Vibration-Induced Linewidth Broadening in Long Range FMCW Lidar

Nathan Dostart
NASA Langley Research Center
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NASA is planning for sustained human presence on the Moon and Mars.

Operational lunar and Martian bases need periodic resupply, multiple landers.

New/improved sensors need to land payloads in close proximity (< 1 km) and with high precision (< 100 m).
Navigation Doppler Lidar Enables Moon to Mars

Navigation Doppler Lidar (NDL)
- Frequency-modulated continuous wave (FMCW) lidar system
  - 1550 nm, fiber-optic system

NDL measures spacecraft attitude, velocity, and altitude during descent
- <1 cm/s velocity resolution, ~10 cm range resolution
- >5 km operational range

Precise measurements enable reduced landing uncertainty

Small size allows for redundancy, supports small landers

2 NDL units flying to the moon in 2023
NDL Operational Schematic

- FMCW for range/velocity measurements
- 3 channels allow for vectorial position/velocity

![Diagram of NDL Flight Units]

LO – Local Oscillator
BS – Beam Splitter
PD – Photodiode
PBS – Polarizing Beam Splitter

Graph showing:
- $f_{\text{Opt}}$ vs. time (t): Up Ramp, Down Ramp, Dwell
- $f_{\text{RF}}$ vs. time (t): Transmit Path, Return Path, Het. Freq., Delay, Doppler

Legend:
- Blue: Transmit Path
- Red: Return Path
- Green: LO Path
- Orange: Doppler

NDL Flight Units:
- Seed
- Freq. Mod.
- Amp.
- Tele.
- PBS
- 1:3 LO Tap
- 3x
- PD
- BS

LO – Local Oscillator
BS – Beam Splitter
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NDL ETU mounted on mobile shaker and observed target truck up to 4 km

Characterization of signal loss and noise under flight-like conditions
- Maximum estimated vibe loads during landing – 3.9 grms
- Use data to project NDL performance (range, meas. error) during lunar landing

Clear degradation of signal and precision with range and vibe level
Range Measurement Under 1.8 grms Vibe

Channel A Range = 591.8 m

Channel B Range = 590.5 m

Channel C Range = 589.04 m
Delayed Self-Heterodyne Linewidth Measurement

- Laser mounted on vibe table
- Vary vibe frequency from 0 to 14.4 grms (GEVS)
  - 3 dB steps, -30 dB to 0 dB
- 125 MHz AOM offset frequency
- 100m or 30km delay line
- 100 spectra averaged over
  - 20 MHz bandwidth, 1 kHz resolution
  - 20 kHz bandwidth, 1 Hz resolution
  - Combined into single extended spectrum
Results – 100m Delay Line

- Measured “effective linewidth”
  - 2\textsuperscript{nd} moment of frequency PSD
  - Correlates with observed frequency spread, not laser “true” Lorentzian linewidth – range dependent

- Track peak power
- Approximately 10 kHz/grms
Results – 30 km Delay Line

- Approximately 850 kHz/grms
- At highest vibe levels (> 5grms) measurement bandwidth insufficient for linewidth calculation
Estimating Performance for Vibe and Range

- Clear linear trend of frequency broadening with vibe level
- Apparent dependence of signal drop on vibe level, but clear delineation between “short” and “long” range performance
  - Knee of range performance depends on vibe level
Range Testing with NDL System

- Applied vibe levels to seed laser while observing distant target
  - Hangar, 750 m -> (1.5 km RT)
- Correlated measured frequency spread and frequency drop of NDL with linewidth measurement results
NDL Test Results

- Frequency broadening linear with vibe (84 kHz/grms)
- Approximate -10dB/dec drop of signal with vibe
  - Comparable to linewidth measurement past range knee
Future Work

- Analysis of physics behind vibe-induced broadening
- Full characterization of laser phase noise
  - Not well described using only standard drift/flicker/white noise terms
- Measure linewidth and performance at more ranges
- Establish dependence of laser phase noise on vibe frequency content
Summary

- Measured laser linewidth for both short and long ranges as a function of vibe level
- Correlated linewidth measurements with observed lidar signal drop and frequency spread during environmental testing
  - More work need to fully explain observed trends and provide detailed design improvements
- Strong dependence of FMCW lidar on vibration, especially at long range
Thanks to the NDL Team

Keep an eye out for us on the Moon in 2023!
Sig Drop vs Freq
100 m Results

100 m Delay

Observed Linewidth at 100m

Linear: y = 10.24x - 1.348

Observed Signal Drop at 100m

Effective Linewidth (kHz)

Vibe Level (g_{rms})