A Seismic Profiler for the Construction and Resource Utilization Explorer (CRUX)

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Abstract—A modular integrated suite of instruments and software known as the Construction Resource Utilization eXplorer (CRUX) is being developed for the U.S. National Aeronautics and Space Administration (NASA) to provide semiautonomous reconnaissance of the lunar and planetary surfaces [1]. One component of the CRUX, the seismic profiler (SEIP) instrument, is described in this paper. The hardware is described and examples of synthetic and real (Earth) seismic data are presented and discussed. Because of the advances in the electronic hardware and digital analysis methods that have occurred since the Apollo lunar missions, this instrument will have the flexibility to gather and analyze seismic data in a number of different ways to enhance the usefulness of the seismic information.

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1. INTRODUCTION
The goal of the CRUX is to characterize regolith resources, surface conditions, and geotechnical properties to help select optimal sites for conducting future lunar and planetary missions [1]. Because seismic waves are directly related to density and strength parameters and can be used to make measurements over large areas, the SEIP is an important component of the CRUX.

The most detailed information about the subsurface will be produced by the borehole and ground penetrating radar (GPR) measurements (on the order of centimeter accuracy). The seismic profiler measurements will complement these results by providing deeper but lower resolution information about the regolith, and by extending the strength measurements laterally away from the boreholes.

Active seismic measurements conducted during the Apollo missions [2-4] provide a detailed view of the shallow seismic structure of the lunar regolith. A surface layer, ranging from 2 to 20 meters thick, has a very low P-wave velocity of about 110 m s\(^{-1}\) and consists of unconsolidated, fine grained soil with a bulk density of about 1500 kg m\(^{-3}\) [5-6]. The second layer has a speed of 250 ± 50 m s\(^{-1}\) and a thickness of tens of meters. Below this is a layer with a speed of about 1200 m s\(^{-1}\). With these seismic parameters as a guide, the design of a system to automatically conduct and analyze seismic refraction measurements has begun and is in the very early stages. Future efforts on this project will include other methods of seismic data collection and analysis using the SEIP hardware.

After a discussion of some of the SEIP design considerations, simple theoretical seismograms are constructed and analyzed. Preliminary real Earth measurements are presented in the following section.
2. SEIP DESIGN CONSIDERATIONS

An integrated hardware and software system will be designed to measure the seismic compressional wave (P-wave) and shear wave (S-wave) velocities in the shallow regolith. This system will use an active source to generate the waves and will detect the wave arrivals as a function of horizontal distance from the source. Since seismic measurements sample roughly one-fourth the horizontal offset, measuring wave arrivals over 20 meters will provide information down to about 5 meters in depth. Because ice inclusions or ice-bonded soils are expected to have much higher velocities than the normal regolith (at least 1000 m s\(^{-1}\) [7]), the system will also be able to detect and map these inclusions.

The seismic profiler will be used to extend and complement the borehole and GPR measurements. The purpose of the seismic profiler is to extend lunar regolith strength measurements tens to hundreds of meters away from a borehole, detect shallow ice inclusions or areas of ice-bonded soil, and determine the depth of the regolith. These goals will be accomplished by designing an autonomous hardware and software system to measure the seismic P-wave and S-wave velocities in the shallow regolith. Because the seismic wave velocity is a direct measure of the elasticity and density of the material it passes through \((V_p = \frac{E}{\rho^{1/2}}\), where \(E\) is Young's modulus and \(\rho\) is the density), it can be used as an index of the strength as well as aspects of the composition (e.g., loose soil vs. soil with ice vs. rock) as a function of depth. For example, P-wave velocity is commonly used as an index of soil rippability for construction projects [8]. The results of the automatic software measurement system will be reported to the CRUX for mapping and fusion with other sensor measurements.

The hardware needed for the seismic profiler includes a source of the seismic waves (a solenoid-driven impactor or other device [9-11]), seismometers to detect the wave arrivals, communication (by a cable or radio link), digitizers, and computational hardware. The type, number, and spacing of the receivers to give suitable performance will be determined in the design effort. Specialized seismometers with very low weight and power requirements will be incorporated into the design [12]. Attention will also be needed to design a suitable low power source of the seismic impulses.

There are a number of methods available for data collection and interpretation with the same hardware. The primary method that will be discussed in this paper is the seismic refraction method [13]. Here, an active vibrational source induces motion in the regolith that is recorded by the seismometers. The recordings are analyzed to determine horizontal travel time vs. distance, which is then converted to velocity vs. depth. Since the seismic velocity is an index of the regolith’s elastic modulus, this information gives the shallow stratigraphy and mechanical properties of the regolith. A low power source inducing a relatively long time series (seconds) will probably be used and the arrival times determined by correlation with the source function.

Because the seismic refraction method depends only on travel time and velocity measurements, the seismic sensors do not require amplitude calibration. However, for other applications a calibration capability may be desirable, and this capability can be included in the sensors by driving the sensor feedback coils [12] with a known electrical pulse and measuring the response.

The seismic velocity measurements should be capable of detecting ice saturation levels as low as 5% or less in the lunar regolith. This sensitivity to low saturation levels is possible because even minimal quantities of ice can cement soil grains together, rapidly increasing the elastic moduli and seismic velocities [14-16].

Other methods that will be investigated include surface wave analysis and microtremor analysis [17-18]. Data to implement both of these methods can be collected with the same hardware. These methods use more computationally intensive analysis methods to determine the subsurface structure, and also provide information on the shear properties of the regolith.

3. THEORETICAL SEISMOGRAMS

To help in the development of the SEIP software and hardware design, a simple theoretical model of seismic wave propagation was investigated. This model assumes that the regolith consists of two horizontal layers and includes only compressional waves. These waves, including the direct, reflected, and refracted seismic arrivals, are included in the model.

To construct a noise-free synthetic seismogram at a given sensor location, the travel times and amplitudes for the three waves are computed, and a regolith impulse response consisting of a spike with the same size as the wave amplitude is placed at the expected wave arrival time. The source function is then convolved with this simple regolith impulse response to produce a seismogram, the particle velocity time series.

The precise nature of the noise in a time series is often difficult to model accurately, but is critical in assessing signal processing methods. Here, two types of noise are included in the time series, correlated noise and additive noise. The correlated noise (where “correlated” means that the noise is correlated with the source function as any true seismic arrival will be) is computed by adding a sequence of uniformly distributed random spikes to the impulse response of the regolith. This process models wave scattering from inhomogeneities in the regolith (like boulders, etc). An amplitude of 0.08 (or a maximum amplitude of 8% of the direct wave amplitude) has been
assigned to this type of noise.

The uncorrelated noise is another uniformly distributed random noise sequence, but this sequence is added to the time series itself after convolution of the source function with the regolith impulse response. Because it is uncorrelated, this type of noise can be reduced by averaging many seismograms, and it is often the noise used in estimates of signal to noise ratio (SNR). The noise levels in the example time series is twice the amplitude of the direct wave, corresponding to a SNR of 0.5.

The SEIP will probably record different types of data including controlled active source measurements (like a solenoid driven force transducer or an explosive bolt), uncontrolled active source measurements (drilling, rover maneuvers, or ascent stage impacts), and passive measurements (ambient noise without active sources). The examples provided here are all for a controlled solenoid driven forcing function. We are still investigating what source functions to use to drive the solenoid, so here we just used a simple “chirp” function, a sine wave that continuously sweeps from a low frequency to a high frequency over a short period of time. A function like this has the advantage of having a relatively broad frequency band and measurements can be easily stacked to improve the SNR. For these examples we used a frequency band of 50 to 250 Hz over a two second period.

In this theoretical example, the assumed seismic velocities are 110 m s$^{-1}$ for the 3-m-thick surface layer, and 1200 m s$^{-1}$ for the underlying half space, similar to the parameters measured for the Apollo shallow regolith. The bottom layer has a relatively high but not unreasonable velocity. The additive noise level is 200%, much worse than encountered in the Apollo missions.

Theoretical time series are computed for six sensors, spaced two meters apart in a straight line along the surface. The source was located two meters from the nearest sensor. This geometry gives seismograms at distances of 2, 4, 6, 8, 10, and 12 meters from the source location. The particle velocity time series for each sensor is 2 seconds long and sampled every 0.1 ms. Figure 1 shows the theoretical seismograms computed for this example.

Data processing

The methods are still under development. For this example, a very simple processing method is used: the cross correlation between the sensor time series data and the source function is computed, and the two largest local maxima times are found. The times of these maxima usually correspond to the direct and refracted waves’ arrival times, although the relative amplitudes of the maxima do not always correspond to the same wave.

Figure 1. Theoretical seismograms calculated for a simple model of the lunar regolith consisting of two horizontal layers with compressional wave velocities of 110 and 1200 m s$^{-1}$, and an upper layer thickness of 3 meters. A swept frequency source from 50 to 250 Hz was used, and additive noise with twice the amplitude of the direct wave is present.

Figure 2 shows the processing results, while Figure 3 compares the theoretical travel time curves with the travel times points automatically picked using the correlation processing. The lowest line segments on the travel time curves are the lines needed to determine the subsurface properties, and we do not expect to match all the secondary arrivals in real measurements because of interference between the different waves at short propagation distances. (Note also that the theoretical lines will be unknown for real measured data.)

The correlation method works well in this example with a SNR of 0.5, and even for 500% additive noise (SNR = 0.2, not shown here). It also found the direct wave for 1000% (SNR=0.1), but picked the reflection instead of the refraction at most longer propagation distances.

This processing method will almost certainly not perform as well on real data, because the simple model does not entirely match the actual regolith. The main shortcomings of the model are the inclusion of only three wave types
Figure 2. Data processing of the theoretical seismograms shown in Figure 1. The left column shows the early time portion of the theoretical time series, the right column shows the cross correlation with the source function, and the automatically picked travel times at the two largest local maxima.

(ignoring shear waves and surface waves), the lack of intrinsic attenuation (which will distort the waveforms), and the assumption of perfect source performance.

The data processing discussed here is only the first step in the SEIP software design. Still to be developed are the mapping of the travel times to specific line segments, fitting lines to the travel time points, and inverting the travel time lines to determine the velocities and layer thickness. In addition, methods for analyzing passive seismic data will also be implemented.

When the automatic seismic data processing is completed, the seismic analysis software will report the following information to the centralized CRUX decision support and mapping system: the number of layers detected, the seismic velocities of the layers, the layer thicknesses, whether ice is present (an indication based on whether a velocity of 1500 m s\(^{-1}\) or larger was detected near the surface), and, possibly, the layer interface slopes if they are not horizontal. The latter parameter can only be reported if measurements can be obtained with the source at both ends of the sensor array.

4. PRELIMINARY EARTH MEASUREMENTS

Although the hardware development is just beginning, a preliminary measurement using a solenoid-driven shaker can be presented. These measurements were conducted outside of the CRREL main building in a seismically noisy area close to generators, compressors, and intermittent vehicle traffic.

Four vertical component geophones were installed at the ground surface, spaced 0.5 meters apart, for an array length of 1.5 meters. The shaker was placed on the ground next to one of the geophones and weighted down. Measurements were made using a continuous fixed frequency sinusoidal source function.

Figure 4 shows a measurement made when the shaker was turned off. The RMS levels are approximately 5 µm s\(^{-1}\).

Figure 3. Comparison of the automatic travel time picks from Figure 2 with the theoretical travel time curves used to construct the theoretical seismograms. Circles are the times of the largest local maxima, triangles the second largest.

Figure 4. Ambient noise measurement made with the shaker turned off. The RMS levels are approximately 5 µm s\(^{-1}\).
geophone in the array. These correlations are then picked automatically, and an analysis of these times reveal a primary wave arrival with an apparent velocity of 250 m s\(^{-1}\) across the array. (The direction of arrival is opposite to that shown below when the shaker is turned on.)

Figure 6 shows an example of a measurement made with the shaker oscillating at 40 Hz. The signal produced by the oscillator is very strong at the closest geophone, and rapidly decays from 92 to about 9 µm s\(^{-1}\) (rms) in propagating 1.5 meters. The higher frequency nature of the time series is still visible at the longer distance compared to the ambient noise presented in Figure 4, and the SNR could be improved if needed by stacking multiple measurements.

The correlations are shown in Figure 7. The strong correlation at 41.7 Hz (the actual output of the shaker measured from the close geophone time series) is visible for all of the sensors without any filtering or processing. The automatically picked arrivals fall on a straight line as expected with a slope corresponding to a velocity of about 136 m s\(^{-1}\), a typical value for a very shallow soil. Measurements at frequencies of 14, 20, and 30 Hz gave similar values for the velocity.

**5. CONCLUSIONS**

The current status of the seismic profiler instrument under development for the CRUX has been discussed in this paper, and examples of theoretical and actual refraction measurements have been presented. We have shown that a simple cross-correlation method can potentially be used to automatically determine the seismic refraction travel times from recorded time series. Additional development of the processing methods will need to include provisions for sloping subsurface layers and the automatic selection and fitting of line segments to the distance vs. travel time curve (Figure 3). This instrument will have the flexibility to use a variety of data collection and analysis methods in a semiautonomous fashion, and will be capable of complementing and extending borehole and other measurements during lunar or other survey missions.
REFERENCES


BIOGRAPHIES

Don Albert is a research geophysicist at the US Army Engineering Research and Development Center’s Cold Regions Research and Engineering Laboratory. He has conducted seismic and acoustic experiments in Alaska, Norway, Greenland, and Antarctica, and has published papers on theoretical, experimental, computational wave propagation topics. He has a PhD in geophysics from Scripps Institute of Oceanography.

Bruce Banerdt has been a research geophysicist at the California Institute of Technology's Jet Propulsion Laboratory since 1977, where he does research in planetary geophysics and instrument development for flight projects. He has been on science teams for numerous planetary missions, including Magellan, Mars Observer, Mars Global Surveyor, and Rosetta. He was the US Project Scientist for the international Mars NetLander mission, for which he was also principal investigator of the Short-Period Seismometer experiment. He led the Geophysics and Planetary Geology group at JPL from 1993-2005, and is currently Discipline Program Manager for Planetary Geosciences. He has held several visiting appointments at the Institut de Physique du Globe de Paris. He has a BS in physics and a PhD in geophysics from the University of Southern California.