Assessing Potential Geophysical and Environmental Impacts from Frequent Rocket Launch Missions at Kennedy Space Center

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Summary

Kennedy Space Center (KSC) in Florida has been utilized for space missions over many years with a gradually increasing number of rocket launches. There have been multiple studies where air-coupled acoustic waves and infrasound originating from launched rockets were used for operational purposes, such as locating booster trajectories as a function of changing atmospheric conditions [1,4]. However, no study has utilized the acoustoelastic waves as a signal source for subsurface seismic investigations. We conducted a dispersion analysis using the seismic energy recorded from the Artemis I rocket launch at KSC in November 2022, and from these results we generated depth-sensitivity kernels at different wave frequencies. The kernels were compared with sedimentary core data to verify boundaries of carbonate layers above the Floridan Aquifer System. Accumulative information of bedrock-sediment boundary across the sedimentary platform could especially provide geo-structural evidence that manifests the configuration of coastal features. Continuous dispersion analysis of seismic recordings from consecutive rocket launches also has potential to identify non-stationary environmental effects, such as reorientation of sedimentary structures and fluctuation of the saltwater/groundwater lens from gravitational tides, which may affect erosional susceptibility of coastal features.

Method

Surface wave dispersion. We have adapted a continuous wavelet transform (CWT) method to construct the Empirical Green's Functions (EGFs) and calculate the seismic surface wave group velocity dispersion from the rocket launch signal [5]. From the pre-processed seismic velocity signal of the launch event, the seismic travel-times were found by converting UTC time to the relative time from lift-off and normalized by the distance from the launch pad (Figure 1). CWT is applied to the converted seismogram and involves a convolution of the time-series with a scaled and translated version of a mother wavelet, which is a function of non-dimensional time. We employed the most widely used "Morlet" wavelet, which is a plane wave modified by a Gaussian function and processed the data in the frequency domain for fast computation. Spectral amplitude was normalized for each frequency array (converted to wave periods) to visualize a robust trend in frequency dependent dispersion and to extract the group velocity curve.

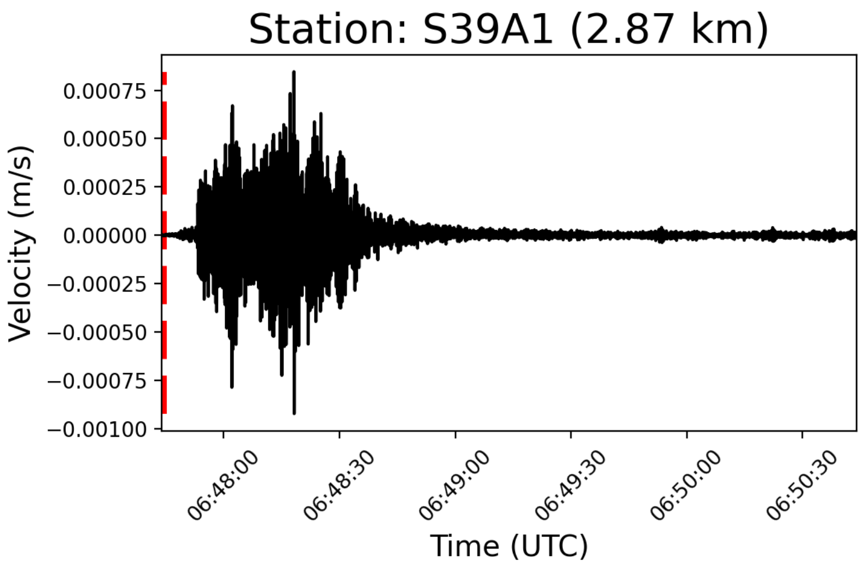

Figure 1. Example seismogram of the Artemis I rocket launch on 16 November 2022 recorded 2.87 km away from the launchpad. The red dashed line indicates the exact time of lift off, and we can observe the signal originating from the rocket exhaust making contact with the launchpad, and directly generating seismic energy, and seismic energy from atmospheric coupling once the rocket has lifted off and exhaust no longer makes direct contact with the ground.

Depth-sensitivity kernels. To consolidate the group velocity results into a 1-dimensional profile, the depth-sensitivity kernels were computed using the software package "Computer Programs in Seismology" [3]. A series of partial derivatives of the dispersion velocities (U) with respect to a reference shear wave velocity (b) structure were calculated, where the peaks in these kernels (dU/db) indicate depths of peak sensitivity for distinct wave periods.

Results

We were able to measure the dispersion from the vertical component of the seismic signal and derived a coherent group velocity curve for wave periods greater than 5 s, but a weak connection was found in spectral peaks for periods shorter than 5 s (Figure 2). The multi-modal signals that concurrently arrive at the receiver interrupts the normalization process, especially for short-period waves that require further quality control processes. Despite the weak and scattered spectral signal, short-period waves display a trend of decreasing velocity away from the peak velocity near 1.2 s period. The drop in velocities below 1.2 s period may represent a steep boundary condition indicating an increase in primary or secondary sedimentary porosities.

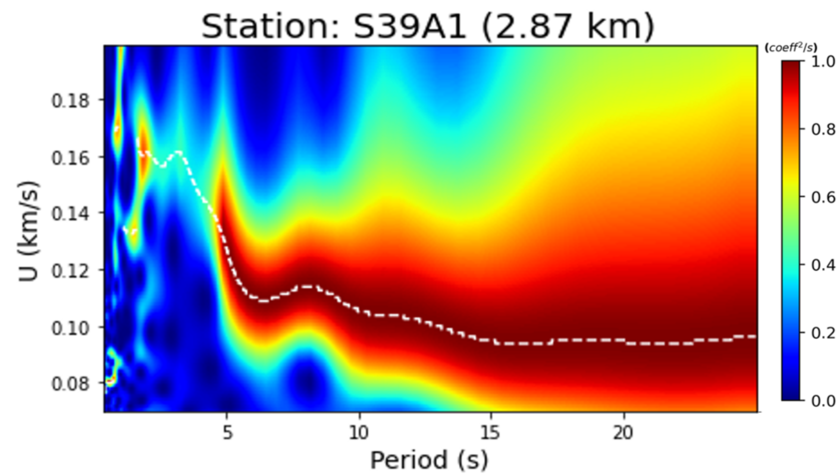

Figure 2. Amplitude normalized continuous wavelet transformed seismic signal. The white dashed line traces the maximum spectral value along the period distribution and corresponds to distinct group wave velocities (U). The colors represent amplitudes of normalized spectral power (unitless coefficients).

Sensitivity Kernels were computed from a reference model that incorporates carbonate sedimentary layers above the Upper Floridan aquifer system (Figure 3 (A)) [5]. Generally, longer period waves have greater sensitivity at deeper depths. We found that the 1 s period wave has the greatest sensitivity around 50 m depth, which corresponds to the boundary between the Ocala Limestone and the Hawthorn Group [2]. The shallowest boundary between the confining carbonate unit (Anastasia Formation) and surficial aquifer (sand and clay) resides at approximately 9.2 m depth at this location, which requires improved short-period velocity measurements for better detection [2]. A gradual increase in depths of peak sensitivity with increasing wave period is observed with several jumps at 2 s, 3.8 s, and 14.5 s that may indicate carbonate layer boundaries and change in depositional compositions and characteristics (Figure 3 (B)).

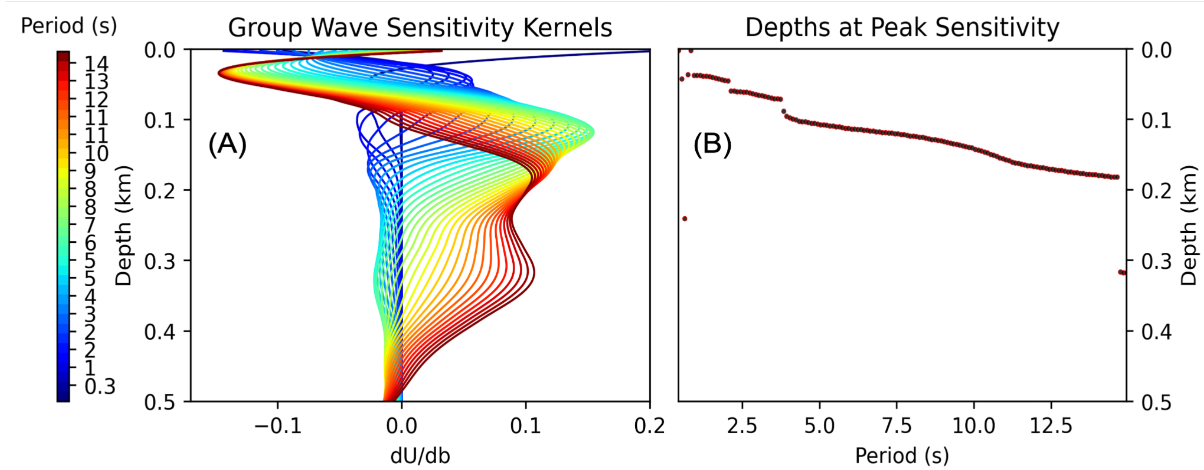

Figure 3. (A) Full depth-sensitivity kernels computed from the extracted dispersion curve. The partial derivatives (dU/db) represent the sensitivity values at different group wave periods. (B) Reduction to show only the depth of peak sensitivity for different seismic wave periods.

Conclusions

Rocket launch signals recorded with seismic sensors were able to be processed to function as an EGF for measuring surface wave dispersion. The Rayleigh wave group velocity curve was extracted from the dispersion measurements with reasonable velocities for wave periods greater than 5 s. This demonstrates that comparing the spectral dispersion of successive rocket launches should be capable of discerning changes in the subsurface medium associated with both the high energy discharge from rocket launches as well as environmental effects, which is essential to monitor in maintaining a sustainable coastal environment. Sensitivity kernels were computed and compared with sedimentary core data for ground truthing the group velocity curve where the carbonate layer boundary between the Ocala limestone and the Hawthorn group aligned well with the depth of peak sensitivity for 1 s period waves. However, it is necessary to intensify shorter period wave signals to increase the signal-to-noise ratio for robust dispersion measurements and to identify shallower (< 40 m) geologic structure. Detecting phase-coherent signals among multiple rocket launch signals or accumulating rocket launch events may further enhance the overall dispersion quality.

References

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