S E S   2 0 2 4
Twentieth Anniversary International Scientific Conference
SPACE, ECOLOGY, SAFETY
22 – 25 October 2024, Sofia, Bulgaria

SEISMOLOGICAL INSTRUMENTS FOR SPACE RESEARCH

Edelvays Spassov

Kinemetrics, Inc., Pasadena, CA, USA
e-mail: espassov@yahoo.com

Keywords: *Seismological Instruments, Space, Mars, Moon*

Abstract: *Seismological equipment is sensitive and complex. It is even harder and more complicated if sending such instruments out in Space. Based on the instrumentation success during the NASA' InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) mission to Mars in 2018–2021, here we present some of the specific features and achievements of the equipment on that mission. Some interesting results of the deployment of the seismic instruments on Mars will be presented as well. Now NASA has planned new missions such as lending on the far side of the Moon and on the Jupiter icy moon Europa (possibly the best chance of finding life in the Solar System). The instruments requirements for such missions are even more stringent and some of the initial steps of improving the seismic instruments for the new space trips will be presented.*

Introduction

Our understanding and knowledge about the Earth and the space have increasing improved through the years. This progress has accelerated significantly in the recent times, supported by similarly significant advances in both science and instrumentation.

Our knowledge about the Earth specifically comes from a wide variety of methods and disciplines, following the above-mentioned progress. One thing however has remained unchanged. The only direct data and information we receive for the deep Earth comes exclusively from the seismic waves, they are the only approach we have to probe directly and quantitively the deepest parts of our planet – Fig. 1. Seismic models, methods, and instrumentation apply to an extremely wide range of values. Seismic instruments offer the highest spatial resolution of investigation, the seismic waves having the shortest wavelength, and suffering the lowest distortion and attenuation during propagation.

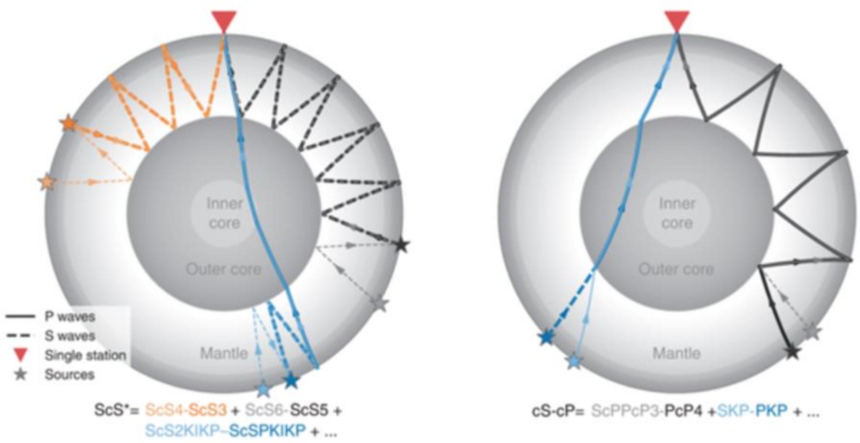

Fig. 1. Seismic waves probing the Earth

Logically, similar methods, models [1] and interpretation can be successfully applied to the planets if we are able to deliver, install, operate and collect data from the seismic instruments in space.

Seismic Instruments

One of the first known seismic type instrument is probably the Chang Heng seismoscope dated 132 BC. In 1857 Irishman Robert Mallet laid the foundation of instrumental seismology. And in ~ 1987 US & European scientists started the contemporary Global digital seismology, installing the first real broad-band digital seismic network to cover the globe with same type of instruments, producing same type of quality data with higher fidelity. At moment, the seismic instruments are generally divided to highly sensitive, with wide dynamic range sensors (seismometers and accelerometers) and highly reliable with high resolution (24–26 dB) digitizers, located in the field next to the sensor. Table 1 below present some seismic station/network evolution milestones.

Table 1. Seismic instruments advancement

Parameter\Decade	1980	1990	2000	2010
Number of resolution bits	12	16	24	24-26
Maximum sampling rate, sps	50	200	1,000	5,000
Dynamic range at 100 sps IEEE definition) –digitizers/sensors, dB	60 dB	90 dB	130 dB	138 -151/172
Timing accuracy	100 ms	1 ms	0.01 ms	0.001 ms
Power consumption for 3 channels	10-12 W	6-8 W	1-2 W	0.3 W
Typical local storage capacity	5 MB	50 MB	500 MB	64,000 MB
Typical data amount for a 1-month deployment	N/A	0.07 TB @ 50 sps/16bit 50 stations	0.7 TB @ 100sps/24bit 200 stations	7 TB @ 200sps/24bit 1,000 stations

This kind of layout (sensor and digitizer on-site in close proximity) improved significantly both the quality of obtained data and the completeness of the recorded data, with large projects such as USArray (400 constantly relocated stations) reaching data return above 97% over 12 years of continuous operation! Other public projects such as the Italian Strong motion Network with 436 strong motion stations have reached 100% station and data availability in continuous operation over 10 years. Two specific main factors contributed to such high standards – significantly improved communications and advancements in seismic instruments development in just last 20230 years. Fig. 2 present the extend and the scale of seismic digitizers improvement in the last 30 years.

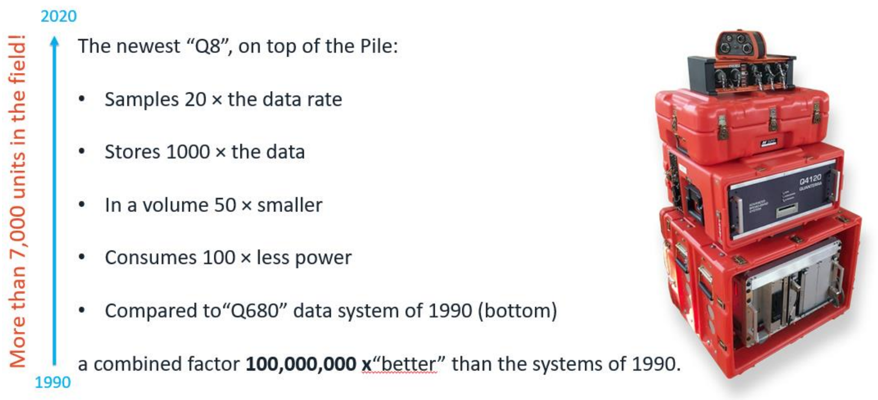

Fig. 2. Sample of a (Kinematrics) digitizer advancement in the last 30 years

InSight mission to Mars

The first seismic instruments in space were deployed on the Moon during the Apollo missions 11, 12, 14, 15, 16 (1961–1972). Those instruments were far from the quality of todays' instruments market and delivered data for a limited time. Nevertheless, this data provided unvaluable information about the Moon to the science community and offered the first direct and quantitative models for the Moon structure and history. It took some 46 years to send improved instruments to another planet – Mars. There are many reasons for that time gap, but here are some of the technical requirements for such instrument if it to be delivered so far in space [6]:

- Designed to work after radiation exposure of 3,000 rads (that will kill 50% of the humans after a month)
- Works at temperature ~100 degree C to kill Earth bugs before launch
- Working on Mars at temperature < -50 C
- 10 cent transistor will cost ~$700 screen to work in Space
- Sustain 205 days travel in Space
- Launch Weight 333,000 kg, Instruments - 50 kg

On November 26, 2018, NASA InSight mission (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) has landed two high quality seismometers on Mars, one of which started recording on Sol4 while still in the lander. One of those instruments called Short Period (SEIS-SP) was a collaboration development between Imperial College of London, Oxford university, UK and the American technology company Kinemetrics. The other seismometer, called SEIS-VBB (Broad-band), was developed by a consortium of French universities. SEIS-VBB was made operational on Sol70. The InSight mission had also other instruments delivered on the Mars surface:

- HP3 (Heat Flow & Physical Property Package)
- RISE (Rotation & Interior Structure Experiment)
- SEIS (Seismic Experiment for Internal Structure)
    - SEIS-VBB
    - SEIS-SP

It took 17 years of development and testing, and 180 authors from numerous institutions to develop the Seismic instrumentation, 15 scientists directly involved in the SEIS-SP development and millions of dollars to deliver instruments to be trusted to work as required.

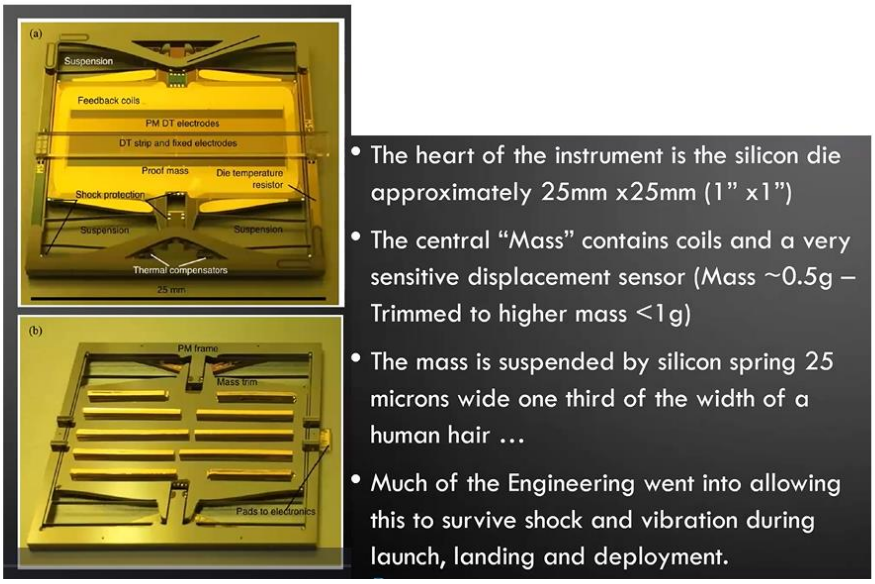

Fig. 3. SEIS-SP Seismometer [6]

- SP was switched on first during the flight and the horizontal sensors recorded "ambient" noise the lowest noise possible (no trust and vacuum space)
- Although called Short-Period, it's a wideband 10 s – 100 Hz seismometer

- Rugged, designed to withstand takeoff & landing accelerations, strong flight vibrations, as well high cosmic radiation
- Designed to operate at -65 degrees Celsius and with 15 degrees tilt

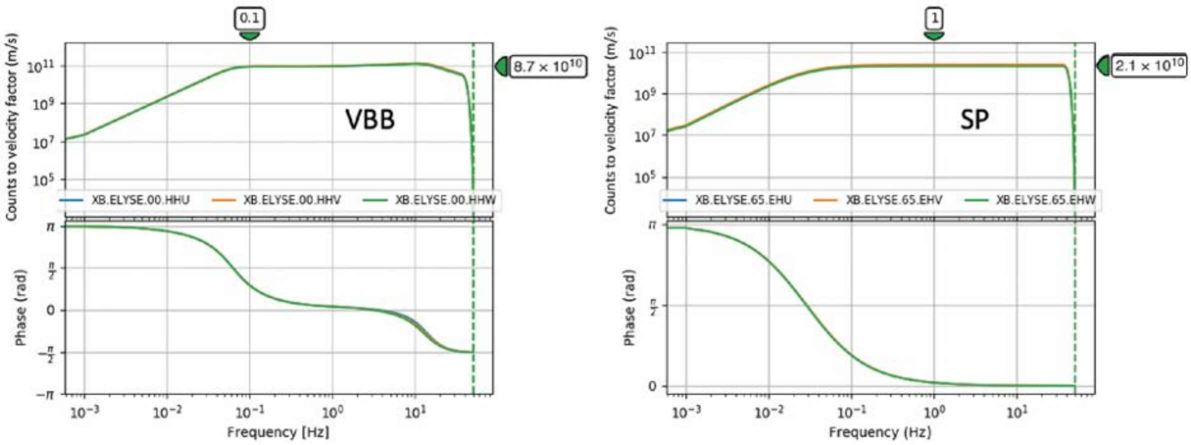

Fig. 4. Velocity response function for the VBB and SP sensors derived from calibration coil sweeps after deployment on Mars [3]

Although designed by the requirements to work only 2 years, the instruments kept working for full 4 years and the data transmission only stopped because of dust covering the solar panels and draining of the batteries.

SEIS-VBB, the international seismometer of NASA’s InSight mission, has operated on Mars from February 2019 until mid-December 2022. Its careful installation and shielding allowed the Very-Broad-Band sensors of SEIS to reach ultra-low noise during the much of the night. Noise was much larger during the rest of each day, but still 10 times lower than the quietest sites on Earth in the 0.1–1 Hz bandwidth.

1319 events were detected including a Mw = 4.7 marsquake, which excited surface waves and likely normal modes, 90 teleseismic events were registered down to Mw = 2.5 and for the 40 largest of them distances were determined. 8 meteorite impacts were also confirmed by orbital crater imaging, two with very large craters. During the windy period, SEIS also detected several thousand pressure drops associated with atmospheric vortices, and during sunset thousands of very shallow local thermal cracks. InSight mission also delivered some milestones in Space seismology:

- First time ever noise data measured in zero-gravity.
- Operational and deployment-ready immediately after landing
- Recorded Martian wind frequency and direction

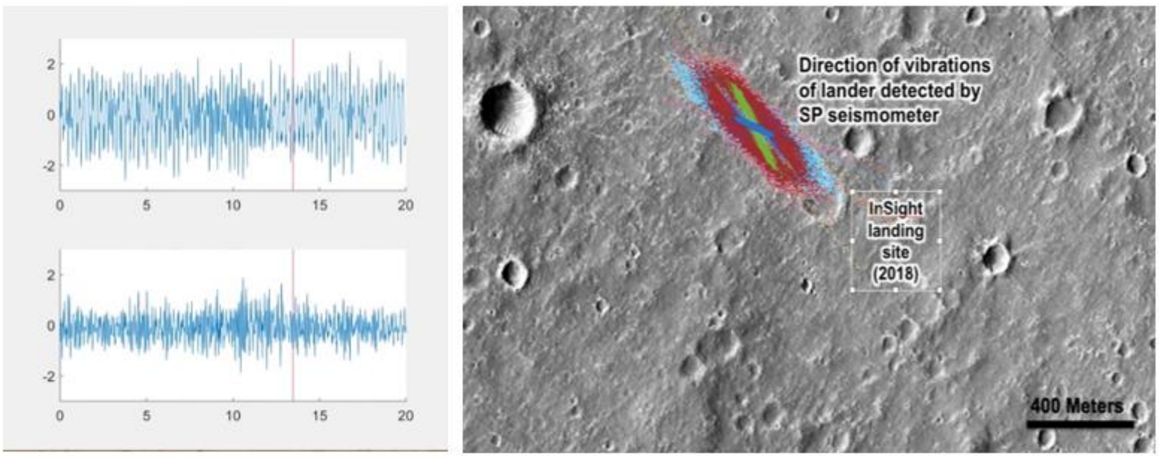

Fig. 5. Time-domain wind recordings and Calculated direction(s) of the wind noise [4]

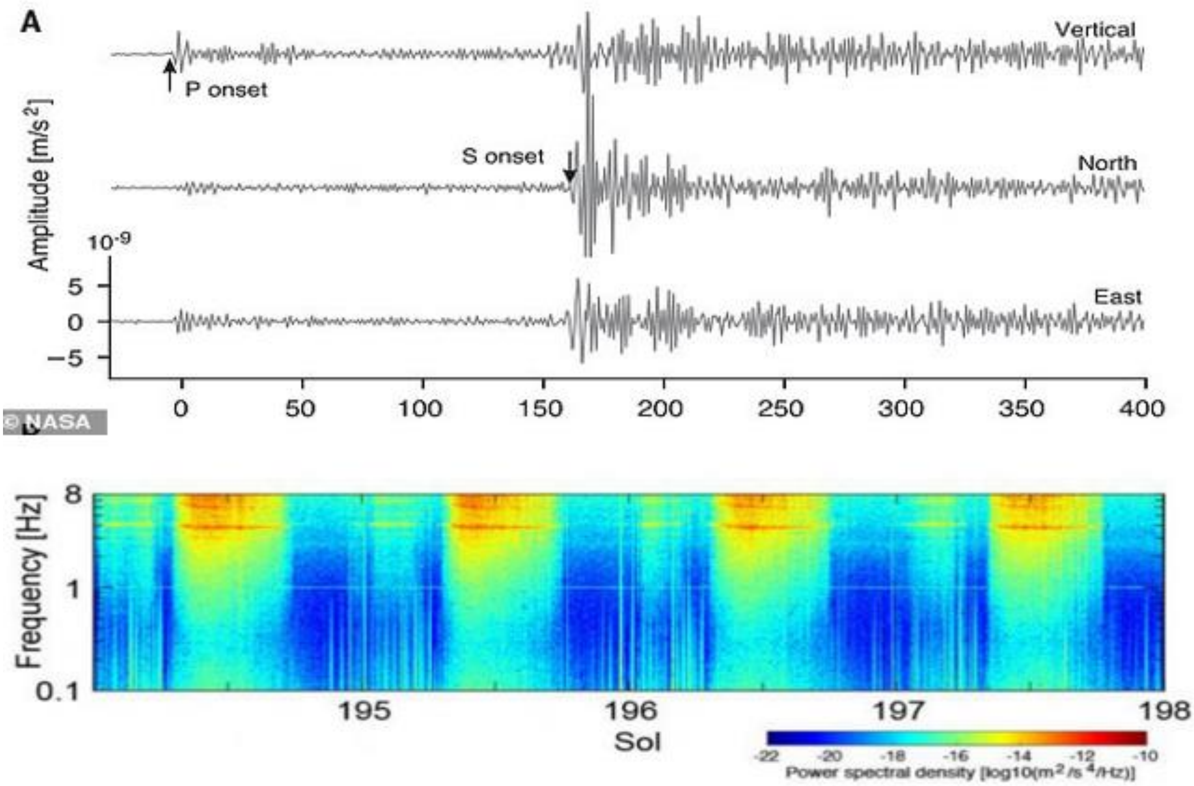

Fig. 6. MARS quake seismogram and temporal variations in low-frequency P-waves were related to distant changes in wind & solar irradiation, and the low-frequency Rayleigh waves related to the wind direction in the region near the lander [2, 3]

Ultimately, InSight contributed to the return of planetary seismology and initiated 4 missions in development to have also seismometers. In an ever changing political, financial and technological environment, there is one claim we can do – whichever is the next mission with seismic instruments, they will be better and more robust and will improve our understating of the planets around us.

Next Missions

After the initial success of InSigh mission, the plan for a next mission was concentrated on Europa Moon of Jupiter. Here are some points why Europa was selected as the next target and some of the additional challenges:

- The Icy Moon Europa has an ocean beneath the ice, protecting it from radiation
- Perhaps this moon is the best chance of finding Life
- It will take 7 years to get there and land
- 300,000 Rads of radiation, -120 ^{o}C on the surface

Gradually, in the constantly changing space research environment, this plan was put on hold (for now) and the next priority mission was to put instruments on the far side of our Moon. In this space race, several countries have already achieved success in lending spacecrafts there and even collecting data – China, Japan, India. Placing a modern seismic instrument there will be a definite large step ahead. So, taking the progress made towards the planned seismometer for Europa, the development team is now concentrating on designing and testing a new Luner Seismic Package (LSP).

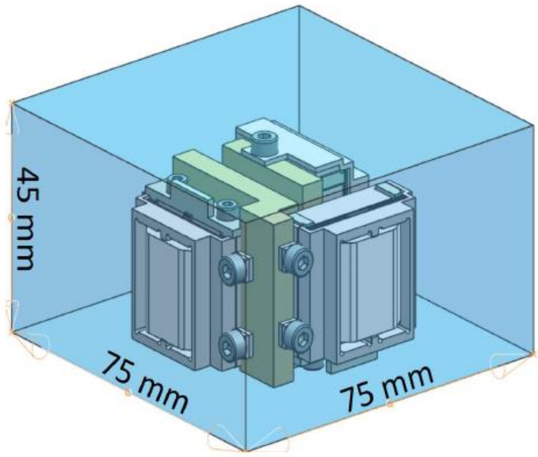

Fig. 7. Initial design of LSP – triaxial MEMS sensors and Proximity Electronics [6]

The Lunar Seismic Package (LSP) evolved from the InSight Short Period (SP) seismic sensor and Back End Electronics (BEE) [6]. The LSP has simple objectives (questions):

- Is seismicity different on the far side of the Moon?
- How do impact processes shape the lunar crust inside & outside Schrodinger crater?
- What is the current rate of micrometeoritic impacts?

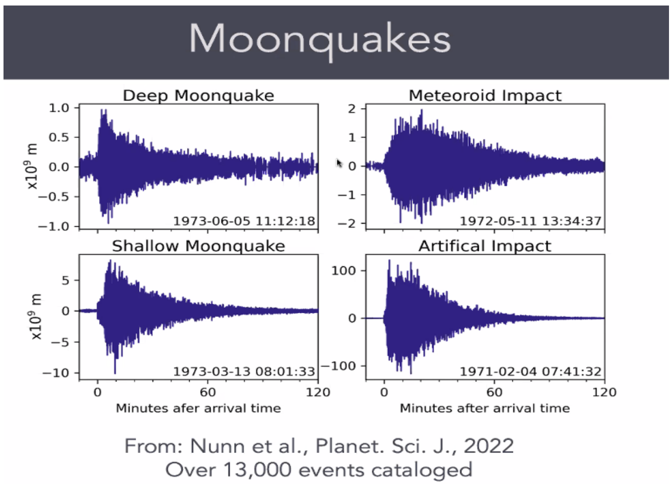

Fig. 8. Difference between Moonquakes and Meteoroid Impacts

LSP Sensor Package Optimization for the Lunar Missions is:

- Triaxial, Identical Sensors
- Lower noise than InSight SP
- Enhanced Calibration
- Sensor head, proximity electronics and magnets can be packed in ~50 mm cube
- 360 mW for sensor+feedback (triaxial)
- Does not require leveling in lunar gravity

Conclusions

Based on the instrumentation success during the NASA' InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) mission to Mars in 2018–2021, we present here some of the specific features and achievements of the equipment on that mission. Based on the InSight success, now NASA is planning new missions such as lending on the far side of the Moon and on the Jupiter icy moon Europa (possibly the best chance of finding life in the Solar System). The instruments requirements for such missions are even more stringent and some of the initial steps of improving the seismic instruments for the new space trips are discussed.

References:

1. Maren Böse, Simon C. Stähler, Nicholas Deichmann, Domenico Giardini, John Clinton,Philppe Lognonné, Savas Ceylan, Martin van Driel, Constantinos Charalambous, Nikolaj Dahmen, Anna Horleston, Taichi Kawamura, Amir Khan, Martin Knapmeyer, Guénolé Orhand-Mainsant, John Robert Scholz, Fabian Euchner, and W. Bruce Banerdt. Magnitude Scales for Marsquakes Calibrated from InSight Data. BSSA, 2021.
2. Savas Ceylan, John F. Clinton, Domenico Giardini, Maren Böse, Constantinos Charalambous, Martin van Driel, Anna Horleston, Taichi Kawamura, Amir Khan, Guenolé Orhand-Mainsant, John-Robert Scholz, Simon C. Stähler, Fabian Euchner, William B. Banerdt, Philippe Lognonné, Don Banfield, Eric Beucler, Raphaël F. Garcia, Sharon Kedar, Mark P. Panning, Clément Perrin. Companion guide to the marsquake catalog from InSight, Sols 0–478: Data content and non-seismic events. Physics of the Earth and Planetary Interiors Volume 310, January 2021.
3. Amir Khan, Savas Ceylan, Martin van Driel, Domenico Giardini, Philippe Lognonné, Henri Samuel, Nicholas C Schmerr, Simon C Stähler, Andrea C Duran, Quancheng Huang, Doyeon Kim, Adrien Broquet, Constantinos Charalambous, John F Clinton, Paul M Davis, Mélanie Drilleau, Foivos Karakostas, Vedran Lekic, Scott M McLennan, Ross R Maguire, Chloé Michaut, Mark P Panning, William T Pike, Baptiste Pinot, Matthieu Plasman, John-Robert Scholz, Rudolf Widmer-Schnidrig, Tilman Spohn, Suzanne E Smrekar, William B Banerdt. Upper mantle structure of Mars from InSight seismic data. Science, 2021.
4. Martin van Driel, Savas Ceylan, John F. Clinton, Domenico Giardini, Anna Horleston, Ludovic Margerin, Simon C. Stähler, Maren Böse, Constantinos Charalambous, Taichi Kawamura, Amir Khan, Guenolé Orhand-Mainsant, John-R. Scholz, Fabian Euchner, Martin Knapmeyer, Nicholas Schmerr, William T. Pike, Philippe Lognonné, William B. Banerdt. High-Frequency Seismic Events on Mars Observed by InSight. Journal of Geophysical Research: Planets. 2021.
5. Savas Ceylan, John F. Clinton, Domenico Giardini, Maren Böse, Martin van Driel, Fabian Euchner, Anna Horleston, Taichi Kawamura, Amir Khan, Guénolé Orhand-Mainsant, John-Robert Scholz, Simon Stähler, Constantinos Charalambous, W. Bruce Banerdt, Raphaël F. Garcia, Sharon Kedar, Philippe Lognonné, Mark Panning, Tom Pike, and Suzanne E. Smrekar. Overview of observed seismic signals on Mars. EGU, 2020.
6. I. Standley, M. P. Panning, S. Calcutt, W. T. Pike, S. Kedar, C., Nunn, M., Brent Blaes, William Walsh, Menooa Badalian, J. Liu. The Lunar Seismic Package. AGU 2020, Poster, 2020.
7. Kedar, S. Panning, M. P. Standley, I. M. Blaes, B. R. Walsh, W. Calcutt, S. B. Pike, W. T. Pierce, D. R. Schmidt, B. E. Hobbs, T. E. Badalian, M. Liu, J. Franklin, G. W. The Europa Seismic Package. AGU 2020.