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Introduction to the special issue on Mars seismology

Philippe Lognonné[1*], Sharon Kedar[2], Victor C.Tsai[3]

(1) Université de Paris, Institut de physique du globe de Paris, CNRS, F75005 Paris, France
(2) Jet Propulsion Laboratory - California Institute of Technology, Pasadena, CA 91109, USA
(3) Dept. of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI 02912, USA

*Corresponding author : lognonne@ipgp.fr

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Introduction

More than 1000 Martian days after its successful landing in Elysium Planitia on Mars on November, 26th, 2018, the InSight mission (Banerdt *et al.*, 2020) continues to operate the Seismic Experiment for Internal Structure of Mars (SEIS) (Lognonné *et al.*, 2019), nearly 45 years after the pioneering Viking seismic experiment (Anderson *et al.*, 1977).

Prior to InSight's landing, very little was known about Martian seismic activity. It had been assumed to be roughly between that of the Earth and Moon, with 5-500 events per year with a magnitude larger than M4 (or a seismic moment release between 10^{17} Nm/yr and 10^{19} Nm/yr) (Phillips 1991; Golombek *et al.* 1992; Knapmeyer *et al.* 2006; Plesa *et al.* 2018). The integrated SEIS system was therefore designed to enable the detection of a M4.6 event at a global range (Lognonné *et al.*, 2019). Several pre-launch papers, including those published in two issues of Space Science Review (The Insight Mission to Mars I & II, 2017, 2019; Banerdt & Russel, 2017) described detailed system assumptions and requirements for the expected instrument, environmental noise, seismic activity, internal structure and seismic signals.

The first post-landing results (Banerdt et al., 2020; Lognonné et al., 2020; Giardini et al., 2020) showed that Mars was much less active than thought prior to launch, with a significant deficit of large magnitude events. The 4 largest magnitude events reported during the first 500 sols (Martian days) of the mission were initially estimated to be in the range of 3.5-3.7 (Clinton et al., 2021). All but one of these magnitudes have been re-restimated to be 3.7 by Böse et al. (2021) using a calibration with Earth moment magnitude M_w. This suggests that none of the marsquakes detected before mid-August 2021 had seismic moments larger than 10^{15} Nm.

Fortunately, the significantly lower than expected event ground acceleration has been compensated by much lower recorded noise than expected. This very low noise is due in part to the careful installation of SEIS by the InSight robotic arm (*Figure 1*), thermal and wind protection from the Wind and Thermal Shield (WTS), and the performance of the 3-axis Very Broad Band (VBB) instrument of SEIS itself. These resulted in a noise floor about 10 times below the pre-launch requirement during the low noise portions of the Martian day. This low-noise daily time window, which begins around Martian sunset and lasts only about 6 hours, has not surprisingly included the times of the majority of detected events (Giardini *et al.*, 2020; Clinton *et al.*, 2021). No low-frequency events and only a few high-frequency events have been detected during the noisier daytime. The amplitude of both noise and event signals recorded by SEIS is therefore exceptionally low compared to the Earth and is very close to that observed on the Moon (see Lognonné & Johnson, 2015 for a review of comparative planetary seismology).

Following the initial post-landing results (Lognonné *et al.*, 2020, Giardini *et al.*, 2020, Knapmeyer-Endrun *et al.*, 2021, Khan *et al.*, 2021, Stähler *et al.*, 2021) and an AGU special issue on InSight (InSight at Mars, 2021), this BSSA special issue on the seismology of Mars presents new analyses of SEIS data, as well as seismic instrumentation reports that describe instrument responses related to SEIS sub-systems, and analyses pertinent to the design of future planetary seismometers. Six of the following papers (Barkaoui *et al.*, 2021; Dahmen *et al.*, 2021; Hurst *et al.,* 2021; Kim *et al.,* 2021; Stott *et al.*, 2021; Zweifel *et al.*, 2021) are devoted to better understanding the recorded Martian seismic noise, which not only remains challenging to understand but is also a key for future improvement of all seismic event analysis. Two papers focus on seismic (Böse *et al.*, 2021) and infrasound (Garcia *et al.*, 2021) events. Two others (Menina *et al.*, 2021; Karakostas *et al.*, 2021) focus on the interpretation of high-frequency events, and particularly their attenuation and scattering properties, following up on earlier studies (Lognonné *et al.*, 2020; Giardini *et al.*, 2020; van Driel *et al.*, 2021). The final paper discusses possible future planetary seismic instrumentation (Erwin *et al.*, 2021).

Observations

The first series of 6 papers (Barkaoui *et al.*, 2021; Dahmen *et al.*, 2021; Hurst *et al.*, 2021; Kim *et al.*, 2021; Stott *et al.*, 2021; Zweifel *et al.*, 2021) focuses on the analysis of Martian seismic noise, SEIS instrument performance, and their consequences for understanding SEIS data.

Stott *et al.* (2021) quantify the lander-generated noise reduction achieved by the deployment of SEIS. Prior to deployment, while still on the lander deck, SEIS was extremely sensitive to lander vibrations, with a wind sensitivity larger (Panning *et al.*, 2020) than that of the Viking lander seismic experiment (Anderson *et al.*, 1977). They demonstrate that placing the instrument on the ground reduced the noise by a factor of 100 to 1000, emphasizing the importance of ground deployment for planetary seismology.

However, despite its careful robotic installation on the ground and its shielding against temperature fluctuations and wind effects, SEIS remains sensitive to lander-generated noise, ground deformation generated by atmospheric pressure drops, thermally-induced cracks and shifts related to the large surface temperature variations, and crosstalk between SEIS and its housekeeping signals. The latter are described in detail by Zweifel *et al.* (2021) who describes the acquisition electronics and show that "tick" noise from this cross-talk is stable enough to be removed efficiently by data processing. Lander resonances are studied in detail by Dahmen *et al.* (2021), who catalog the major lander resonances up to 9Hz and characterize their dependence on temperature and wind, and their time-variable damping factors, polarizations and amplitudes. Hurst *et al.* (2021) focus their analysis on resonances of the sensor assembly system and especially those related to the Load Shunt Assembly, designed to decouple the SEIS sensors from mechanical noise transmitted by the electrical cable connecting it to the lander. The two analyses confirm that no resonances are observed below 1 Hz, but that these resonances must be accounted for in any analyses of signals above a frequency of 1 Hz. Continuing with seismic noise, Barkaoui et al. (2021) analyze the stochastic properties of recorded noise using machine learning algorithms, allowing for efficient tracking of transient events (e.g., atmospheric pressure drops and thermal "glitches"), but more importantly detecting and clustering glitches that repeat with stable offset times. The recorded seismic noise also affects noise correlograms, and Kim *et al.* (2021) perform an in-depth study of the impact of glitches in noise autocorrelations (Deng & Levander, 2020; Compaire *et al.*, 2021; Schimmel *et al.*, 2021; Knapmeyer-Endrun *et al.*, 2021). They discuss these previous autocorrelation results and conclude with guidance for making future autocorrelation interpretation more robust.

Bose *et al.* (2021) present an updated methodology for determining marsquake magnitudes from SEIS data as an update to previous methodologies (Bose *et al.*, 2018). They confirm that the largest quake detected prior to October 2020 had a magnitude of 3.7, a maximum magnitude significantly smaller than that expected prior to launch.

The two papers on attenuation/scattering (Menina *et al.*, 2021; Karakostas *et al.*, 2021) extend the analysis (based on only a few events) previously made by Lognonné *et al.* (2020), by using 13 and 19 events, respectively, and different scattering theories. Menina *et al.* (2021) use elastic radiative transfer theory to study the energy envelopes of high-frequency events. They show that the typical coda decay time is frequency independent and that some events are best explained by propagation in a mostly dry medium, with possible stratification of scattering properties. Karakostas *et al.* (2021) use the two-layer diffusion model of Dainty *et al.* (1974), developed for Apollo seismic analysis. They confirm that the higher frequency events appear to have depths that are shallower than the lower frequency events. However, they do not find variations in coda properties with distance as expected, and suggest that there is significant lateral variation of diffusivity and scattering layer thickness near the InSight landing site.

Following the possible detection of infrasound events suggested by Martire *et al.* (2020) and an infrasound origin for part of the recorded noise (Stutzmann *et al.*, 2021), Garcia *et al.* (2021) perform an extensive search of the seismic and pressure data for pressure infrasound signals that produce ground signals through compliance effects. They reject most candidates, leaving only 2 infrasound candidates, on sols 421 and 521, with satisfactory compliance ratios. The origin of these two events remains unknown.

Lesson learned for future missions in planetary seismology

Several of the papers already described provide important constraints for designing future planetary seismological missions. These include constraints on lander noise (Stott *et al.*, 2021), design of future service loops and cables (Hurst *et al.*, 2021), design of future high-performance acquisition electronics (Zweifel *et al.*, 2021), the importance of pre-launch characterization of lander resonances (Dahmen *et al.*, 2021), the importance of minimizing thermal glitch occurrence and strength (Kim *et al.*, 2021), and the potential for machine learning in automated planetary geophysical stations (Barkaoui *et al.*, 2021).

The final contribution of this issue from Erwin *et al.* (2021) provides further guidance for future planetary seismic deployments. They analyze the impact of internal friction in seismometer Brownian noise and show that this noise has been underestimated at very long periods in most of the previously developed seismometer noise models. Although this noise is overshadowed by thermal noise for SEIS on Mars, the associated 1/f noise will have important implications in the design of future seismometers for the Moon, especially when attempting to reach performance levels about 10 times better than the Martian SEIS VBB.

Closing thoughts about future missions in planetary seismology

Collectively, the papers in this special issue describe valuable insights for understanding the signals from seismic activity on Mars, and for planning future seismometer deployments on extraterrestrial bodies. Anyone analyzing seismic records still being sent back from Mars by InSight will need to be aware of the analyses in the papers in this special section, to prevent misinterpretation of apparent signals and to understand the original of the signals present in the SEIS data.

More importantly, with the anticipated future seismic exploration on both Mars and other terrestrial bodies in our solar system, the lessons learned from the SEIS experience will improve future data acquisition on extraterrestrial bodies. Planned missions to Mars (Exomars, Zelenyi *et al.*, 2016), the Moon (Farside Seismic Suite, Panning *et al.*, 2021; Chang'e 7, Zou *et al.*, 2019) and Titan (Dragonfly, Turtle *et al.*, 2020; Lorenz *et al.*, 2021) have seismometer packages, exciting developments that may result in the possibility for new types of planetary seismology, such as 2-station seismology on Mars and the Moon.

This already impressive series of missions with seismometers over the next decade may be complemented by new missions, if selected, such as the Europa lander (e.g; Kedar *et al.*, 2020, Burke *et al.*, 2020), the Lunar Geophysical mission (Neal *et al.*, 2020, Weber *et al.*, 2021), a geophysical package on Artemis (Lognonné et al., 2020) or even gravitational-wave detectors on the Moon that may enable the detection of lunar free oscillations (Harms *et al.*, 2021). Seismology is therefore well on its way towards solar-system-wide comparative seismic studies, a new frontier for understanding the planets and planetoids in our solar system and more broadly the origins of our solar system. Lessons learned from Apollo, Viking and now InSight about the design of planetary seismometers, their deployment and operation, and seismic signal processing and signal interpretation will help us perform the best seismic monitoring of these terrestrial bodies and lead to the better scientific understanding of our solar system through future missions.

Data and Resources

SEIS consists of a 3-axis Very Broad Band (VBB) seismometer and a 3-axis Short Period (SP) seismometer, deployed successfully on the surface in February 2019. SEIS provides continuous 20 samples-per-second (sps) data for the VBB sensors, as well as selected “event” data at rates up to 100 sps for both the VBB and SP. In addition, pressure and wind speed are monitored by the Auxiliary Payload Sensor Suite (APSS) experiment (Banfield *et al.*, 2018).

All SEIS data (Mars SEIS data service, 2019a, 2019b) through June 30, 2021 are available at the Data Center of the Institut de Physique du Globe de Paris (IPGP), the Data Management Center of the Incorporated Research Institutions for Seismology (IRIS DMC), and the NASA Planetary Data System (PDS). The APSS data are available at NASA PDS. The InSight marsquake event catalogue (Clinton *et al.*, 2020; InSight Marsquake service, 2021), which provides timing of events as well as preliminary information such as seismic phase arrival times and, when possible, magnitudes and locations of the marsquakes, is also available for the same time period at the same repositories. Future data and catalogues will also be released every quarter.

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Author addresses:

Philippe Lognonné
Equipe Planétologie et Sciences Spatiales, Case 7071
Université de Paris, Institut de physique du globe de Paris
35, rue Helene Brion
75013 Paris, France

Sharon Kedar
Jet Propulsion Laboratory
4800 Oak Grove Dr.
Pasadena, CA 91109, USA

Victor Tsai
Department of Earth, Environmental and Planetary Sciences
Brown University
324 Brook Street
Providence, RI 02912, USA

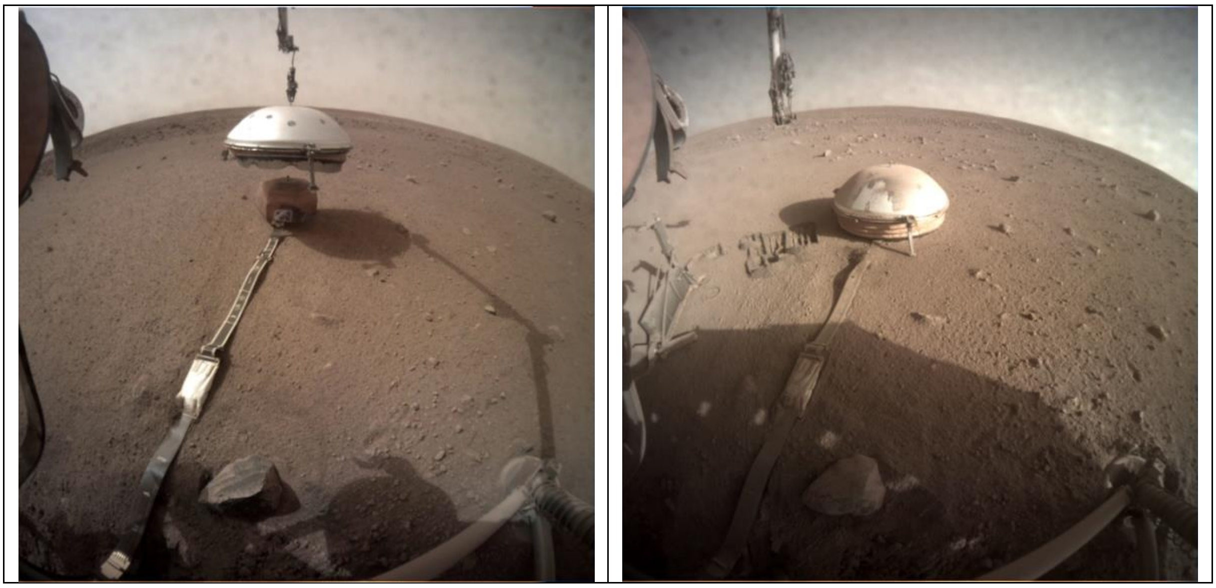

Figure 1: A) The Sensor assembly of SEIS on the ground just prior the deployment of the Wind and Thermal Shield (WTS), on February 2, 2019. B) Picture taken on September 27, 2021 showing the fully installed WTS two and a half years later. These two images were taken on sol 66 and sol 1008 since InSight landing, respectively.