

Seismology Across the Solar System

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Introduction

The space age began with geophysics, at least officially. When the Soviet Union launched Sputnik in 1957, it was declared a contribution to the International Geophysical Year – as was the US American Vanguard satellite project, approved in 1955.

At that time, scientists like Harold Jeffreys or Keith Edward Bullen, well known for their contributions to seismology, were already exploring the interior structure of terrestrial planets using astrometric and geodetic methods. The upcoming possibilities to actually take measurements on the surfaces of these planets not only supported, but revolutionized this research.

The following pages give a brief summary of the projects and the results of seismological experiments throughout the solar system, from wary first steps to carefully orchestrated campaigns and future opportunities. We will, however, leave the fruitful field of helioseismology aside, which is based on very different methods of observation and interpretation.

First Steps to Alien Worlds

Seismology entered into planetary research early, more or less immediately after NASA was founded.

The Ranger project for unmanned landing on the Moon was essentially conceived in November 1958, when Harold Urey explained how the exploration of the Moon could contribute to the understanding of the Earth's origin. This project evolved into a series of nine missions, three of which carried a short-period seismometer encased in a balsa wood sphere to survive a rough landing. The first of these, Ranger 3 (1962), missed the Moon due to a malfunction of its onboard computer. Two months after John Glenn's first flight, Ranger 4 (1962) crashed unintentionally into the far side of the Moon, but at least returned photos during flight. Ranger 5 launched in October 1962, but after a series of electrical failures onboard, control was lost, and it missed the Moon by 720 km (Hall, 1977).

The Surveyor I (1966), III (1967), and VI (1967) landers carried out experiments on the Moon that ranged somewhere between soil mechanics and seismology – the entire lander was used as the pendulum mass,

with force sensors in the lander's legs, and near-surface seismic velocities were estimated (Choate et al., 1969).



Figure 1: At Apollo 11, Buzz Aldrin deploys the first seismometer on another planetary body. Photo by Neil Armstrong (NASA image AS11-40-5947).

Big Science and Small Bodies

The Moon. Science was a strong focus for the Apollo missions and the Apollo astronauts deployed seismic experiments during each landing (Fig. 1; for a recent review, see Nunn et al., 2020).

The Moon is seismically active. This was one of the great surprises of the Apollo seismic experiments given the prevailing view before the missions that the Moon was geologically dead (e.g., Urey, 1952).

The seismometers recorded many signals, but these were very different from any signal previously seen on Earth and were initially difficult to interpret. However, a strong clue came from the seismic event caused by the deliberate crashing of Apollo 12's ascent stage after the astronauts left the Moon, recorded on Apollo 12's seismometer. Latham et al. (1970) noted the similarity

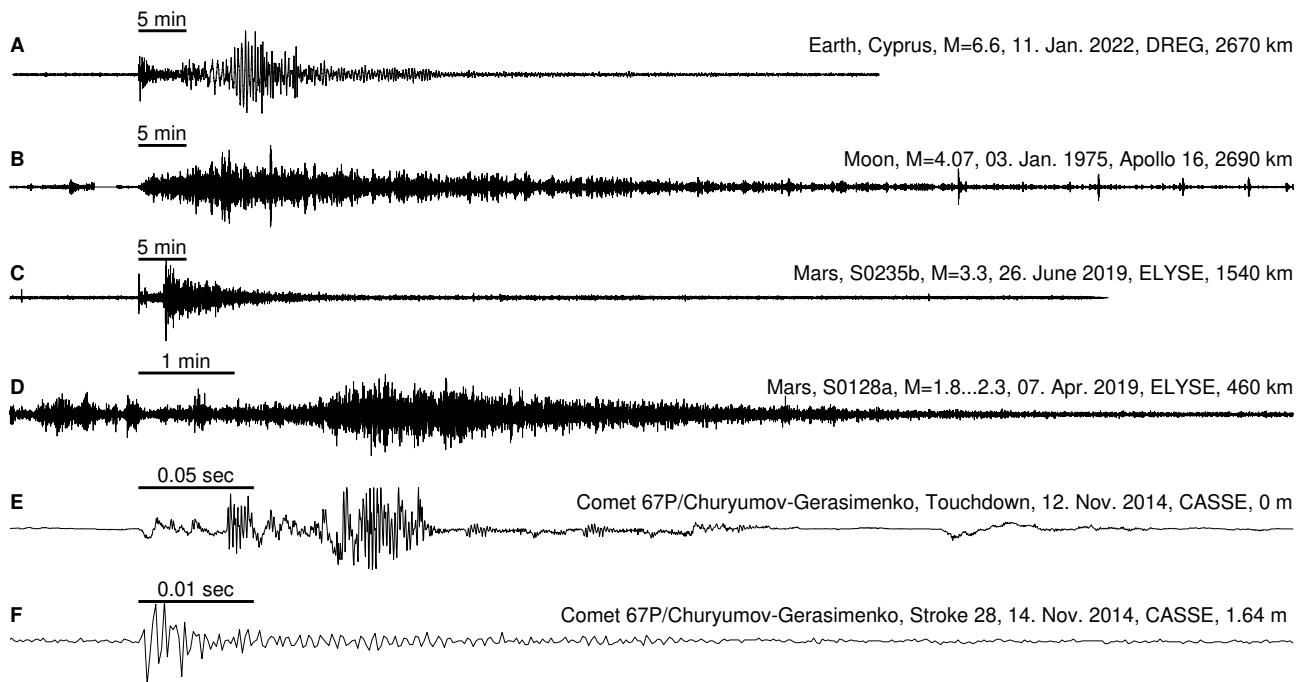


Figure 2: Examples of vertical motion seismograms. A) ground velocity of an earthquake on Cyprus, recorded at station Dreilägerbach (Bensberg Observatory), Germany, showing a sharp P arrival and surface waves, B) ground displacement of the strongest recorded shallow moonquake, from Apollo 16, showing an emergent arrival, no surface waves, and scattering coda, C) ground velocity of Martian Broadband event S0235b, showing sharp P and S arrivals but no surface waves, D) ground velocity of Martian Very High Frequency event S0128a, emergent P arrival hidden in noise, no surface waves but scattering coda, E) acceleration acting on the sensor due to the touchdown of Philae on 67P/Churyumov-Gerasimenko, showing complex lander motion and clipped amplitude, F) ground acceleration due to MUPUS hammer stroke no. 28 on 67P/Churyumov-Gerasimenko, at 1.64 m from the sensor. Horizontal bars denote time scaling, amplitudes not to scale.

between the artificial impact and many of the signals, and deduced that they were produced by meteoroid impacts or shallow moonquakes.

As shown in Figure 2B, the moonquake seismograms last over an hour (the largest event recorded lasted for over five hours). The energy takes a long time to reach its maximum (the rise time) and then slowly decays (the decay time). The Moon has been bombarded by meteoroids for its entire history. The impacts have left a highly fractured layer near the surface, known as the megaregolith. The thickness of the layer is debated, but recent estimates suggest it may be approximately 100 km thick (Gillet et al., 2017). The seismic waves have low attenuation due to low volatile content (e.g., Garcia et al., 2019). Low attenuation and strong scattering combine to create the distinctive shape of lunar seismic signals. Over 13 000 natural events were recorded on the passive seismometers at Apollo 11, 12, 14, 15 and 16 (Nakamura et al., 1981). Nakamura et al. (1981) classified more than 1700 of these events as meteoroid impacts, 28 as shallow moonquakes and more than 7000 as deep moonquakes. Recent work suggests that shallow moonquakes occur at approximately 50 km depth (Gillet et al., 2017), agreeing with earlier work suggesting that they occur deeper than the crust-mantle boundary (Nakamura et al., 1979).

The cause of these quakes remains a mystery. Deep moonquakes occur at depths from 700 to 1200 km, and are probably tidally driven (Nakamura et al., 1982). Additionally, the Apollo engineers deliberately crashed several of the used Saturn IV-B booster rockets and Lunar Ascent Modules into the Moon.

Using the seismic data, along with constraints from the total mass, radius and moment of inertia of the Moon, a picture of the Moon's interior gradually emerged. By the 1980s, it was commonly accepted that the Moon has a well-defined crust and mantle, and that the lower part of the mantle appears to be partially molten (Nakamura, 1983). Signals reflected from the lunar core could be detected only in 2011 (Weber et al., 2011) – more than 30 years after the shutdown of the seismometers.

“Overall, the Apollo and Viking missions taught us to expect the unexpected when it comes to the seismology of other planets.” (Nakamura, 2020)

The Apollo missions detected the first seismic events from another planetary body. There were many surprises, including that the Moon is geologically active, the shape of the seismic signals themselves, the thickness of the scattering layer, and that the Moon was differentiated into crust, mantle and core. There will

be many new surprises in the coming years.

Vikings on Mars. In September 1976, Viking landers I and II landed on Mars, each carrying a triaxial short-period seismometer (Anderson et al., 1977). The Viking I seismometer failed to uncage, but Viking II recorded seismic data in Utopia Planitia for more than a year. Since a deployment of the instrument on the ground was considered as too complex an operation, the instrument was operated on the lander deck, about 1 m above the planetary surface. This had the consequence that it was exposed to the wind much more than a surface installation would have been, and was also sensitive to vibrations due to the operation of other experiments, like motions of the camera, or the soil sampler. All in all, after comparing seismometer data with all other known activities and wind speeds, only one candidate marsquake remained. The Viking seismic experiment did not return groundbreaking geophysical results, but was considered as a successful demonstration of the feasibility of seismic experiments, and, with one candidate event recorded under unfavorable conditions, indication that such experiments would indeed record useful data.

Venera. The most unlikely place to expect a seismic experiment is probably the surface of Venus: farther from the Sun than Mercury, but still hotter, and an atmospheric pressure that literally flattens any spacecraft within hours. Nevertheless, the Soviet Venera 13 and 14 landers (both 1981) carried seismometers sensitive for vertical ground displacement in the micrometer range, with a sensor resonance frequency of 26 Hz. Data were recorded in chunks of 8 s duration, with 200 s and 400 s breaks in between, and an automatic event detector counting events during these breaks. On Venera 14, significant ground motions were recorded that could not be related to the measured wind speed, the recordings of an onboard microphone, or mechanical activities of the lander. These might be due to venusquakes, although an unambiguous identification is not possible (Ksanfomaliti et al., 1982).

Comets. The first successful seismic experiment on another celestial body after Venera 14 was conducted in 2014, about 500 million kilometers from Earth on comet 67P/Churyumov-Gerasimenko. The Philae lander of the Rosetta mission carried three accelerometers in its landing feet (Fig. 3), sensitive at audible frequencies, as well as piezoelectric transmitters capable of sending tiny beeps. Plans were for recording the touchdown on the comet (a sound file of this signal became somewhat famous in the internet), and repeated sounding of the subsurface to monitor changes as the comet approaches the sun. The adventurous history of uncontrolled bouncing interfered with plans, but it was finally possible to record hammer strokes of Philae's thermal probe (Fig. 2F), and to determine that the comet has a ~50 cm hardened crust covering a fluffier interior (Knapmeyer et al., 2018).

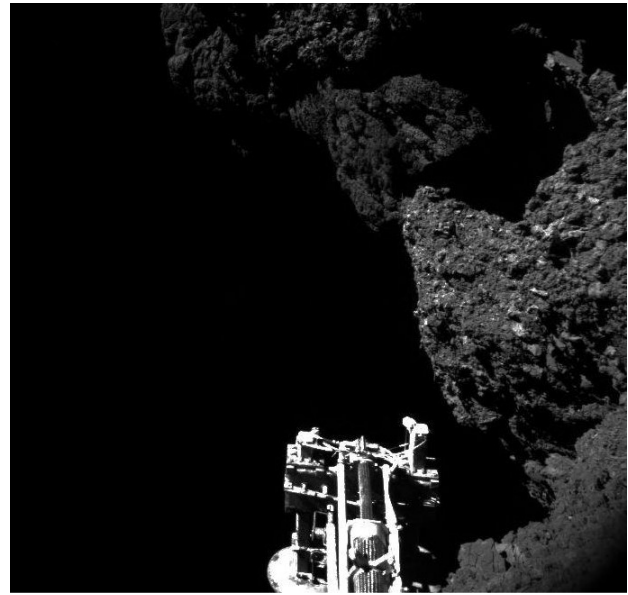


Figure 3: The Leg 2 foot of Philae at the Abydos site on 67P/Churyumov-Gerasimenko. The circular pad on the lower left side of the foot is the lid of the sole which houses this foot's accelerometer; the transmitter sole is not visible (ESA/Rosetta/Philae/CIVA camera 3, image clipped at top and left side).

InSight on Mars. In 2018, seismology finally returned to Mars with NASA's InSight lander. The first dedicated geophysics mission to Mars, aimed at determining the internal structure of the red planet was also the first to robotically deploy a seismometer to the surface of another world (Fig. 4). SEIS (Seismic Experiment for Interior Structure, Lognonné et al., 2019) contains two sets of sensors: three short period sensors etched from single silicon wafers, and three more traditional, broadband pendulum components. These six components are providing an unprecedented dataset and have, so far, delivered a near-continuous seismic record for over 1000 sols.

During those 1000 sols over 1200 marsquakes have been detected. The signals from these events are quite different from what we see from earthquakes (Fig. 2C, D). Marsquakes are small in magnitude (only a few events are greater than magnitude 4) and the energy is highly scattered leading to long, emergent coda reminiscent of those seen for lunar quakes recorded during the Apollo missions (Fig. 2B, D). The implication here is that the crust of Mars is highly fractured and not as wet as Earth's where we see clear seismic phases, usually with sharp onsets, but not as dry as the lunar crust where moonquakes are even more emergent and can ring for hours.

The majority of marsquakes show two phases, likely either P/S, Pg/Sg, or in some cases PP/SS, allowing source distances to be calculated (Fig. 2C). The tricky part with only one seismic station and highly scattered coda is determining a backazimuth for these events.

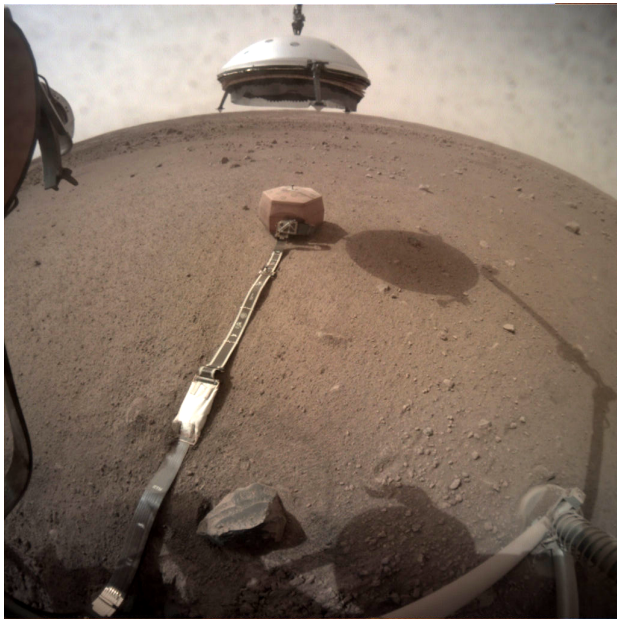


Figure 4: The InSight seismometer, two minutes before its wind shield is lowered to the ground (image credit: NASA/JPL-Caltech, imaged on 02. Feb. 2019, 10:17 LMST, C000M0066_602378269EDR_F0000_2699M).

Most of the few known epicenters cluster around Cerberus Fossae – an extensive system of young, volcanic faults located around 1700 km from InSight. This cluster of events implies that the seismicity is not just related to planetary cooling but that geological processes are still ongoing.

Even though only a few events have precise source locations, these events have already revealed the interior structure of Mars. Receiver function techniques have shown that the Martian crust has an average thickness of between 24 and 72 km (Knapmeyer-Endrun et al., 2021). The inversion of direct and reflected P and S phases shows a thermal lithosphere that is 400 to 600 km thick (Khan et al., 2021). This is twice the thickness of Earth's lithosphere. There is also evidence of the start of a mantle transition zone at around 1050 km depth but there is no mineralogically distinct lower mantle.

Below this quasi-transition zone lies the liquid core with a radius of 1830 ± 40 km (Stähler et al., 2021). This measurement is at the upper end of previous estimates for Mars' core size and implies that the core contains a large proportion of light elements with 10 to 15 % (in weight) sulphur. This in turn suggests that the core is unlikely to be able to solidify.

These results are impressive for one small seismic station and, with the mission still active, there are likely to be many more revelations about the structure of Mars and the rate of seismicity on the red planet.

Future Prospects

The Moon. Seismology will be key to unravelling some of the Moon's mysteries over the coming decade. Artemis is a NASA led, international, human spaceflight program with a goal of landing humans on the Moon in the mid-2020s. Like its predecessor, Apollo, the program has ambitious science objectives (NASA, 2020). Several of these objectives could be answered by seismic missions, including understanding the variability of thickness of the Moon's crust and megaregolith, the Moon's tectonic history and the driving mechanism of shallow moonquakes, and monitoring the meteoroid-impact flux.

Two seismic missions to the Moon are currently planned for launch in 2024 or 2025. NASA's Farside Seismic Suite will land in Schrödinger crater on the Moon's farside and include a single seismic station deployed on the deck of a lander (Panning et al., 2021). The mission will investigate the asymmetry of the Moon, and whether the Moon's farside is as seismically active as its nearside. The Farside Seismic Suite will also benefit from advances in the monitoring of nearside meteoroid impacts using impact flashes monitored from Earth (e.g., Suggs et al., 2014). These flashes provide location and time of the impact and thus make impacts a semi-controlled seismic source for the investigation of the Moon's interior. Also currently planned for 2024, the China National Space Administration's planned Chang'e 7 mission will include a seismometer and target the lunar south pole (Zou et al., 2020).

Additionally, the Lunar Geophysical Network (LGN; Fuqua Haviland et al., 2022) will be proposed to NASA's New Frontiers 5. The LGN would have up to four geophysical stations and global coverage of the Moon, enabling the mission to tackle some of the biggest remaining questions about the structure of the Moon.

Mars. The next seismometer is scheduled for launch in September 2022, landing in June 2023, with the ESA ExoMars mission. A seismometer provided by IKI, the Space research Institute of the Russian Academy of Sciences, is housed on the landing platform (*ExoMars Surface Platform* 2022). Its landing site will be in the Oxia Planum/Mawrth Vallis region, closer to the Valles Marineris region, which, from InSight's landing site, is shadowed by the Martian core. (Due to the current political situation, ESA has canceled the 2022 launch of ExoMars, which implies a delay by at least two years.)

Titan. In the 2030's, a New Frontiers class NASA mission, Dragonfly (Fig. 5), will explore Saturn's largest moon, Titan. This mission represents the first attempt to investigate an icy ocean moon through seismology. Titan is a unique world, as it not only has a subsurface ocean, but a thick methane-rich atmosphere as well. Due to the thick atmosphere, Dragonfly will be able to fly to multiple locations using its eight rotors.

Its geophysical and meteorological payload DraGMet (Barnes et al., 2021) includes two geophones mounted to each of Dragonfly's skids, in addition to a more sensitive instrument which can be lowered to Titan's surface via a winch (Lorenz et al., 2019). Like our Moon, Titan will experience tidally driven seismicity (Hurford et al., 2020). Dragonfly will help constrain the current rate of seismic activity in Titan's ice shell as well as in its lithosphere. If it is sufficient, DraGMet might be able to go a step further and constrain the internal structure of Titan, including the thickness of the ice shell, depth of the subsurface ocean, and whether or not high-pressure ices (ice V or VI) exist between the ocean and silicate interior. Titan's ice shell may be several tens to a few hundreds of kilometers thick, and the ocean could be hundreds of kilometers deep.

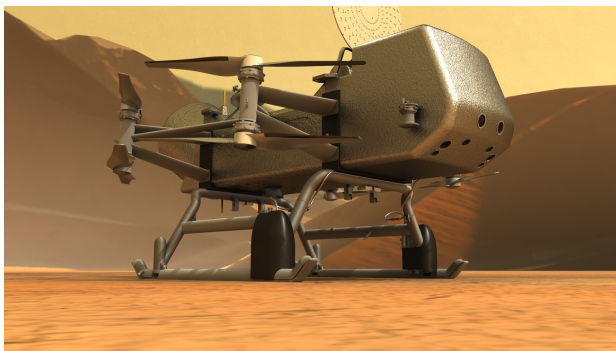


Figure 5: Artist's rendition of Dragonfly on Titan's surface. Image Credit: Johns Hopkins APL

The outer Solar System. In addition to Dragonfly, there are further mission concepts to visit the outer solar system. Notably, these include the mission concepts Europa Lander (Hand et al., 2017) and Enceladus Orbilander (Mackenzie et al., 2021). These missions might also carry seismic instruments as part of their payloads. Like previous planetary missions, these missions would aim to measure the current rate of seismicity and constrain the internal structures of the moons. These moons are expected to be seismically active due to tidal forces (Hurford et al., 2020) and may have interesting seismic sources and behaviour. Observations have shown that plumes are erupting from Enceladus' South Pole Terrain (Porco et al., 2006). The plumes erupt through large cracks in Enceladus' ice shell, and seismic instruments might be able to record this cryo-volcanic activity. Constraints on Europa's seismicity may provide evidence for, or against, subsumption in the ice shell, and further indicate if Europa does have plate-like tectonics, a mechanism that so far is unique to Earth.

The understanding of icy ocean worlds will greatly benefit from seismic exploration. Through seismology we can better understand the structure and dynamics of ice shells and subsurface oceans. Data from seismic investigations may help provide clues about how material from the oceans could be exchanged with the ice shells and surface, and could have implications for

habitability studies.

Technology. Seismometers have been bulky in the past, although InSight's SEIS is far from the 17 tons of the historical Wiechert seismometer in Göttingen, Germany. Micromechanics as used for the SEIS short-period sensors, optical instead of capacitive or inductive sensing, and the new DAS technology, using laser interferometry in glass fibers, will allow for more light-weight and versatile sensors in future missions. Machine Learning techniques will support the detection and classification of quakes, and improve the completeness of event catalogues.

Conclusion

Each of the small and large worlds presented here is not just another version of Earth, the same picture in different colors. Each is a new world, with its own history and surprises.

Not all space missions are equally successful – the remote and often hostile environments on other worlds allow for many ways and dimensions of failure, from partial to fatal. The successes, on the other hand, like Apollo and InSight, show that seismic experiments, even when small compared to Earth standards, can provide vivid snapshots of the deep interior of entire planets, and reveal previously unknown geological activity.

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Data availability

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Apollo. Apollo active and passive seismic experiment data are currently available from the Data Archives and Transmission System (DARTS) website of the Japan Aerospace Exploration Agency (JAXA): <https://www.darts.isas.jaxa.jp/planet/seismology/apollo/index.html>.

Viking. The Viking seismic data are available from the Geosciences Node of the NASA Planetary Data System at: <https://pds-geosciences.wustl.edu/missions/vlander/seismic.html>.

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MPS, ISAE-Supaero, LPG, MFSC. https://doi.org/10.18715/SEIS.INSIGHT.XB_2016.

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