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Low-cost chirp linearization for long-range ISAL imaging application

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Summary

- Hardware Outline
  - System Overview
  - Tunable Laser
  - Frequency Monitor
- Chirp duration rationale based on atmospheric turbulence
- Hardware Chirp Linearization
- Software Chirp Linearization
- Chirp Quality measured from Impulse Response

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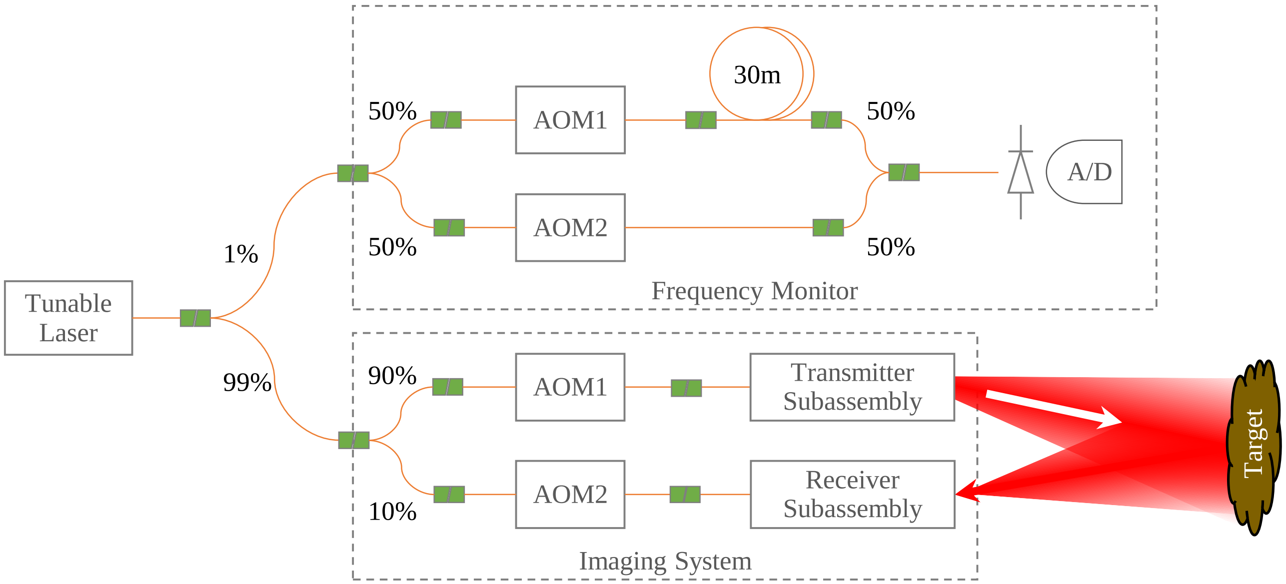
System Overview

- Tunable laser
- Frequency Monitor measures chirp rate
- Imaging system observes the target



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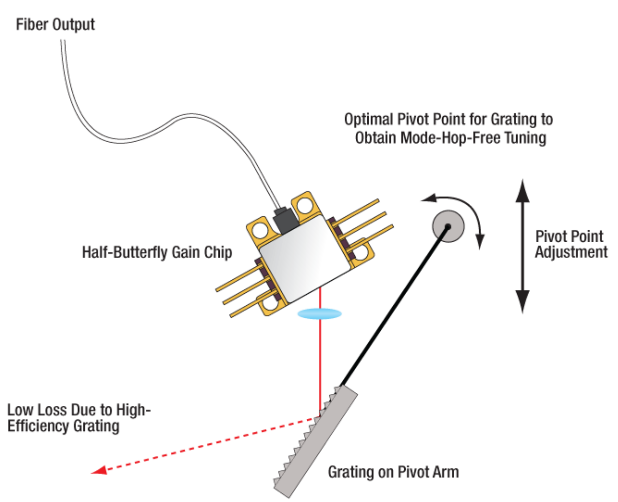
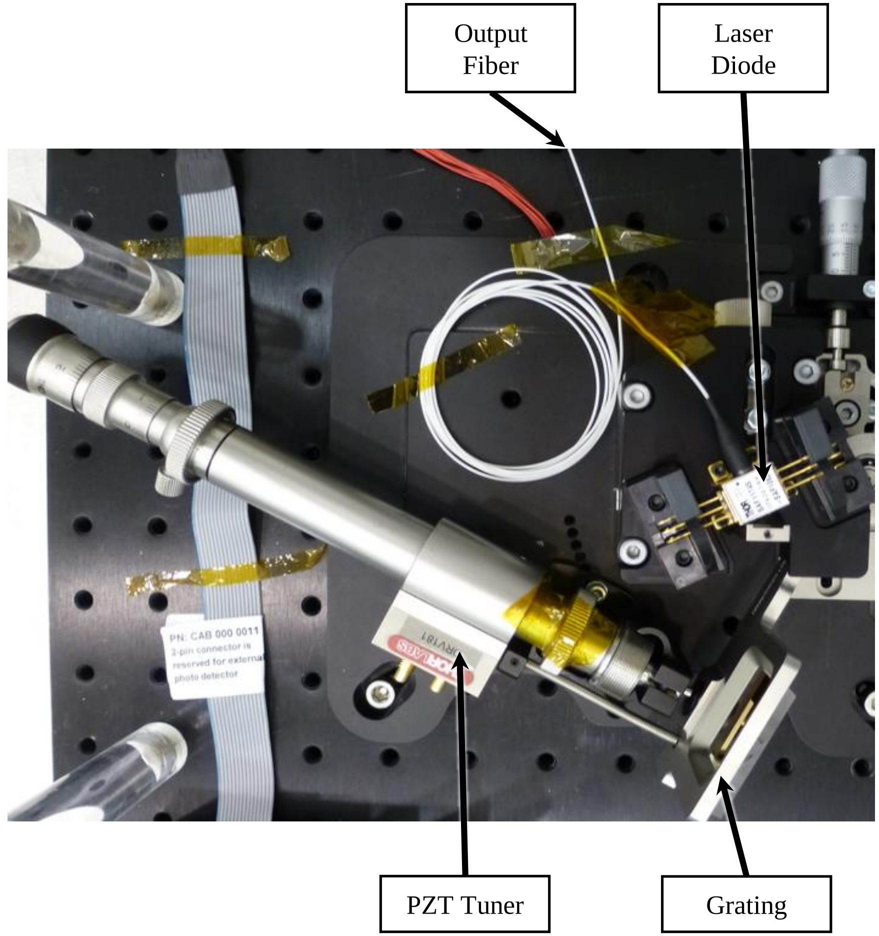
Tunable Laser

- Thorlabs TLK-1300R Fiber-Coupled Littrow external cavity laser
- 50mW
- 10dB tuning range of 130 nm, 1310 nm center wavelength
- Electric servo tuner replaced with Thorlabs DRV181 PZT



www.thorlabs.us



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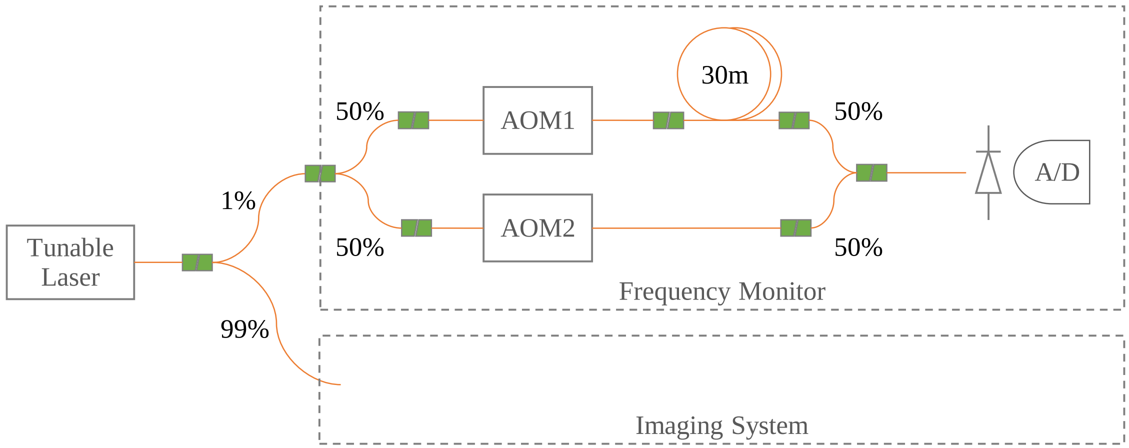
Frequency Monitor

- Fiber Mach-Zehnder interferometer with 30m path length difference
- AOM frequency difference 400kHz
- Beat frequency measured by photodiode: $\Delta\tilde{f} = \frac{d\tilde{f}}{dt}\frac{x_D}{c} + \Delta f_{AOM}$
- Batch 1000 voltage measurements, FFT, identify frequency of peak as $\Delta\tilde{f}$, solve for $\frac{d\tilde{f}}{dt}$



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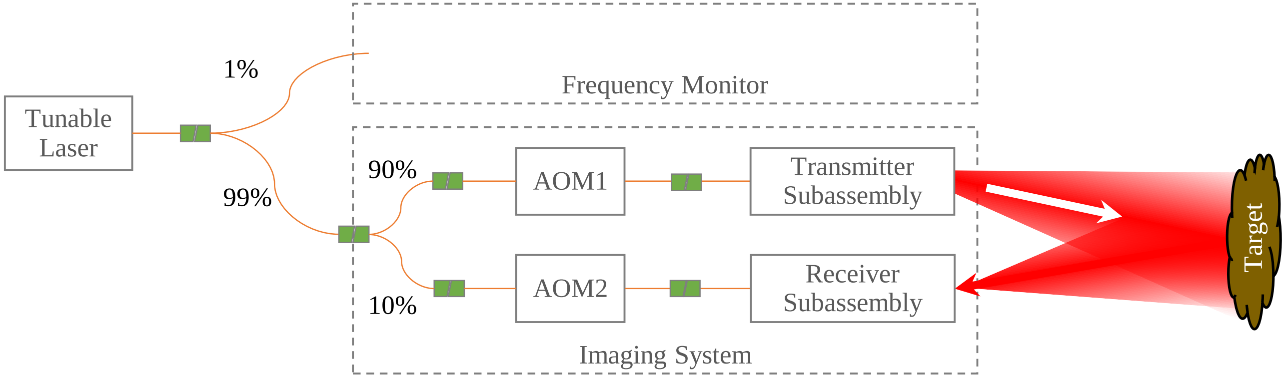
Imaging System

- AOM frequency difference 900kHz
- 90% laser power illuminated the target
- 10% laser power acts as local oscillator for heterodyne detection
- Range-to-target varies from 2 meters to 400 meters for different tests



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Long Range Testbed

- 400 meters from transmitter/receiver to mirror target
- Observed effects of atmospheric turbulence using non-chirped signal
- Used unwrapping of phase of return signal to determine limit on chirp duration

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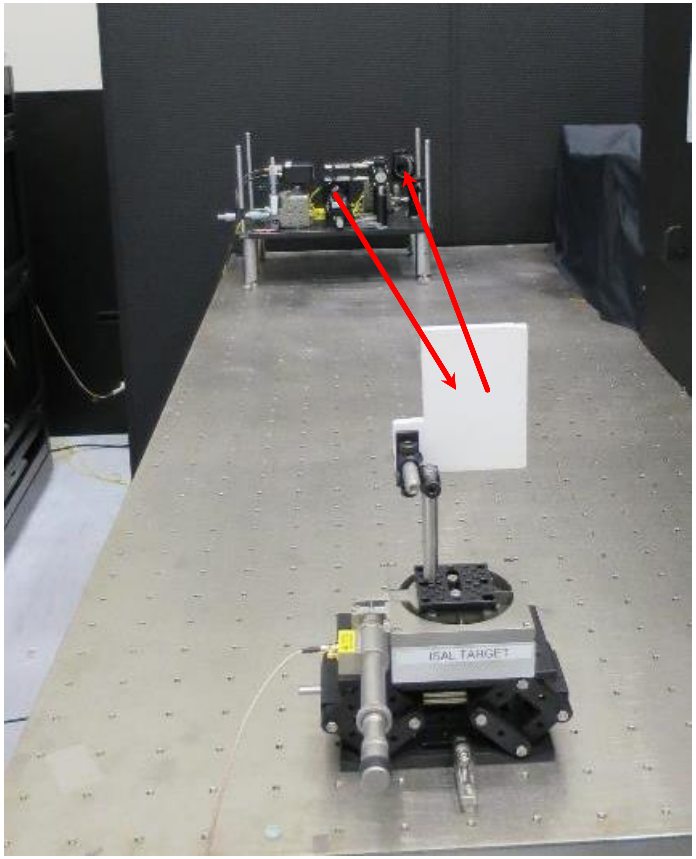
Tabletop Testbed

- 2 meters from transmitter/receiver to target
- ISAL imaging demonstrations
- Operates at high or low CNRs
- Operates with or without synthesized atmospheric turbulence



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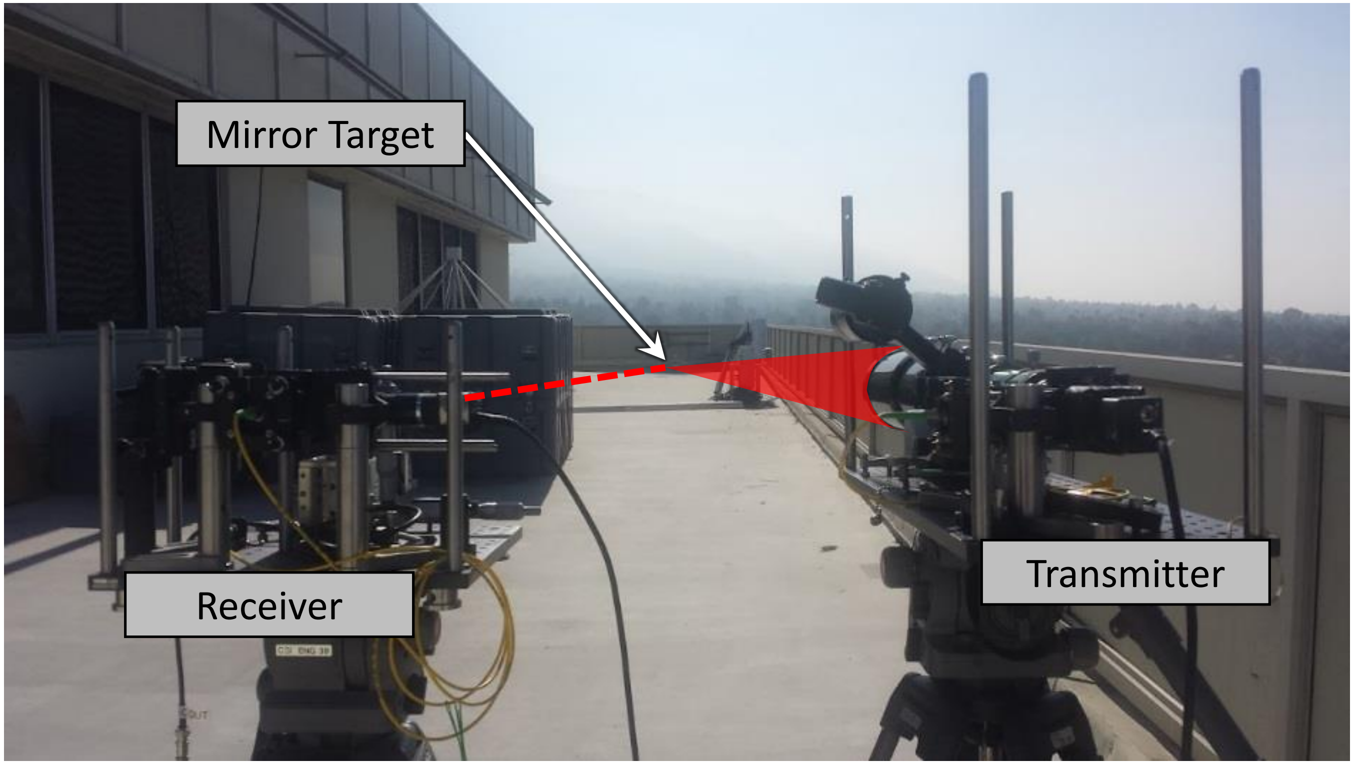
50m Atmosphere Characterization



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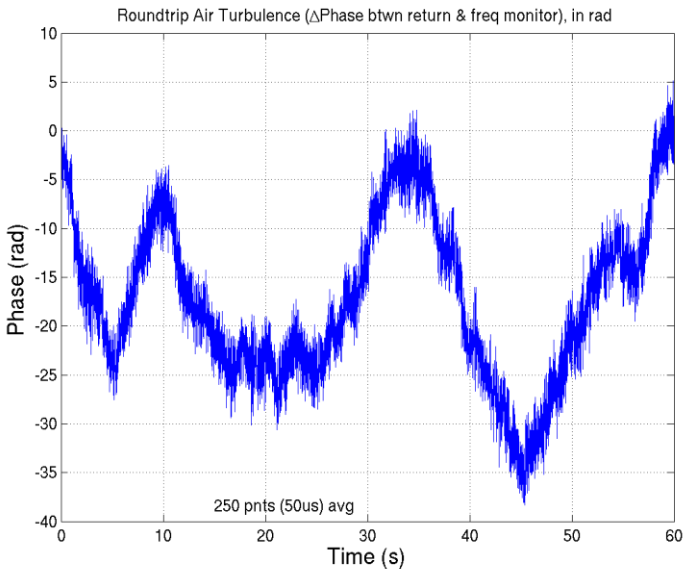
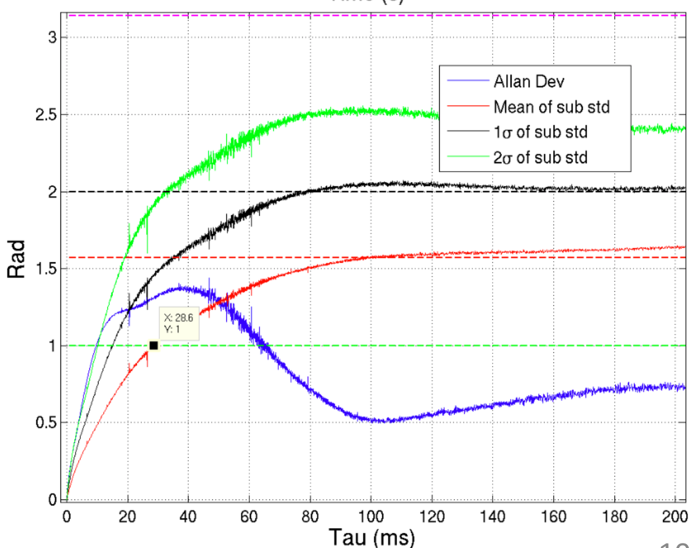
Phase Unwrapping

- Atmospheric turbulence will cause the phase of the return signal to drift
- To focus an image from the ISAL system, the phase must be connected between pulses
- Phase drift between pulses must be less than $\pi/2$
- Phase of non-chirped signal unwrapped.
    - Allan deviation of phase computed for inter-chirp drift
    - Standard Deviation of pulses' phase (sub std) computed for intra-chirp drift
- Chirp rate between 20 and 40 milliseconds





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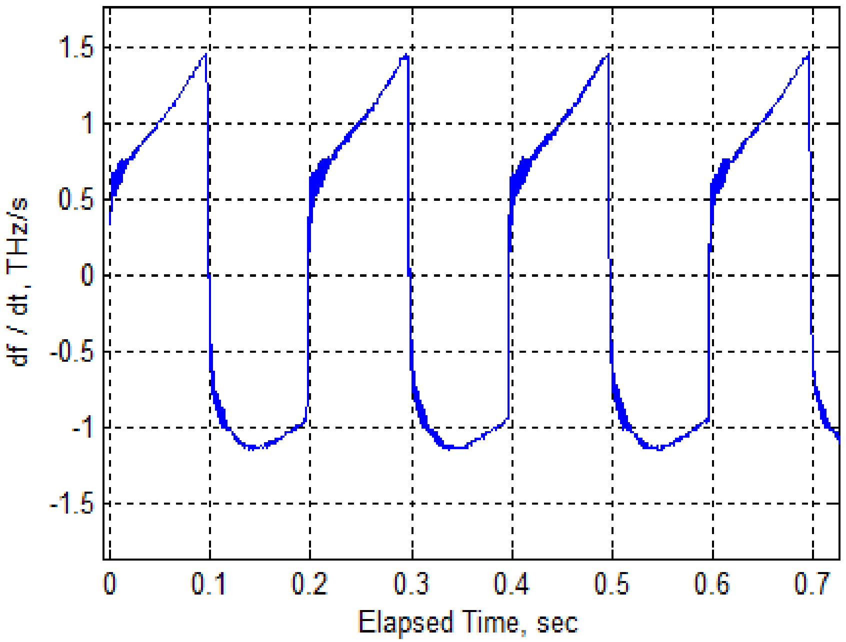
Uncompensated Chirp

- Laser uses a PZT to move a grating to tune the laser
- Control input is a triangle wave which would ideally give a square wave for chirp rate
- Frequency monitor gives the chirp rate
- PZT is not closed loop and has finite frequency response
- Ringing is observed when PZT changes directions
- Constant control rate does not give constant tuning rate



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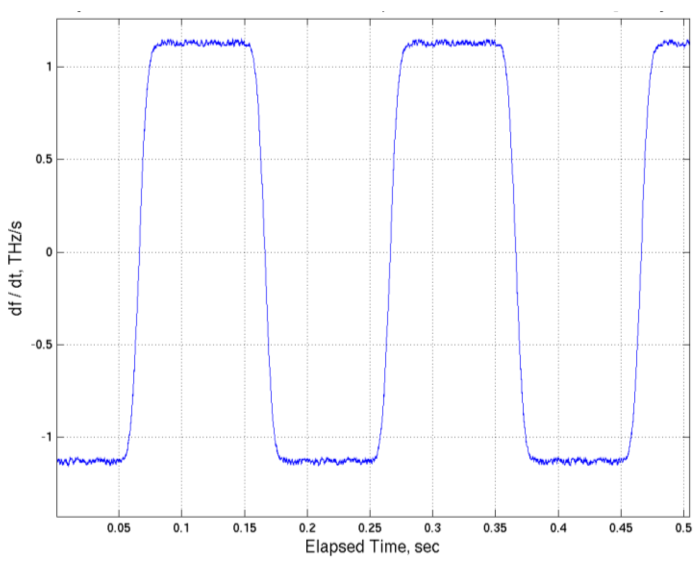
Iterative Compensation

- Control is open loop, but loop can be manually closed by iterating on the control input
- Shift response to compensate for time delay in PZT controller
- Compute error between control and response
- Proportional gain: 0.5
- Low-pass filter (moving window average) smooths the control input to remove ringing from feed-back signal when PZT reverses travel direction
- Several iterations performed



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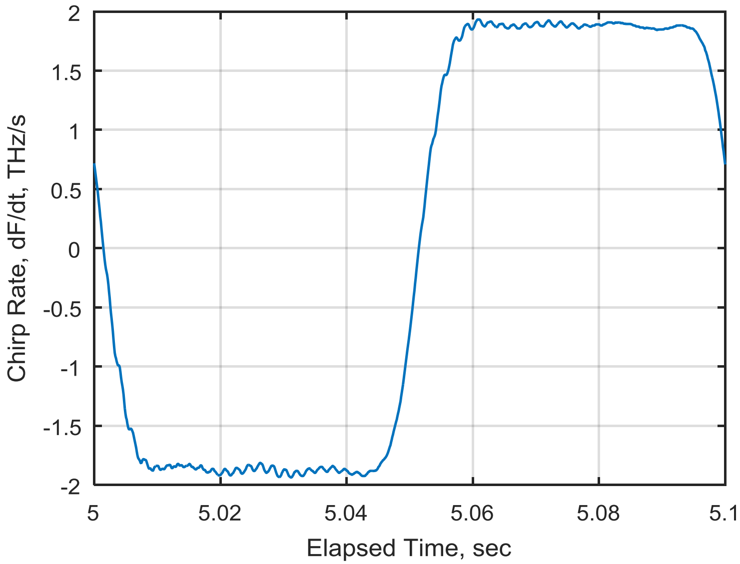
Post-processing

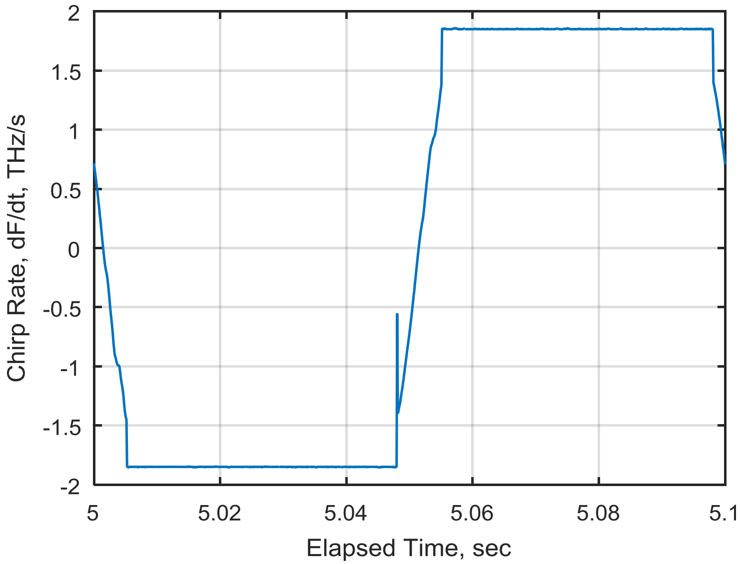
- The chirp rate can be manipulated by distorting time
- Voltage history from the receiver photodiode can be resampled in time to compensate for fluctuations in the chirp rate
- The noisy chirp rate $\frac{d\tilde{f}}{dt}$ is measured by the frequency monitor
- The phase progression is related to the passage of time:
  $$\varphi = \left(\frac{d\tilde{f}}{dt}\frac{x}{c} + \Delta f_{AOM}\right)\left(\tilde{t}_f - t_0\right)$$
- Replace the noisy chirp rate with a constant and introduce pseudo time:
  $$\left(\frac{d\tilde{f}}{dt}\frac{x}{c} + \Delta f_{AOM}\right)\left(\tilde{t}_f - t_0\right) = \left(\frac{d\bar{f}}{dt}\frac{x}{c} + \Delta f_{AOM}\right)\left(\bar{t}_f - t_0\right)$$
- Take photodiode voltage history V_i and sample at fractional index
  $$i' = i + \sum_{j=0}^{i} \frac{\left(\frac{d\tilde{f}(t_j)}{dt} - \frac{d\bar{f}}{dt}\right)\frac{x}{c}}{\frac{d\bar{f}}{dt}\frac{x}{c} + \Delta f_{AOM}}$$

Chirp Rate

Before Resampling



After Resampling



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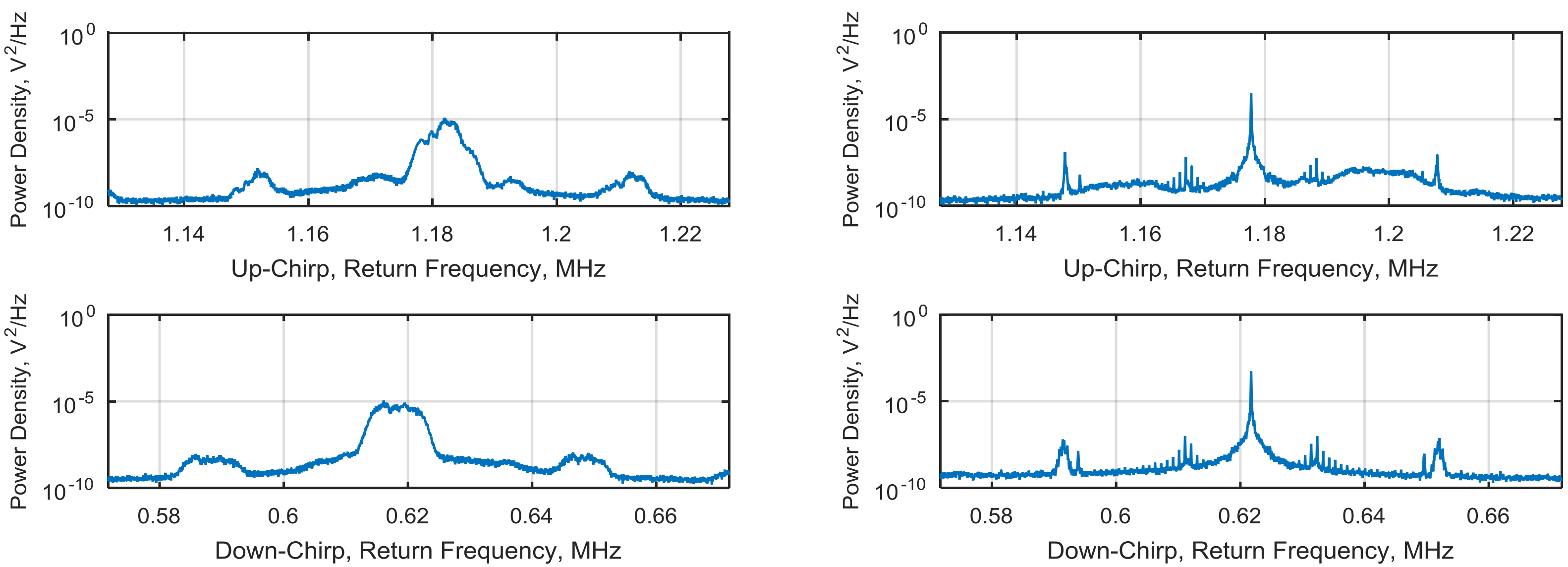
Frequency Monitor PSD

Before Resampling **After Resampling**



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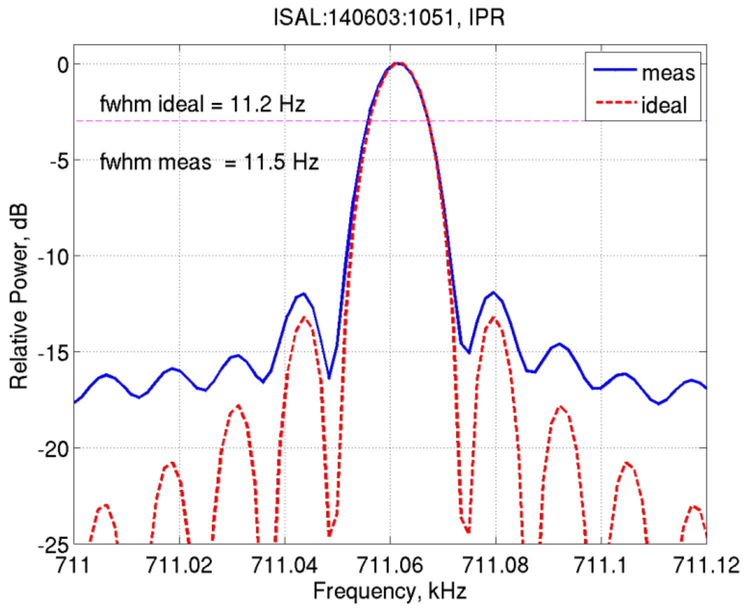
Impulse Response (IPR)

- Shiny metal ball as target of ISAL transceiver (nearly perfect point target)
- Resample voltage history to linearize chirp
- Averaged PSD of ~200 linearized chirps
- Main lobe closely matches the theoretical IPR function. Difference indicates loss of 0.04mm of range resolution out of 2mm total resolution.



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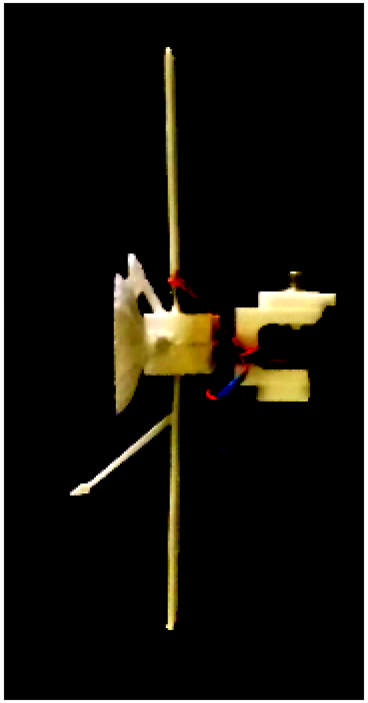
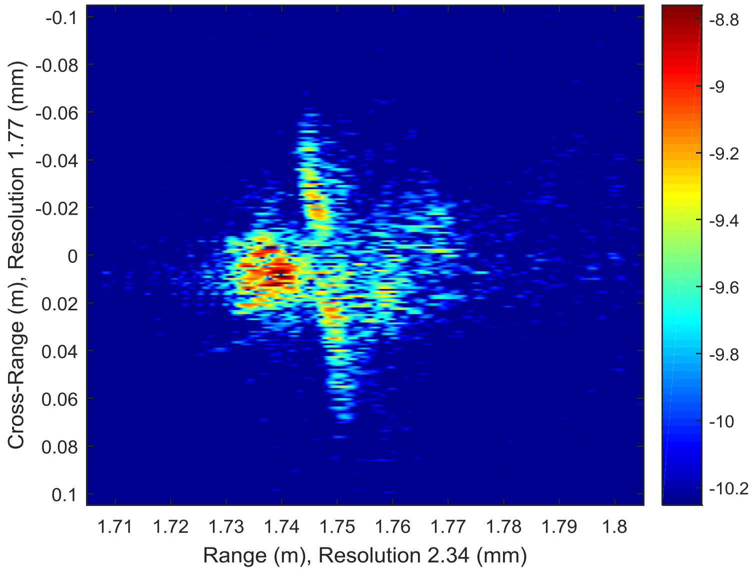
Example Imaging Result

Illumination Beam

Top View





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Conclusions

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