-2} \mu\text{m}^{-1}$$

In 3.5 m aperture, this leads to $2.09 \times 10^{-11} \text{ W nm}^{-1} \text{ arcsec}^{-2} \rightarrow 5.6 \times 10^7 \text{ photons s}^{-1} \text{ nm}^{-1} \text{ arcsec}^{-2}$

or 0.056 photons ns⁻¹ nm⁻¹ arcsec⁻² arriving at telescope

→ detected ←

Using $\eta f \Omega$ from throughput calculations takes this down to

$$\boxed{0.002 \frac{\text{photons}}{\text{ns} \cdot \text{nm} \cdot \text{arcsec}^2}}$$

* Therefore our signal can not become confused by background photons.*

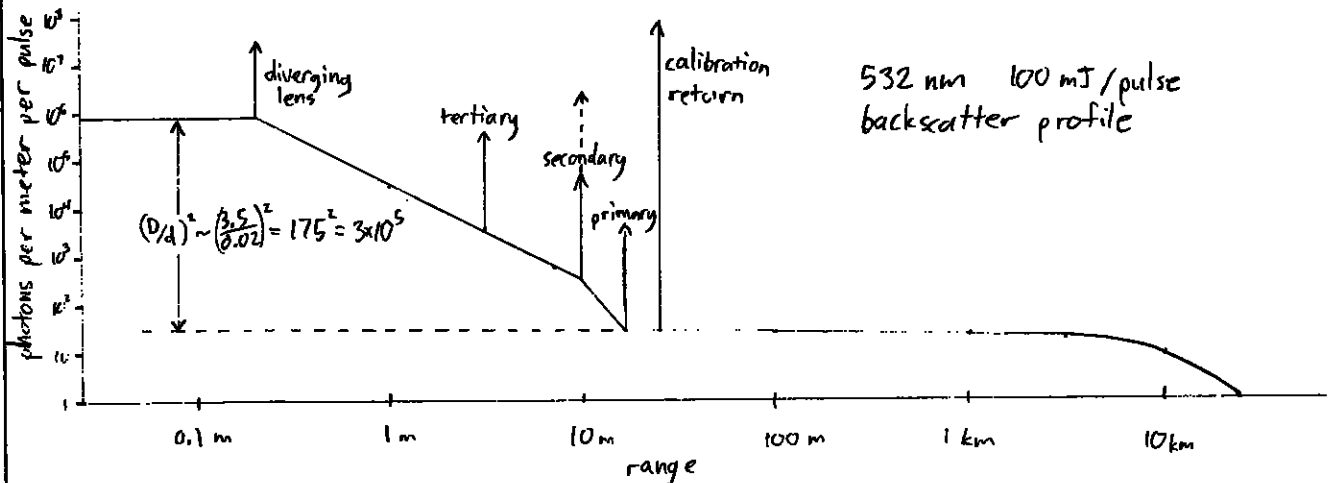
But we still have to worry about false triggers, shutting down the APD element for some time (dead times of 100-200 ns are typical)

Probability that background photon strikes somewhere in array (2x2 arcsec?) within one "dead time" of expected lunar photon arrival approaches 1!

Grating the detector (few 10's ns window when high voltage is applied) not only alleviates this problem, but also reduces probability of dark current hits. You just have to make sure the high voltage is on at the right time.

Backscatter @ 532 nm is $1.2 \times 10^{-6} \text{ m}^{-1} \text{ sr}^{-1}$ at APO altitude

For a collimated "laboratory" beam diameter of 30 mm (175 x smaller than exit beam) this corresponds to 10^6 photons per meter sent back to a 2" square array from the collimated beam within the lab. Once beyond the scope, it's 30 photons per meter sent back toward the detector, falling off as atmospheric density decreases



* For McDonald, detected background in 5" aperture $\rightarrow 2 \times 10^{-3} \text{ photons ns}^{-1} \text{ nm}^{-1}$
 \rightarrow one in five difficult to distinguish from signal (which is 10^{-2} per pulse).

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System Performance - Background & Noise (continued)

Integrated air backscatter toward detector (2" x 2" area)

- collimated section: $0.2 \text{ m} \times 10^6 \text{ m}^{-1} = 2 \times 10^5$ photons $\propto (D/d)^2$
 - enroute to secondary: $\Rightarrow 2 \times 10^5$ photons $\propto (D/d)^2$
 - secondary to primary: 3×10^3 photons $\propto (D/d)^2$
 - atmosphere: 3×10^5 photons
- $D = 3.5 \text{ m}$
 $d =$ collimated beam diameter
 (assumed 20mm)

keeping the section of outgoing collimated beam that is visible to detector ~~short~~ is important

A bigger collimated beam helps the backscatter, at the substantial cost of scaling all optics

To put backscatter into perspective, retro-reflector for collimation sends

$$N_{\text{ret}} \approx N_L \times \left(\frac{d_{\text{cc}}}{D}\right)^2 \left(\frac{\phi_{\text{det}}}{\lambda/d_{\text{cc}}}\right)^2 = N_L \left(\frac{\phi_{\text{det}} d_{\text{cc}}}{\lambda D}\right)^2$$

where $N_L = \#$ launched, $\phi_{\text{det}} =$ angular scale of detector (2")
 d_{cc} is corner cube diameter, $\lambda =$ wavelength

$$\rightarrow \sim 7 \times 10^{10} \left(\frac{d_{\text{cc}}}{1 \text{ cm}}\right)^4 \text{ photons, overwhelming integrated backscatter}$$

Therefore, the filtering used for calibration will completely block any backscatter.

Lens surfaces, and especially dusty ones, will also send many photons back.

Worst case: 1% of surface scatters into $4\pi \rightarrow$

$$N_{\text{znt}} = 0.01 N_L \frac{(D/d \phi_{\text{det}})^2}{4\pi} \sim 6 \times 10^7 \text{ photons} \rightarrow \sim 1\% \text{ of calibration strength}$$

One last source of background to consider: our laser returns from lunar surface.

Using range equation with 0.5 albedo, 2π scatter \rightarrow 0.026 photons per pulse could be detected. The range will be many ns off, but can still trigger the APDs!

This noise source is more significant than the sunlit lunar surface for us, owing to the fact that these photons have the right passwords for our spatial/spectral/temporal filters.

Oh - one question of relevance: does the APD secondary have a central hole? If not, approximately 1.3×10^7 photons head back toward the detector real estate directly off the secondary. This could potentially serve as a calibration source (in lieu of a retro-reflector) if its position is known absolutely as a function of telescope focus. Otherwise, it is a relevant noise source as the calibration is concerned.

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System Performance — Eye Safety

The number quoted by Eric Silverberg regarding eye safety was $1 \mu\text{J}$. There was some question as to whether this is in 1 cm^2 or into an eyeball.

Taking the conservative $1 \mu\text{J cm}^{-2}$ limit, the APO area of $\sim 9 \times 10^4 \text{ cm}^2$ allows a dosage of $\sim 110 \text{ mJ}$. I assume the figures relate to total intake. If only one pulse is taken in, we're probably fine with a "laboratory" laser energy of $\sim 150 \text{ mJ}$ per pulse. Various inefficiencies will eat this number down to acceptable levels by the time it hits United Flight 264.

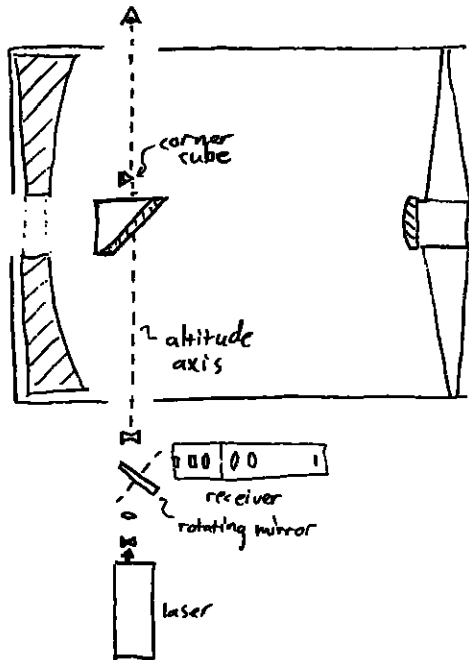
But are we dealing with one pulse or more? At 20 Hz rep rate, and a beam diameter of 3.5 m, and a 60° zenith angle (worst case), a plane going slower than 140 m/s (~ 280 knots) could be exposed to two pulses. Thus commercial airliners are in the one-pulse category, small commercial planes two-pulse, and small general aviation planes (at ~ 100 knots) are subject to three. Fortunately, situated at 9,500 feet, the cone up to 12-14,000 feet (where small planes fly) has very little volume. Plus, flying over 9,000+ foot mountains at night isn't a popular activity — smart pilots fly over the valleys.

Before we deem our system eye-safe, we should get the official word on what safe is.

If the secondary provides the calibration signal, special care must be taken to know where the secondary is in an absolute sense. Complicating matters, the secondary moves for focus control. However, this motion generally compensates thermal expansion/contraction of the telescope structure. If the optics are low-expansion glass material (surely they are) then the physical spacing between primary & secondary doesn't change appreciably if focus is maintained.

Note that when focus is maintained, the secondary position is more stable than that of a corner cube at the exit aperture. (near top of telescope).

An alternate placement of the corner cube near the intersection of axes may eliminate much confusion about thermal expansion and flexure. If I remember correctly, the APO scope has a Nasmyth focus, which means there's a tertiary mirror very near the axis intersection. Attaching the retro-reflector behind this mirror, if carefully done, will put the corner cube precisely on the altitude axis. This minimizes the need for surveying - just watch how it moves when the telescope moves in altitude.



Besides ease of locating w.r.t. the telescope's fixed coordinates and simplicity of surveying, this placement also puts the retro-reflector in the good central part of the beam where illumination is likely more uniform than out near the edge.

I think we want the back tip of the corner cube on the axis, as this represents the optical midpoint between entrance surface & exit surface (same physical surface), we'll need to remember to compute the refractive delay within the prism.

In this position, care must be taken that the prism doesn't shadow itself. The mounting arm must allow light to pass through from the secondary to the primary between the corner cube and the tertiary. The mount may also need to be retractable so-as not to interfere with other observations.

Now with photons coming back from the corner cube and/or secondary (would it really be so bad if we got both?), we need to address the pesky issue of:

Attenuation

With no attenuation, we expect 3×10^9 , 2×10^8 , or 5×10^7 ~~detected~~ photons across the array (2" array assumed) for 10mm diameter, 5mm diameter corner cubes, or secondary, respectively. The rotating mirror employing AR coatings instead of an "air hole" may knock 10^2 off this, if the 45° incidence AR coat can transmit 99% of the photons. This leaves about 10^6 of necessary attenuation for the corner cubes, or 10^5 for the secondary. The goal is to record 10-30 photons per pulse on the array (assuming 10×10 array).

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System Performance - SLR tie in

In my opinion, the cm-level uncertainties in atmospheric delay and crustal motion are unlikely to become mm-level uncertainties by our bold modeling efforts.

If we let the SLR community tackle these problems, they are sure to result in knowledge of the two LAGEOS orbits to < 5 mm precision. Potentially, their modeling advances will be transferable to our modeling effort. Failing this easy transference, we still have an accurate orbit as a reference.

Ranging to the LAGEOS satellites from APO near the epoch of lunar ranging will enable us to measure the atmospheric delay & crustal displacement relative to the well established orbit (which is measured daily around the world).

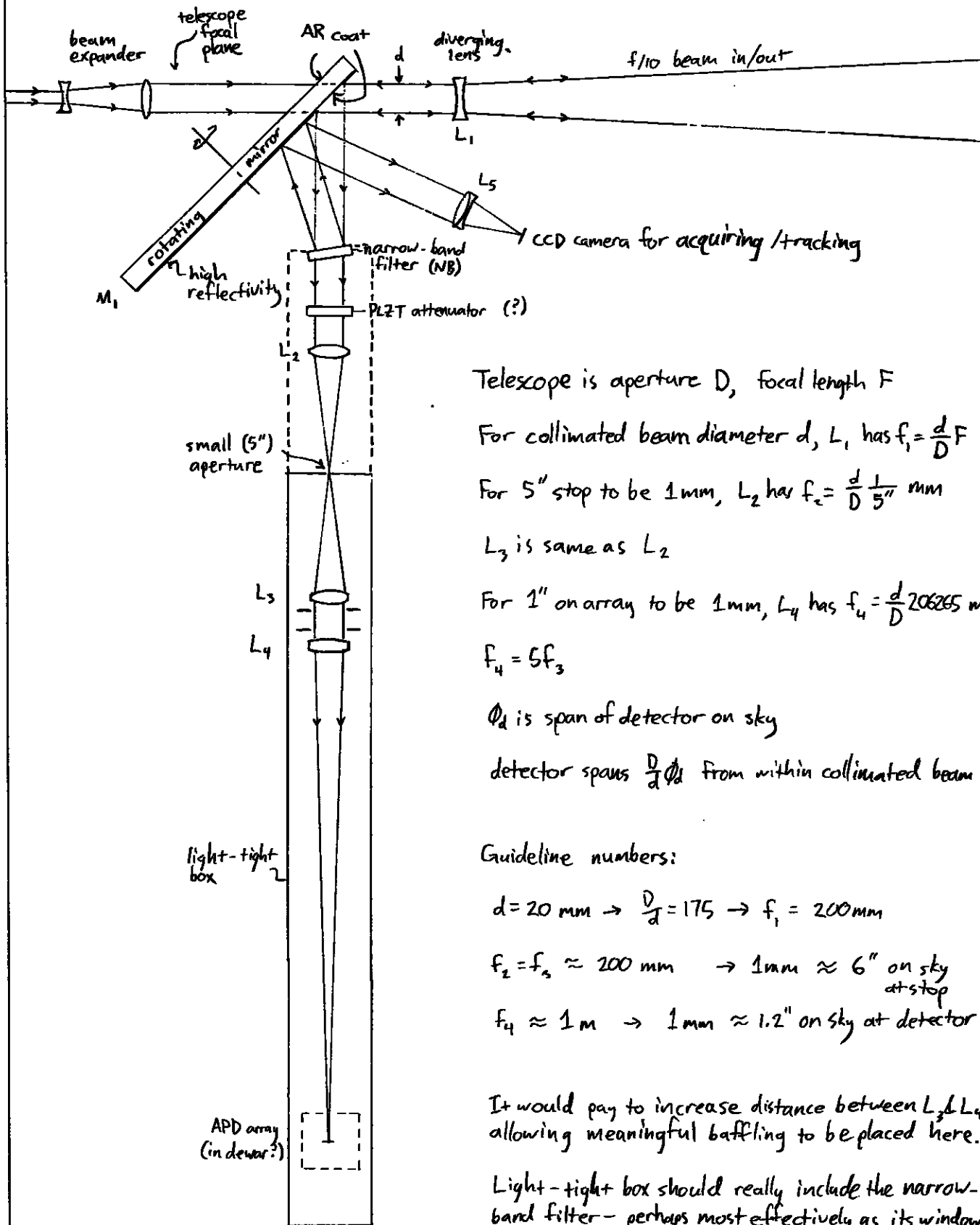
It would be nice to have SLR capability with the same instrumental setup, though we may not want to burden the 3.5 m with a task easily performed by a separate, compact unit. We should get info on this SLR 2000 system. Can we afford one? Can we convince someone interested in SLR that they should set up at Apache Point? Can astronomers cope with a nearby, independent laser operation?

Our sensitive lunar setup would detect $\sim 10^8$ photons per pulse from LAGEOS! We could degrade this almost arbitrarily with telescope defocus (also eases pointing/tracking demands). We could also bump the laser power down significantly either via laser tuning or by reflecting most of the beam to a dump.

Even if we have a separate, independent SLR setup, establishing the offset between the two systems would be greatly facilitated by SLR capability from the 3.5 m.

A secondary, but very important benefit of doing some SLR from the 3.5 m is that we can use SLR to iron out the system before tackling the moon. Going full power on LAGEOS, we'll see the return pulse in our CCD tracking camera! That's a heck of a good way to verify system operation - when you know you are or are not illuminating the target.

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