SPECKLE NOISE IN ORBITAL LASER DOPPLER VIBROMETRY

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Introduction: A Laser Doppler Vibrometer (LDV) records non-contact measurements of a surface's motion. Sava and Asphaug have proposed to record seismic data from orbit around small planetary bodies using LDVs [1]. The simplicity and appeal of using LDVs on orbiters is that landing seismometers on the surface is not required, and full coverage of the body can be achieved over time. However, to reap these benefits, the instrument must be able to operate on unprepared surfaces the same way laser altimeters do. Optically rough surfaces, the case for virtually all rocky materials found on planetary surfaces, produce random diffuse reflection patterns called speckle when illuminated by a laser [2]. A time variant laser speckle pattern distorts the velocity signal recorded by LDVs. We quantify the expected signal distortion from an orbiting LDV and propose a method to eliminate this distortion by exploiting signal diversity.

Laser speckle: Laser Doppler Vibrometers operate by illuminating an object with a laser beam and detecting the light that is reflected back. Motion of the object inline with the laser beam causes the reflected light to be Doppler shifted. The LDV records the frequency shift which can be used to calculate the object's velocity [3]. For a vibrating object that has mirror-like reflectance, LDV velocity measurement noise is strictly determined by the engineering specifications of the LDV itself. However, when an LDV's beam spot moves along a natural rough surface, the case for an orbiter, noise is introduced by an evolving laser speckle pattern [4].

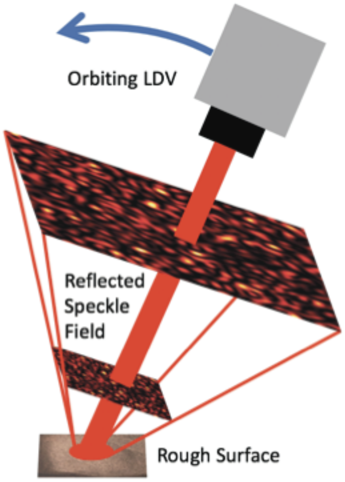


Figure 1: *A laser beam reflected off a surface with roughness greater than the laser wavelength creates a speckle pattern due to interference of light paths originating at different points on the surface. Speckle size increases with distance from the surface. Moving the laser spot on the surface causes the speckle pattern to change.*

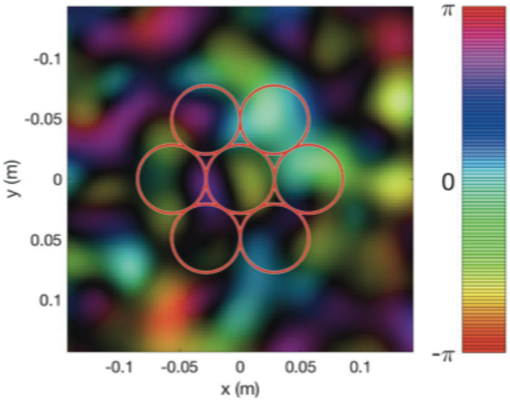


Figure 2: *An example speckle pattern generated by a 775 nm laser focused on a rough surface 1 km away. Color indicates the relative phase of the light. The red circles indicate the closest packing of seven receivers, each at the size of the average speckle. Each receiver records an independent signal.*

We simulate speckle patterns by modeling a rough surface as a collection of randomly placed point scatterers. The path difference between light reflected from each scatterer causes constructive and destructive interference. At a large distance, this interference appears as a speckle pattern. Figure 1 provides a visualization of this scenario. If the laser spot on the rough surface moves, then the observed speckle pattern evolves randomly, appearing to boil [4]. An LDV detector cannot average over multiple speckles because each speckle has a random phase relative to other speckles, as seen in Figure 2. Thus, an LDV detector is typically designed to be similar in size to one speckle [2]. As the speckle pattern evolves, an LDV detector sees the intensity and phase of light change over its detection area. The changing phase appears as a frequency shift to the LDV, and thus manifests as an incorrect surface velocity signal [4]. The faster the LDV moves relative to the target surface, the more the speckle noise affects the signal.

Signal diversity combining: Speckle noise can be mitigated by using multiple LDV receivers. Figure 2 shows a compact arrangement of seven receivers on top of a speckle pattern. Figure 3a depicts the recorded velocity signals from each of the seven receivers as the speckle pattern evolves. Adjacent LDV receivers record uncorrelated speckle noise. Mathematically, the signal from the ith receiver, s_i, can be expressed as,

$$s_i(t) = x(t) + n_i(t), \qquad (1)$$

where n_i is the speckle noise, x is the true signal, and all variables are a function of time, t.

Approximating a signal from multiple independent receivers is known as diversity combining. An optimal signal approximation, $\tilde{x}$, can be achieved using a weighted sum of the signals [5, 6]:

$$\tilde{x}(t) = \sum_{i=1}^{n} w_i(t) s_i(t). \tag{2}$$

The ideal weights are,

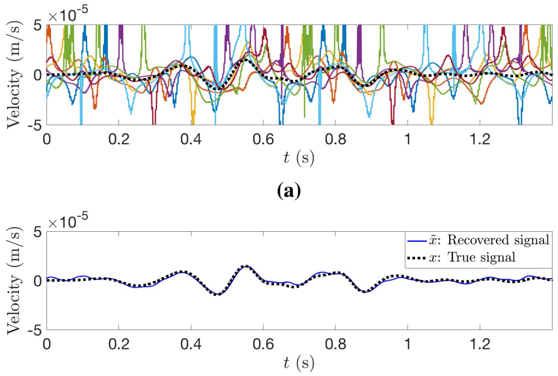
$$w_i(t) = \frac{1}{\sum_{j=1}^{n} \frac{V_i(t)}{V_j(t)}}, \tag{3}$$

where V_i represents the variance of the signal s_i from the true signal. The variance of each signal, V_i, is proportional to the total light intensity on the ith detector [5]. Thus, the relative variance between two detectors i and j, V_i/V_j, is known. In Figure 3b, the seven independent noisy signals from Figure 3a are combined to recover the true signal, demonstrating the effectiveness of this method.

Results & Discussion: We use our simulation method and signal diversity combining to model the signal-to-noise ratio (SNR) of an orbital LDV that records ground motion on an optically rough surface. Figure 4 shows the SNR as a function of peak ground velocity (PGV) and the LDV's orbital angular velocity. This result indicates that at realistic orbital angular velocities, an LDV can accurately record seismic signals with a PGV on the order of 10^{-6} to 10^{-5} m/s. This is roughly equivalent to the PGV one might expect for a station 1,000 km away from a magnitude 7.0 earthquake [7]. This is also about the same PGV that highly sensitive geophones detect in exploration seismology on Earth [8].

Note that we use orbital angular velocity because this combines the dependency on distance and target body mass into one variable. For reference, during Orbital Phase B of the Osiris Rex mission, the spacecraft will orbit at approximately 0.004 deg/sec at a distance of 1 km above asteroid 101955 Bennu [9]. A 10 km orbit above a larger 100 km diameter body would orbit at approximately 0.04 deg/sec. Also note that our simulation only considers speckle noise. Optical components, spacecraft jitter, and pointing accuracy would all generate additional LDV signal noise. However, these noise sources are all dependent on engineering precision and instrument design rather than a fundamental physical limitation in recording the desired signal.

Conclusion: We show that signal diversity combining can overcome the limits of speckle noise for an orbital laser vibrometer. For slow orbital angular velocities, a laser Doppler vibrometer can record ground motion signals on the order of 1 μm/s.



(a)

(b)

Figure 3: *(a) Each of the 7 receivers from Figure 2, records an independent measurement of the ground motion, but are dominated by speckle noise. The black dashed line indicates the true signal. (b) Using optimal signal combining, the true velocity signal can be recovered from the 7 observed signals shown in panel (a).*

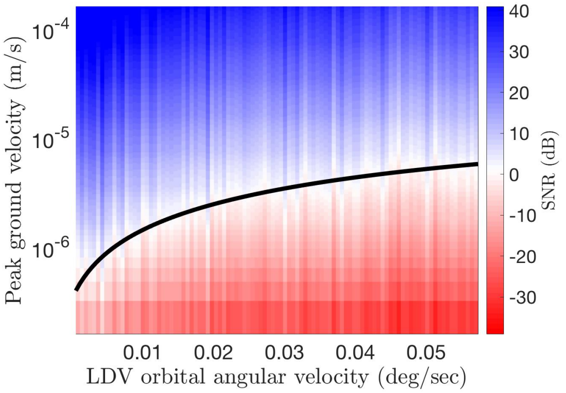


Figure 4: *Assuming that orbital LDVs can perfectly aim at the same point on the surface, only the orbital angular velocity causes an evolving speckle pattern. The peak ground velocity of a monochromatic 1 Hz signal that can be recorded with an SNR of 1 is shown by the black line as a function of orbital angular velocity.*

Acknowledgements: This work was supported by the NASA Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO) program (NNH16ZDA001N).

References: [1] P. Sava et al. *LPSC 50*, 1709, 2019. [2] S. Rothberg et al. *Proc. SPIE*, 5503, 2004. [3] A. Donges et al. *Laser Measurement Technology*, chapter 11, *Springer*, 2015. [4] A. Drbenstedt. *Proc. SPIE*, 6616, 2007. [5] A. Drbenstedt. *AIP Conf. Proc.*, 1600(1), 2014. [6] C. Rembe et al. *AMA Conf. Proc.*, 2015. [7] D. J. Wald et al. *Bull. of Seis. Soc. of Amer.*, 81(5), 1991. [8] A. D. Alcudia et al. *CREWES Res Rep*, 20, 2008. [9] M. G. Daly et al. *Space Sci Rev*, 212, 2017.