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Investigating the shallow subsurface at the InSight landing site using the Heat and Physical Properties (HP^3) probe as a seismic source

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Abstract

The *InSight* (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) mission is the first Mars lander to place an ultra-sensitive broadband seismometer package (SEIS) on the planet's surface. About 1.1 m away from the seismometer, a heat flow and physical properties package (HP^3) was deployed and began hammering a probe into the subsurface to measure the heat coming from Mars' interior and to reveal the planet's thermal history. The probe, which uses a self-hammering mechanism, has generated thousands of seismic signals that can be used to analyse the shallow (meters to possibly few tens of meters) subsurface and shed new light on the elastic properties of Martian regolith.

1. Introduction

In November 2018, InSight successfully landed in Elysium Planitia on Mars [1]. Two scientific instruments were deployed directly on the surface of Mars (Figure 1): (1) SEIS, a package of two three-component seismic sensors and (2) HP^3, a heat flow and physical properties package. HP^3 includes a self-hammering penetrator (mole) that hammers itself into the subsurface to a maximum depth of five meters. The mole hammering generates seismic signals that are recorded by SEIS and can be used to investigate the shallow subsurface just below the landing site [2]. Even though not included in the level-one mission objectives, this ancillary experiment offers a unique opportunity to study the near-surface elastic properties as well as to construct a model of the regolith and possibly the lithologies below (1) to reduce seismic measurement errors for SEIS interpretation and (2) to derive geotechnical parameters that may also be of interest for future Mars missions.

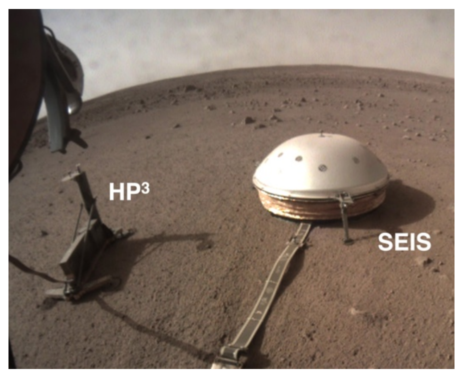

Figure 1: View from the InSight Context Camera showing SEIS and HP^3 on Mars 1.1 m apart.

2. Challenges in recording of the HP^3 hammering seismic signal

The seismic recording the HP^3 hammering was not originally included in the mission planning and, thus, comes as an ancillary activity with a series of challenges such as:

(1) Accurate synchronization of the HP^3 and SEIS clocks are required but challenging because both clocks operate independently.

(2) A high temporal resolution of the seismic signals is desired to perform high-resolution subsurface imaging using the hammer signals with expected frequency content >100 Hz, while the SEIS acquisition electronics was designed to record frequencies <50 Hz.

2.1 Ensuring high-quality timing

Accurate hammer triggering times are required to determine, for example, the near-surface seismic velocities from seismic traveltimes. To correctly link the HP^3 hammering trigger times with the seismic records, all clocks need to be related to the same base. HP^3 and SEIS both run on different clocks with their own drifts that are occasionally synchronized with the lander clock. A high-resolution seismic data analysis requires a synchronization of all clocks with a sub-millisecond accuracy, whereas the mission requirement in nominal operation is an accuracy of <10 ms. To achieve the required timing accuracy, time correlation pairs between all clocks are more frequently taken than regular during hammering to enable a linear interpolation of the clock drifts with an error <1 ms.

2.2 Recording seismic information beyond Nyquist

To record seismic signals with frequencies >50 Hz, which is the Nyquist frequency of the nominally highest sampling rate, the seismic-data acquisition chain has been changed during hammering to record aliased data by omitting anti-aliasing filters when down-sampling the data. A compressed-sensing inspired reconstruction algorithm has then been used to recover the aliased hammering signals [3]. Because of the slow advance of the mole, we have recorded hundreds to thousands of very similar hammering signals. Our reconstruction algorithm exploits the fact that the hammering signals are highly repeatable, resulting in the data showing a linear structure when aligned with respect to the triggering time. The reconstruction algorithm allows then to recover information well beyond the Nyquist frequency, potentially up to 500 Hz (Figure 2).

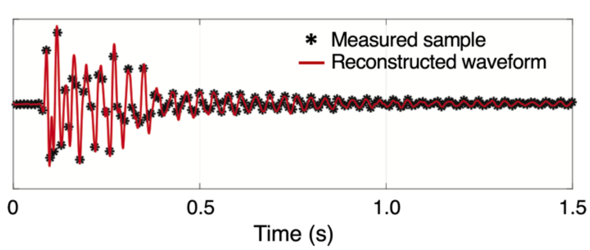

Figure 2: Measured and reconstructed waveform of one hammer stroke (session 3, 28 March 2019).

Seismic-data processing

The reconstructed seismic data and accurate trigger times enable a high-resolution seismic analysis of the data. The first-arrival travel times will allow us to determine the velocity structure between the mole at depth and SEIS at the surface, using, for example, a reversible-jump Markov chain Monte Carlo method.

The reconstructed seismic waveforms will be used for seismic-reflection imaging and full-waveform inversion, if the data quality permits. For the seismic-reflection imaging, we will exploit the fact that the recording geometry with the mole at depth and the seismic receiver at the surface, closely resembles a reverse vertical seismic profiling experiment [4].

3. Conclusions

The hammering of the HP^3 mole into the ground up to 5 m depth has generated thousands of seismic signals that provide a unique opportunity to investigate the shallow Martian subsurface. Understanding the elastic properties as well as resolving the internal structure of the near-surface will help reducing InSight's seismic measurement errors. In preparation for the mission, the team has developed a series of algorithms and workflows to overcome various challenges of this opportunistic experiment and to analyse the data. The workflows were intensively tested on synthetic and field data from an analogue experiment in the California Mojave desert, and are currently applied to the seismic data recorded on Mars during HP^3 hammering.

References

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