Laser Ranging with High Power CW Lasers

M. Shao, S. Turyshev, I. Han, R. Trahan

Jet Propulsion Laboratory, California Institute of Technology

Outline

- Transition to high power lasers (pulsed vs CW)
  - All very high power Radars (Goldstone, Arecibo are CW emitters)
  - All the components for High power radars have counterparts in the optical
- Current High power CW lasers (MOPA) seed laser, high power amplifier
  - High power fiber laser (amplifiers) and their limitations
- Two different types of LADAR, Coherent, Incoherent
  - Coherent LADAR exact analog of microwave RADAR but at ~300 Thz
  - Incoherent LADAR microwave amplitude modulation of a high power laser.
    - Equivalent to a Microwave RADAR, but with an optical carrier.
- JPL Table Mountain Laser ranging (undergoing testing)

Move to High Power Lasers

Arecibo 1MW Radar

- The highest power Radars transmit CW

- The reasons Laser will go this way are similar to why high power Radars are CW.

  - Lower peak power => avoids laser damage to optics

  - High electrical efficiency 3KW in => 1KW optical out

  - All components needed to modulate the laser are readily available.

 - Scaleable to very high powers by phasing multiple laser amplifiers

Goldstone 0.5 MW Radar

Current High Power CW Lasers

- Diode pumped fiber lasers are readily available.

- Lasing occurs in a single mode fiber (pump light into cladding)

- Diffraction limited output. (no worries about thermal effects distorting the output wavefront of the laser.)

- Currently 1.0~1.5KW CW output available

- Multiple amplifiers can be coherently combined for higher power.

KW High Power fiber Laser Amplifier
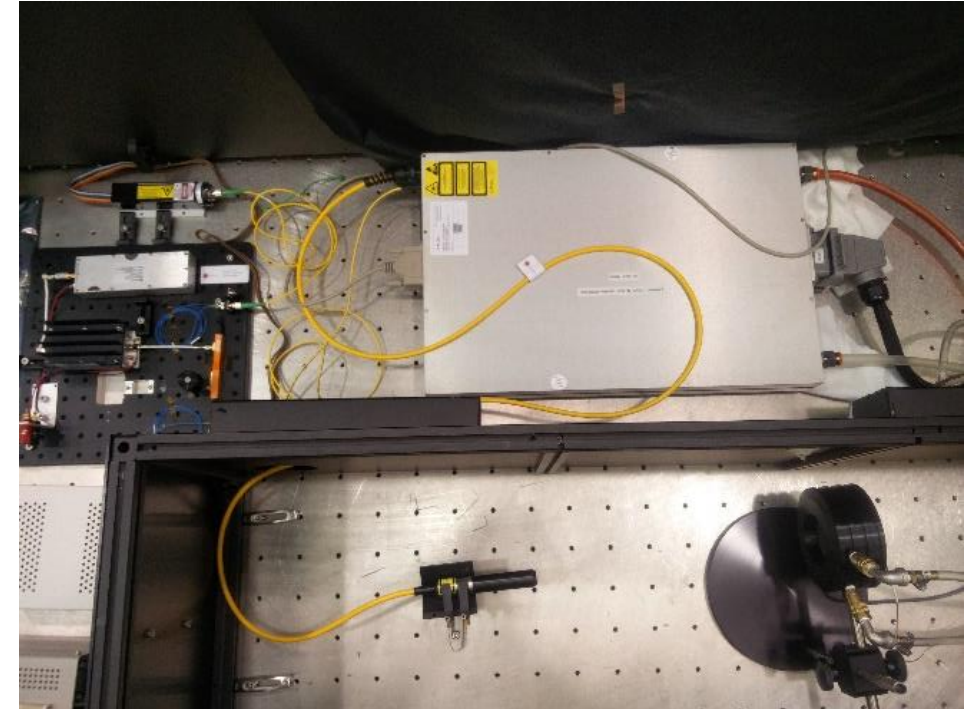
Laser Architecture and Limitations

- Basic MOPA design,
  - For coherent LADAR we use a very narrow band see (1e-14 $\delta\nu/\nu$) line width seed laser so the coherence length is >100,000 km.
  - For incoherent LADAR we broaden the laser line to ~20Ghz.
- Modulator is used to provide a high bandwidth signal for accurate ranging.

High Power
Amplifier

Seed laser

Modulator
Phase, amplitude,
Freq.
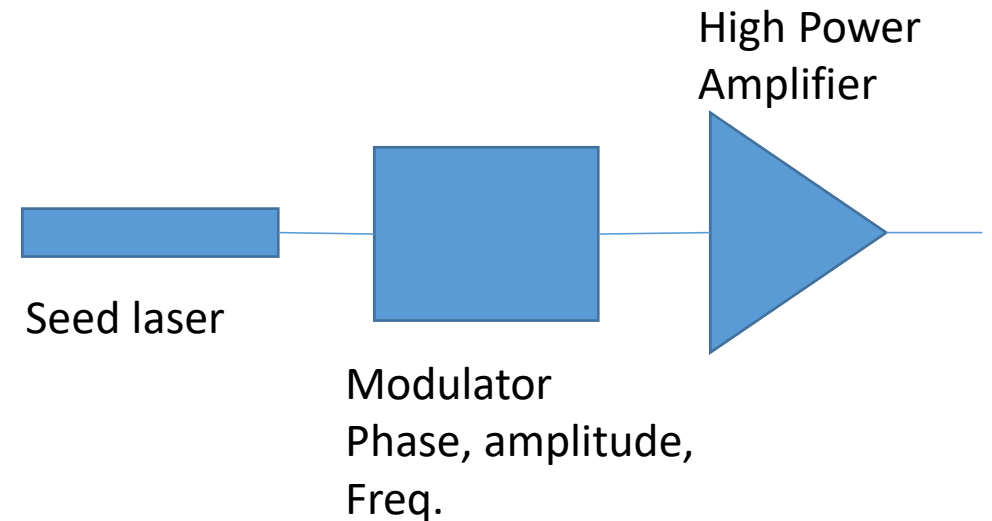
High power amplifier is a multi-stage
Fiber laser that takes 1~3 mW input and
outputs 1KW

High Power Fiber Amplifiers (limitation, precautions)

- The major limitation to high power fiber lasers is SBS (stimulated Brillouin scattering). If the seed laser is single freq, the max power output of our amplifier is ~ 50W. Currently in coherent operation our laser is limited to 50W output.
  - The power density inside the ~30um core of the single mode fiber is extremely high..
- To obtain higher output power, the seed laser must be broadened, typically to 10~20 Ghz. (so the power in every SBS mode << 50W)
- In this mode, we can amplitude modulate the input to the amplifier.
  - However it's important to not have zero optical input to the power amplifier for more than ~100nsec.
- Laser amplification preserves phase and polarization. But most commercial HP Amps use loops of fiber and the output polarization is not stable.

Incoherent LADAR

- Microwave ranging on an optical carrier

- Amplitude modulate the laser at ~1 Ghz, compare the phase of the return with the phase of the 1Ghz outgoing signal

- Phase measurement has a 2p ambiguity distance = $N*\lambda + \phi$
  - λ is the wavelength of the 1Ghz modulation
  - ϕ is the phase of the 1 Ghz return

- As in Radar, N we chirp the modulation freq to determin N.
  - We plan to chirp from ~500Mhz to 1 Ghz.

- Two important details
  - << 1 detected photon/pulse (~ 10^9 pulses/s ~10^4 phot/s)
  - Prevent local backscatter light (with low duty cycle pused lasers one can time gate the receiver)

outgoing   incomming

Photon counting
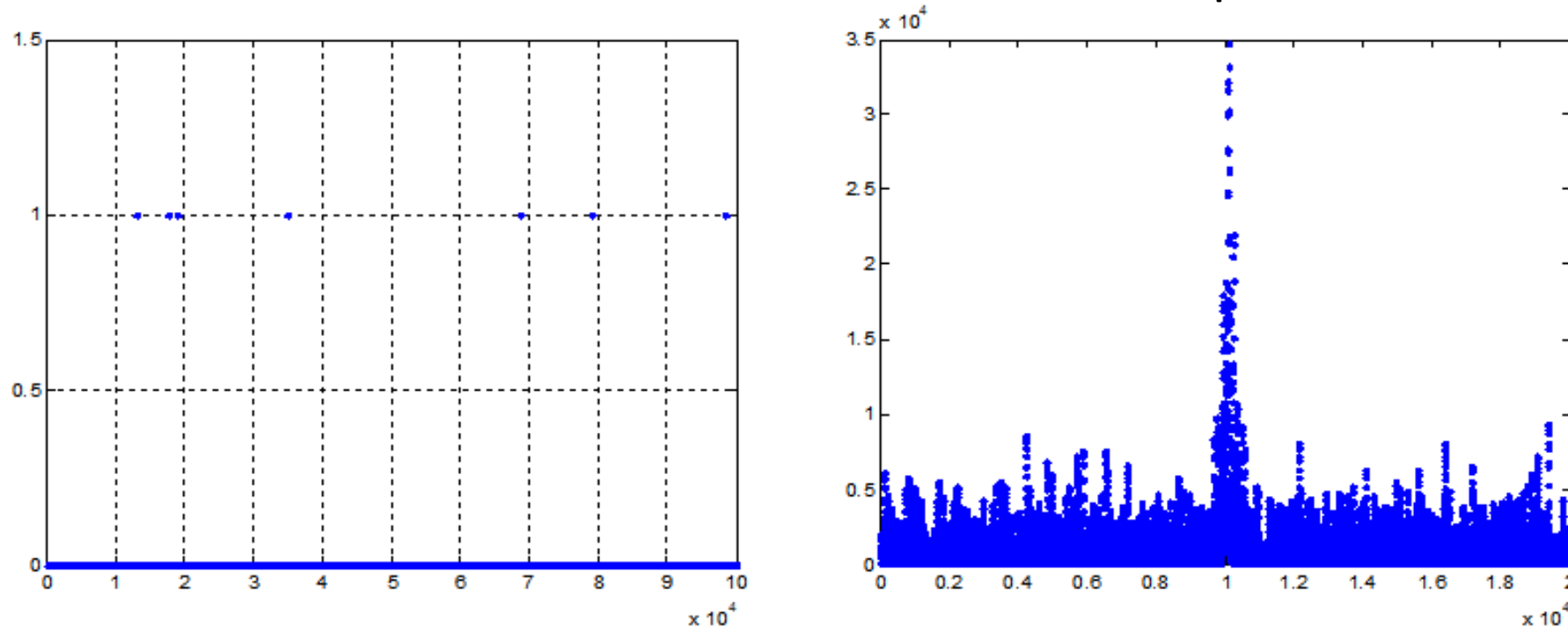Detector

Sub nsec time tagged
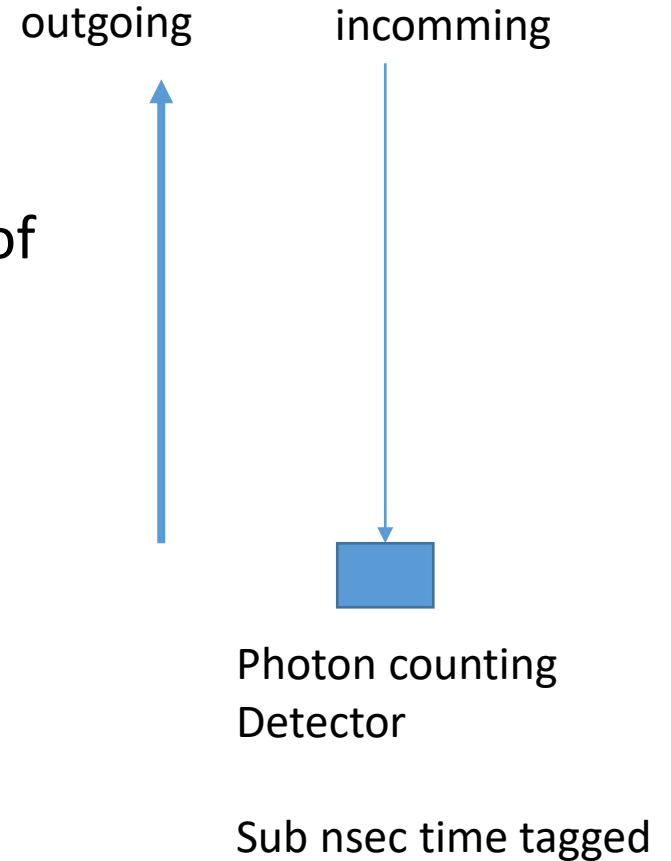
Remove local backscattered light (turn laser off)

- If we're ranging to the Moon, the transit time is ~ 3 sec. Turn laser on for 3 sec, then turn laser off, and receive for 3 sec.

- For satellite ranging, the laser has to be turned on/off more rapidly.

- Current high power laser amplifiers can not be turned on/off rapidly. (The pump diodes can be modulated at Khz freq but the manufacturer doesn't supply a way to do this.)
  - We plan to turn on/off the high power beam optically.
    - Spinning chopper or
    - Frustrated total internal reflection
  - Deflect light into a KW beam dump
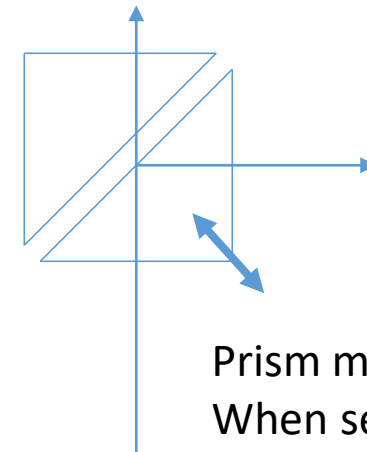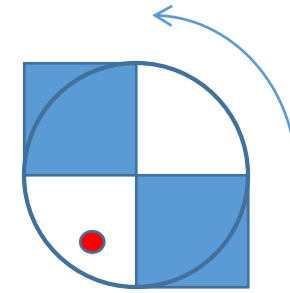
Prism moved with PZT,
When separated TIR
Will divert the beam

Phase Measurement of RF modulation, photon counting

- The optical signal is a 50% duty cycle square wave. ~10^9 pulses/s but < 0.1% of the pulses have a detected photon.

- Generate a time sequence from the time-tagged photons, the FFT. A freq shift of the return Ghz signal is the Doppler shift of the Ghz signal. The phase (complex fft) is used along with the freq chirp (0.5~1.0 Ghz) to measure group delay G_delay = $d\phi/d\nu$

- The phase measurement takes a finite time, the chirp takes a finite time, during which the distance and velocity will have changed. The FFT's are used to get an "approximate" velocity, phase/GD, distance. The final solution will be a non-linear least sq fit of the photon arrival time varying the mean distance and velocity over the integration time of the measurement.

Analysis (signal proc) steps (current thoughts)

- Modulation is chirped from 0.5~1.0 Ghz

Time tagged photons	Time Series Signal	FFT to ID amp/freq/phase	Group delay dist Is $d\phi/d\nu$

Absolute distance measurement for a static target

- The chirp occurs over a few seconds of time and a satellite can move a considerable distance during the chirp.

- Generically, we start with a "guess" of the distance versus time. (based on the orbit of the object)
  - This initial model will have a distance and velocity error.
  - From the initial guess we generate a predicted pulse train (based on the known chirp and orbit model. We take the difference in the photon arrivals detected versus the model as the error signal. And do a NLLS fit varying the distance and velocity at the middle of the chirp. (and maybe acceleration)

Lunar Ranging Photon Budget

- KW laser allows return flux to be ~ 1e5 photons/sec.
  - Could range to a single 3.8cm CC
- Use of single CC avoids spread of signal from CCs at different distances.

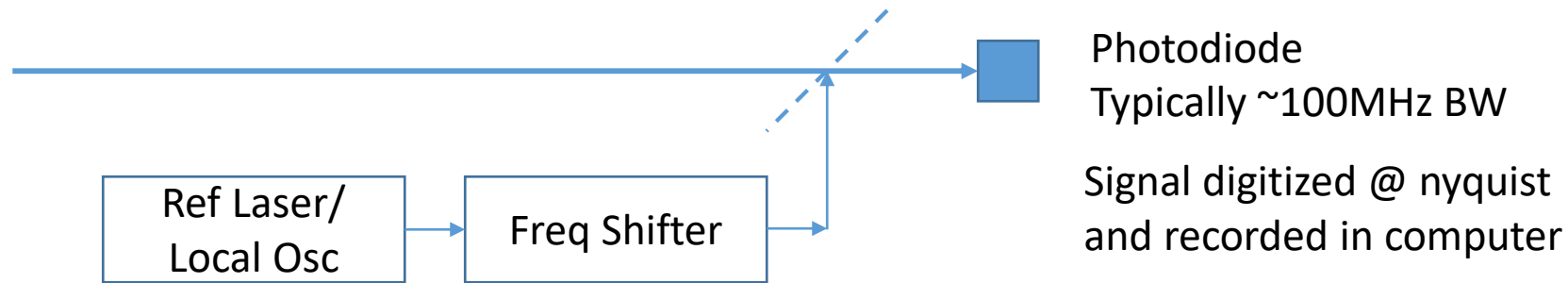|		
Xmittter	1.06um	1000W
Xmit beam	10 urad diverge	
Spot on Moon	3.73 km dia	
CC array	3.8cm	100 CCs
Divergence	28 urad	
Spot on Earth	10.75 km	
Receiver	1m	Total QE 0.2
Received flux	~100,000/sec	Detected phot

Coherent LADAR

- Coherent LADAR is a complete optical analog of RF radar.
- The hardware difference between coherent/incoherent LADAR are:
  - The seed laser is a very narrow line laser (we use a sub hz linewidth 1.064um laser).
  - Heterodyne receiver (not photon counting)
    - Receiver in RF terminology is quantum limited.

Photodiode
Typically ~100MHz BW

Signal digitized @ nyquist and recorded in computer
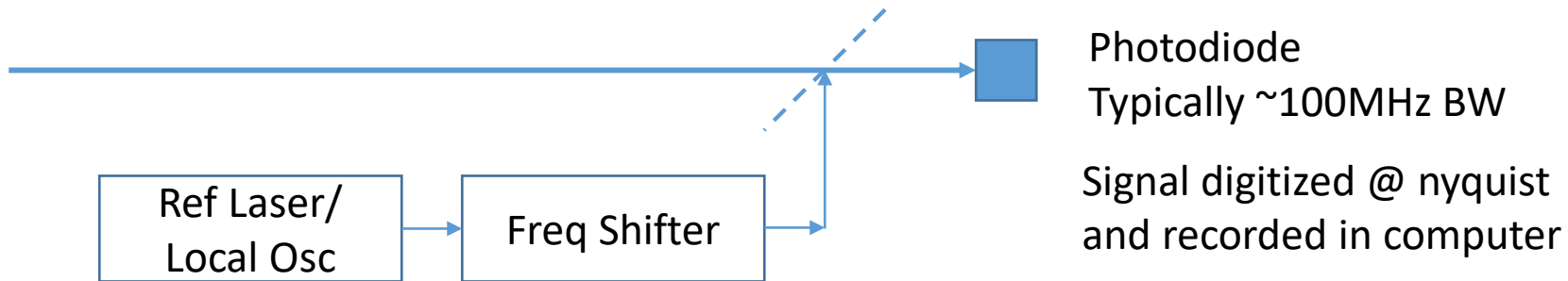
Heterodyne receiver: Is quantum limited when the shot noise of the LO is > detector Noise (typically @ 50~100nW). Freq shifter is to shift the LO to match the Doppler Shift of the return signal within the BW of the receiver. (LEO sat ~ 7Ghz Doppler)

Coherent Doppler Measurement

Photodiode
Typically ~100MHz BW

Signal digitized @ nyquist
and recorded in computer

Ref Laser/
Local Osc

Freq Shifter

- Heterodyne receivers (optical) use 100Mhz or higher BW photodiodes.
  - The return signal is mixed with a LO (laser) whose freq has been shifted to match the Doppler shift of the return signal. (~7Ghz for a LEO satellite) plus a small offset (~1MHz).
  - The Doppler shift of the signal has to known to within the bandwidth of the receiver. At 100Mhz the velocity has to be known to 100m/s (for a 1um laser).

- The signal at the photodiode is [E_return+E_LO]^2 , [$A\sin(w_0 t)+B\sin(w_1 t+\phi)$]^2
  - $A^2+B^2+2*A*B*\sin((w_0-w_1)*t+\phi)$ what's important is the heterodyne gain
  - The detected AC signal is proportion to the LO and signal Efield. One can amplify the received signal by increasing the LO power. As the LO increase, the photon noise from the LO also increase and the SNR stops increasing once the LO photon noise is much larger than the detector noise, the receiver is now operating at the quantum limit. At 10's Ghz frequencies quantum limited receivers are often cooled to 4K. In the NIR/Vis they can be room temperature.

- Looking through the atmosphere, a coherent receiver is limited to an r0 aperture (~15cm for 1um/1arcsec seeing). Unless the telescope also has an adaptive optics system to create a diffraction limited image at the detector.

Why Bother with Coherent?

- Coherent LADAR is other word(s) is laser interferometry where one arm of the interferometer is 1000km to 400,000km away.

- There are many noise/error sources that make micron level ranging not feasible. But for velocity/Doppler measurements, these error sources are common mode and drop out.
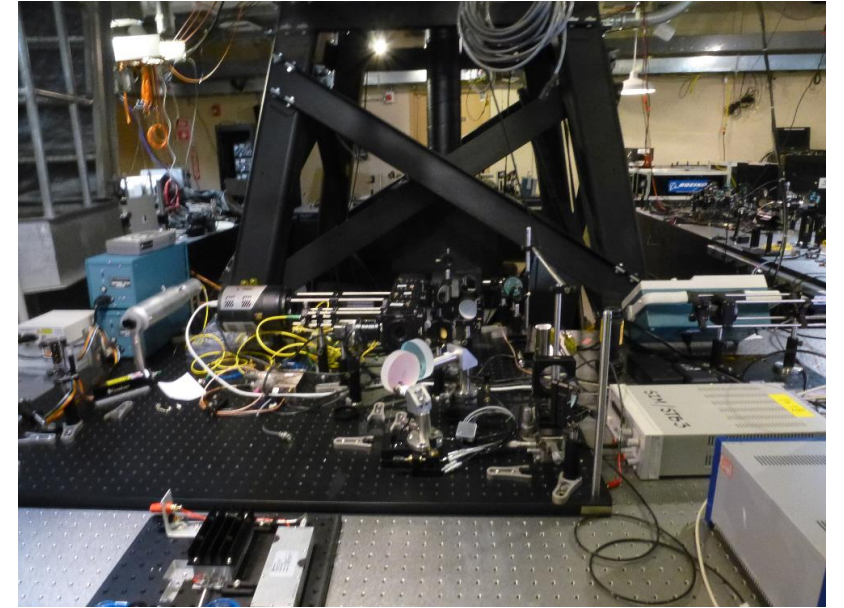

With a 1second data set, the velocity resolution is 1Hz, meaning
That if there are 2 or more CCs in the beam whose radial velocity differed by > 1 micron/sec
They will show up as two different objects. Each CC on a slowly rotating satellite like LAGEOS
could have a unique Doppler signature. If the rotation period is 1 hr, a 30cm "ball" will have
A range of Doppler returns +/- 80 um/sec.

Coherent Ranging

- Coherent range/distance measurements can be made using the same technique as incoherent ranging. That is by changing the frequency of the laser.
    - If one chirps the laser frequency by 10 Ghz, that will give roughly the same ranging precision of a 100picosec pulse.
- The use of a linear frequency chirp in Radars and its data analysis is very well established. The Radar folks call this synthetic aperture radar (SAR). A variation of SAR called inverse synthetic aperture radar is used to image rotating targets.
    - Their corresponding analogs in the optical are called SAL (syn aperture LADAR, and ISAL)
- The major difference between coheren/incoherent chirped modulation is the amount of frequency change.
- In incoherent chirped modulation, the change in freq is comparable to the frequency. (500Mhz to 1 Ghz). But in coherent one can only change the freq of the laser by 10's of Ghz but compared to the laser's 300Thz freq this is a very small fractional change in frequency.
    - The result is that the group delay measurement is orders of magnitude less precise than the Doppler measurement. (cm vs um/s)

Equipment at Telescope

Target acquisition
Tracking and
Laser receiver
(phot counting
Or heterodyne)

KW Laser amplifier

1m Telescope

Summary

- JPL has built (but not yet operational) a high power laser ranging facility at its table mountain facility. It uses the Optical comm group's 1m telescope.
- The facility can transmit up to 50W for coherent LADAR (satellites with corner reflectors) and measure radial velocities with micron/sec accuracy.
  - Using an ultra-stable seed laser with subHz line width.
  - The best observable is Doppler velocity, where micron/sec velocity noise is possible (atmospheric limit
- It should also be able to range to the Lunar CC's in incoherent mode up to 1 KW.
  - The original proposed purpose was to perform differential ranging to different corner cubes on the moon. The differential measurements would be insensitive to many systematic errors in absolute range with ~< 50um precision possible (in < ~1000s)