Questions to Heaven

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Questions to Heaven

Benjamin Fernando and colleagues report on the international cooperation involved InSight's attempt to gather seismic data from the arrival at Mars of China's Zhurong rover.

Space has always been a place where international collaboration and international competition co-exist. As more nations take their first steps into deep space, the opportunities to work together grow more numerous. One field which presents such opportunities is seismology – especially on Mars, which grows busier by the year.

In one of the first collaborations of its kind, scientists working on China's Tianwen-1 mission and NASA's InSight spacecraft worked together to try and detect the seismic signatures of the Zhurong Rover's arrival at Mars. Although no signal was recorded, we present here the results of the experiment in the hope that it may act as a guide for future collaborations of this kind.

The question of whether or not Mars is seismically active has loomed large since the Viking missions of the 1970s (Anderson *et al.* 1977). In 2018, NASA launched the InSight (Interior Exploration using Seismic Investigations, Geodesy, and Heat Transport) mission, equipped with the seismic package SEIS (Seismic Experiment for Internal Structure; Lognonné *et al.* 2019), to try and definitively settle the matter. And indeed, since arriving on Mars nearly three years ago, the spacecraft has recorded hundreds of marsquakes, which appear to be tectonic in origin. But where one question has been answered, many more have emerged.

Although the marsquakes seem to be tectonic, they are not exactly like their previously observed counterparts on Earth or the Moon. Around 30 of them can be interpreted using similar methods used in the analysis of earthquakes, and have been used recently to study the shallow structure below the InSight lander (Lognonné *et al.* 2020), to determine Mars's crustal thickness (Knapmeyer-Endrun *et al.* 2021), and the radius of the core (Stähler *et al.* 2021). Many of the quakes are similar to moonquakes, and suggest that seismic waves are strongly scattered near the martian surface (van Driel *et al.* 2021; Menina *et al.* 2021).

Of the more Earth-like marsquakes, a number are thought to have occurred in the Cerberus Fossae graben system, 1500 km away from the lander (Khan *et al.* 2021; Giardini *et al.* 2020). However, the inference of these locations relies on input from mineralogy models (Khan *et al.* 2021) and is therefore not a purely seismic determination, as might be made on Earth. Detected marsquakes are generally rather small (magnitudes between 3 and 4; Clinton *et al.* 2021), and have not been associated with any specific surface deformation which might be used to determine their location from orbital images. It would therefore be helpful if some 'unusual' seismic source with a clearly defined location and origin time could be observed.

Ground-shaking impacts

One such category of potential sources is impact events – the vast majority being from meteoroids caught by the planet's gravity. When an object enters the atmosphere at hypersonic speeds, it produces an acoustic signal, which is in effect a seismic wave in the atmosphere. This may either be detected directly, or through the coupling of the acoustic wave into the solid ground. If any part of it survives its fiery passage through the atmosphere and strikes the surface, this too will generate a seismic signal, which may be detected (Daubar *et al.* 2018).

The advantage of using impact events is that their locations can be constrained independently of any seismic measurement, through the identification of new craters on the surface from orbit (for those which reach the ground) or from visual recordings of the sky (on Earth, for those which burn up *en route*).

On Earth, seismic recordings of airbursts, sonic booms or impacts themselves are comparatively frequent, one recent and noted example being the Chelyabinsk airburst in 2013 (Heimann *et al.* 2013). On the Moon, many hundreds of impact events were identified during the Apollo era, on account of their seismic signals being very different to other moonquakes excited by tidal forces.

On Mars, however, the very limited number of orbiting spacecraft and limited data downlink means that the frequency at which images of the surface are gathered is low. At best, new craters found from orbit are only constrained to have occurred within a time window of a few months or so (Daubar *et al.* 2013): meaning that ascribing one of many hundreds of marsquakes recorded by InSight in this time period to a particular crater is effectively impossible, even if the signals from such small and distant impacts were detectable. Combined with results from recent modelling which indicates that impact-generated seismic signals are likely smaller than previously thought, this makes it unsurprising that thus far no impact events have been conclusively identified in InSight data (Daubar *et al.* 2020).

Every now and then, however, an 'impact' event occurs where we know in advance exactly the time, location, and rough magnitude. These are the atmospheric entry, descent, and landing (EDL) of spacecraft entering the martian atmosphere and arriving on the surface.

On Earth, seismic detection of re-entering spacecraft is straightforward and has been done many times for both crewed (Hilton & Henderson 1974; Qamar 1995) and uncrewed (Edwards *et al.* 2007; ReVelle *et al.* 2010) missions. On the Moon, the Apollo seismometers also detected the impacts with the surface of spent Saturn IVB rocket stages, which were used to calibrate other seismic measurements (Latham *et al.* 1970).

However, no experiment of this type had ever been attempted on another planet – but with the landings of the Mars 2020 Rover (Perseverance) and the Tianwen-1 Rover (Zhurong) coinciding with InSight's operations in the spring of 2021, such an opportunity presented itself for the first time. Given the rarity of such events, listening for all landings – not just those of spacecraft from the same space agency – is obviously desirable. This requires thorough and detailed international planning and collaboration.

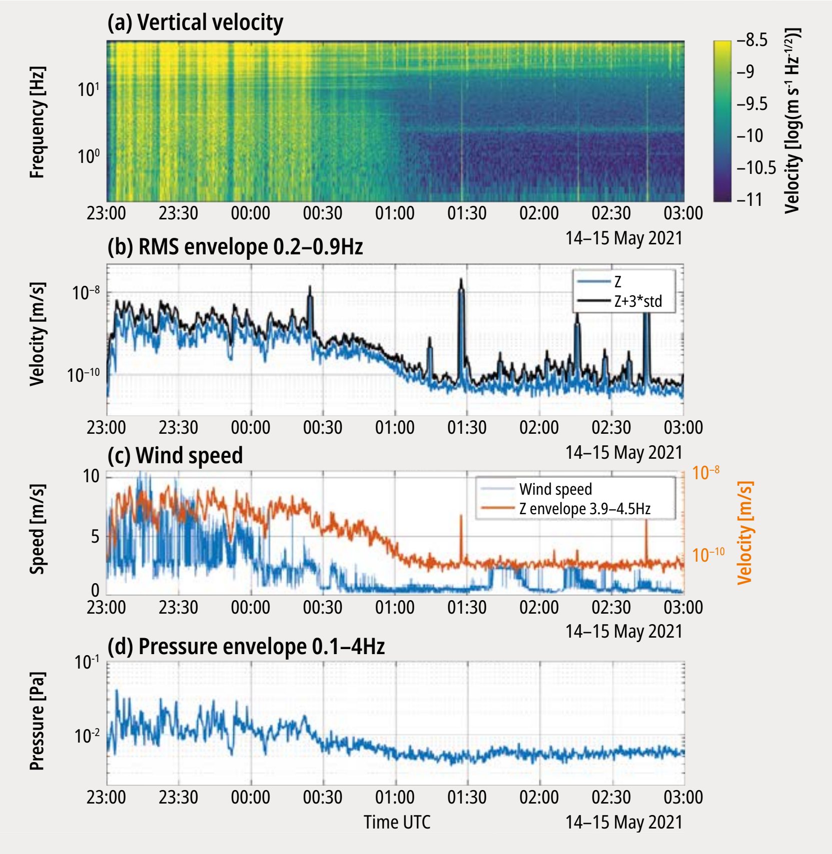
In February of this year, InSight attempted to detect the landing of NASA's Perseverance Rover (Fernando *et al.* 2021a). Although no signal from the EDL was detected, by measuring the noise floor at the time of landing we are able to constrain a key quantity in impact dynamics known as the "seismic efficiency" (Fernando *et al.* 2021b).

The seismic efficiency is the fraction of the impactor's kinetic energy (in this case, that of Mars 2020's balance masses which were the most energetic surface impact) which is converted into seismic waves. All prior estimations of this value for Mars relied upon either modelling or the use of material proxies in a laboratory, so this was the first *in situ* constraint. We found that the seismic efficiency was no more than 3%, which is compatible with previous estimations from modelling and Earth laboratory experiments.

Given the enormous scientific value of the Perseverance-InSight experiment even though the result was a negative detection, we began working up to the landing of Zhurong in the early summer. This was a far more challenging project, requiring communication and collaboration between scientists and engineers from China, the UK, the USA, France, Switzerland, Germany and Belgium.

Tianwen-1 and Zhurong

Tianwen ("Questions to Heaven") is China's opening set of independent deep-space missions. Its first iteration, Tianwen-1, (incorporating the Zhurong Rover) was China's first mission to successfully leave Earth orbit, and launched in the summer of 2020 (Wan *et al.* 2020; Zou *et al.* 2021; Li *et al.* 2021). Unlike Mars 2020, Tianwen-1 entered orbit around Mars after its seven-month cruise,



1 *Data recorded by InSight during the landing window (InSight Mars SEIS Data Service 2019). Panel (a) shows a spectrogram of the vertical ground velocity, while (b) shows the RMS envelope of the vertical velocity in the 0.2-0.9 Hz frequency band most suited to isolating mantle-going phases (blue; labelled 'Z') as well as the RMS + 3 standard deviations (black). In both panels, glitches in the system are recorded as sharp vertical features in the spectrogram and peaks in the RMS envelope. These are clearly aseismic in origin. Panel (c) shows the wind speed (blue) and the RMS envelope of the vertical seismometer velocity in the 3.9-4.5 Hz frequency band (orange) – the latter, in this frequency range, contains a known oscillation mode of the spacecraft which is excited by the wind and can be used as a proxy for the wind speed. The absence of wind measurements in the early morning occurs where the wind speed drops below the instrument threshold, with a clear decrease in wind speed during the transition from late UTC night to early morning (late afternoon to early evening at InSight). Panel (d) shows the RMS envelope of the atmospheric pressure in the 0.1-4 Hz band. Most of the variation is due to diurnal effects.*

rather than initiating a direct atmospheric entry. Entering orbit allowed the Tianwen mission team to refine their choice of landing site and date for the Zhurong Rover, though it made attempting observations using InSight more challenging – not just because the impact velocity of any EDL apparatus would likely be lower, but also because the landing location and time were not known many months in advance. As information about the rover's EDL sequence and hardware was more scarce than was the case for Perseverance, estimating seismic amplitudes was also more difficult.

As InSight's solar panels have accumulated dust over the last three years, the power available to run instruments and the communication arrays has steadily decreased. The combined effects of aphelion and the increase in the atmosphere's optical thickness due to dust during the northern martian winter (spring/summer 2021) took the available power margin to a critical level. Because of this, instruments could no longer be run on a continuous basis – rather, they had to be switched on and off based upon a schedule agreed by the team. For Mars 2020, with an atmospheric entry time that was known down to a minute's precision many months in advance, this was not a problem. But for Tianwen-1, it clearly would be, as the landing date, time, and location were decided and announced much later than InSight planning needed to be done.

Communicating with InSight is a complicated endeavour, involving transmitting messages from Earth through the Deep Space Network to one of the relay spacecraft orbiting Mars, which must then wait for the correct alignment before downlinking commands to InSight. Because of this, InSight works on a pre-agreed two-week planning cycle to ensure that observations can be planned and commanded in a timely manner. This meant that either we had to have two weeks' advance notice of when Zhurong would land, or that we needed to cover all possibilities within all forthcoming planning cycles.

Tianwen's orbit, as verified independently by amateur radio astronomers in Germany, brought it over the same point on Mars' surface roughly every 48 Earth hours, meaning that any particular landing site could be reached during a window a few minutes long which came up every two days. However, whilst the Tianwen team explored where on Utopia Planitia (a vast, mostly flat plain in Mars' northern hemisphere) they wanted to land, developing a detailed plan for InSight remained extremely challenging. This was on account of the fact that the choice of exact landing location would constrain the landing time, and this would determine when InSight's instruments needed to be on. However, due to the precession of the orbit, the landing window would move a few minutes earlier in each 48-hour period.

Given this uncertainty, we implemented a rolling pattern of instrument wakes and sleeps over a 48 hour period, which could be repeated over several weeks as needed. This planning did not come without cost to other mission objectives as the attempt to record Tianwen's EDL was for a time InSight's top science priority and other measurements had to be sacrificed.

InSight's planning

In order to maximize the likelihood of detecting any waves travelling in either the atmosphere or the solid ground from Tianwen's EDL, we decided to switch on as many instruments as possible and at their highest sampling rates during the landing window. Using both the very broad band (VBB) and short period (SP) seismometers offered good sensitivity to the entire frequency spectrum of interest, from a few hundred seconds up to tens of hertz (Lognonné *et al.* 2019).

Because the seismometers are capable of detecting sub-nanometre-per-second level ground motions, they may potentially detect atmospheric acoustic waves as well, through the deformation that such waves produce when they are incident upon the ground.

The atmospheric pressure and wind sensors (APSS – Auxiliary Payload Sensor Suite; Banfield *et al.* 2019) were also turned on, with the dual purpose of detecting any atmospheric waves and excluding wind shaking the lander as the cause of any signal which might be detected during the landing window. With the exact date and time of the EDL still unknown, the InSight team ran a series of models to determine the likely atmospheric conditions and the potential propagation paths of any waves from Tianwen to InSight for a range of landing windows. With a sound speed of maximum 245 m/s, we expected any potential airwave generated by the supersonic entry to arrive between 1.5 and 3 hours post-landing.

The results from these simulations were used to determine how long instruments would remain on, and in what order they would switch on and off. Whether or not any signal would be detectable above the noise floor was very much unknown. The simplest estimates suggested that it would not be, but the enormous uncertainties in our understanding of martian geophysics and the details of the Zhurong's EDL and hardware, together with the potential value of such a detection, led the team to decide that this experiment was worth sacrificing other science opportunities for.

Landing

With the China National Space Administration's (CNSA) mid-late May landing window in mind, the rolling programme of instrument wakes and sleeps was uplinked to InSight at the start of the month and began executing. The gamble of implementing a rolling plan paid off when CNSA and the Government of China announced their target landing location was around 25°N, in the central part of the plain and that the landing would take place on 14 May. This coincided with one of our 'wake' windows during which the spacecraft would be recording data.

Constraints from the orbit, communications, and the need to immediately deploy solar panels into sunlight upon touchdown meant that an early afternoon landing was preferred. With the time difference to InSight, this meant that the landing would occur around 15:00 Local Mean Solar Time at InSight's position. Unfortunately, this is during the noisy part of InSight's day, when atmospheric-induced signals are at their highest amplitude and overprint almost all marsquakes. This contrasts with the landing time of Mars 2020, which was early evening at InSight (one of the quietest parts of the day).

Although this reduced the probability of any body wave (P or S) being detected, the atmospheric acoustic wave, which would be much slower (hours rather than minutes of travel time) would arrive late enough that it might potentially be detectable.

InSight's VBB and SP seismometers were turned on just after noon InSight local time on 14 May (InSight Sol 876), during the warmest part of the spacecraft's day, to ensure that the sensors were warm enough to re-centre themselves. They were placed into their maximum recording rate of 100 samples per second.

The pressure sensor was set to record at 20 samples per second, and one of the spacecraft's two wind sensors at one sample per second. Instruments were kept on for approximately six hours post-landing, to ensure that the arrival windows for both direct P-waves (~5 minutes) and infrasound (1.5–3 hours) were both covered by the full relevant suite of instrumentation.

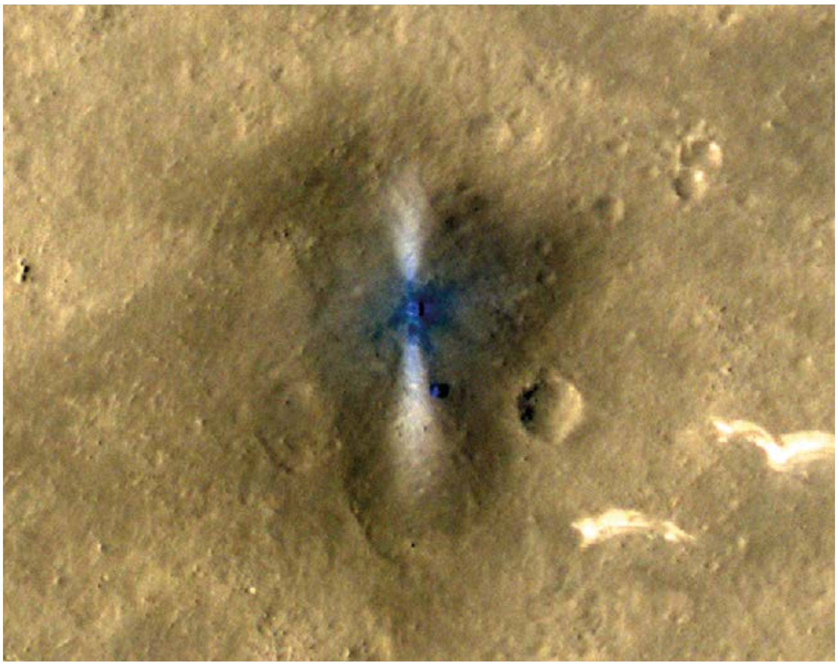
To save power, the spacecraft's second wind sensor and magnetometer were not turned on.

Results and outlook

Just after midnight UTC on 15 May Zhurong landed successfully on Utopia Planitia at 25.1N, 109.9E. InSight's data from this time period were downlinked back to Earth over the next five days. Unfortunately, nothing suggesting any seismic arrival from the EDL was identifiable in the data – and as such we conclude that we did not detect it. Because of the high noise level during the landing window, we could not use the non-detection to place any additional constraints on seismic efficiency beyond what we did for Mars 2020.

Nonetheless, this experiment expanded upon the framework developed for the Mars 2020 landing to involve collaboration between two national space agencies and scientists in many countries. It would not have been possible without the collaboration and co-operation between scientists and engineers on both the InSight and Tianwen-1 teams, and the amateur radio astronomers who helped with orbital determinations.

Over the coming years, the space around Mars is only going to get busier. Although InSight will not be around forever, the potential to repeat this experiment when the next orbital cycle sees more missions landing exists – and the ESA-ROSCOSMOS ExoMars mission, due to arrive in 2022, will also carry a seismometer. Perhaps this exercise may serve as a guide for future international collaborations in deep space. ●



2 *Image of Tianwen-1 landing site taken by the High Resolution Imaging Science Experiment (HiRISE) on 6 June 2021.*

(NASA/JPL/University of Arizona)

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REFERENCES

Anderson DL *et al.* 1977 *J. Geophys. Rev.* **82** 4524
Banerdt WB *et al.* 2020 *Nature Geosci.* **13** 183
Banfield D *et al.* 2019 *Space Sci. Rev.* **215** 4
Clinton JF *et al.* 2021 *Phys. Earth & Planet. Int.* **310** 106595
Daubar IJ *et al.* 2013 *Icarus* **225** 506
Daubar IJ *et al.* 2018 *Space Sci. Rev.* **214** 132
Daubar IJ *et al.* 2020 *J. Geophys. Rev. Planets* **125** e2020JE006382
Edwards WN *et al.* 2007 *J. Geophys. Rev. Sol. Earth* **112** B10306
Fernando B *et al.* 2021a *Earth & Space Sci.* **8** e2020EA001585
Fernando B *et al.* 2021b *Nature Astron. in press*
Giardini D *et al.* 2020 *Nature Geosci.* **13** 205
Heimann S *et al.* 2013 *Seismological Res. Lett.* **84** 1021
Hilton DA & Henderson HR 1974 *J. Acoustical Soc. Am.* **56** 323
InSight Mars SEIS Data Service 2019 *SEIS raw data DOI:***10.18715/SEIS.INSIGHT.XB_2016**
Khan A *et al.* 2021 *Science* **373** 434
Knapmeyer-Endrun B *et al.* 2021 *Science* **373** 438
Latham G *et al.* 1970 *Science* **170** 620
Li C *et al.* 2021 *Space Sci. Rev.* **217** 57
Lognonné P *et al.* 2020 *Nature Geosci.* **13** 213
Lognonné P *et al.* 2019 *Space Sci. Rev.* **215** 12
Menina S *et al.* 2021 *EGU GA Conference EGU***21-14609**
Qamar A 1995 *Seismological Res. Lett.* **66** 6
ReVelle DO *et al.* 2010 *Meteoritics & Planet. Sci.* **40** 895
Stähler SC *et al.* 2021 *Science* **373** 443
van Driel M *et al.* 2021 *J. Geophys. Rev. Planets* **126** e2020JE006670
Wan WX *et al.* 2020 *Nature Astron.* **4** 721
Zou Y *et al.* 2021 *Adv. Space Res.* **67** 812