**FINDING MARSQUAKES: INSIGHT'S MARSQUAKE SERVICE AND THE MARS SEISMIC CATALOGUE.**

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**Introduction:** As mission sol 1440 drew to a close, so did the operational phase of the InSight mission [1] as power reduced below minimum operational levels. However, with more than four years of seismic data recorded by SEIS [2], the seismometer deployed on the surface of Mars by InSight, we here review the marsquake catalogue [3] as created by the Marsquake Service (MQS) [4]. From the quiet early months of the prime mission through to the dramatic events of the extended mission, and finally into the third Martian year of operations, Mars surprised us with nearer, farther, and bigger events. The catalogue now contains not only marsquakes but also meteoroid impacts [5, 6]; surface waves have been observed [7, 8, 9] and catalogued, and all these events are contributing to significant advances in our understanding of the internal structure of Mars.

**The Marsquake Service:** The MQS team includes researchers from across the InSight science team with operations led by ETH Zurich. The team is responsible for prompt data review, event detection, location and catalogue creation and curation. The event detection tools were developed and tested prior to launch [10, 11] and were updated throughout the mission to account for the data observed. Martian seismic data show strong scattering and impulsive arrivals are often smoothed [12, 13, 14]. Waveforms are also often contaminated by atmospheric effects, glitches and other non-seismic features [15].

**Event assignment:** Events are named by the letter S followed by the sol of occurrence and a letter, a-z, to distinguish separate events on the same day such that, e.g. S1090d is the fourth event recorded on mission sol 1090. When a signal is confirmed as a seismic event, MQS assigns phase picks and uncertainties including, where possible and appropriate, Pg, Sg, P, S, Pdiff, PP, SS, PPP, SSS. If low-frequency phases cannot easily be associated with specific body-wave phases they are labelled x1, x2, etc; similarly high-frequency phases that cannot clearly be assigned as Pg or Sg are labelled yn.

The most recent catalogue also includes surface waves: two, large meteoroid impact events [6], S1000a and S1094b, both produced fundamental Rayleigh waves – the first surface waves to be seen within the Martian dataset [7]. S1222a, the $M_w^{Ma}$=4.7 marsquake from May 4th, 2022, demonstrated a breadth of frequency and duration that dwarfs everything else in the catalogue. For the first time we recorded Love waves – both fundamental and their overtones [8], and multi-orbit Rayleigh waves, out to R4 [8, 9].

**The Marsquake Catalogue:** As of January 1st, 2023, the marsquake catalogue [3] contains 1319 marsquakes (Table 1), of which 6 are known meteoroid impacts [5, 6]. There are another 1383 superhigh frequency events (SF) that are linked to thermal cracking nearby to the lander. SF events are labelled in the same way as standard events, but the letter T is used in place of S, e.g., T1159a is the first thermal quake observed on sol 1159.

**Table 1:** Number and type of events catalogued

| Event Type | Total | Quality | | | |
|---|---|---|---|---|---|
| | | A | B | C | D |
| **VF** | 71 | 0 | 27 | 33 | 11 |
| **HF** | 164 | 0 | 76 | 79 | 9 |
| **2.4** | 989 | 0 | 50 | 353 | 586 |
| **BB** | 38 | 8 | 10 | 15 | 5 |
| **LF** | 57 | 6 | 12 | 20 | 19 |
| **SF** | 1383 | 0 | 0 | 323 | 1060 |

Marsquakes are categorized by their predominant frequency content – from the high frequency family of events with energy at 2.4 Hz or above (VF, HF, 2.4), through broadband events (BB) spanning up to and above 2.4 Hz but also below 1 Hz, and down to LF events (energy below 1 Hz) [4]. A location quality (A-D) is assigned based on the quality of phase picks and any available backazimuth determination. Quality A events have a complete location, quality D may not even have a single clear phase pick. Although backazimuths are hard to determine for marsquakes, the work of Zenhäusern et al, [16] has helped produce complete locations for 14 of the events.

**Seasonal and diurnal variability:** Event detectability is heavily dependent on the ambient noise conditions at the lander (Figure 1) with the Martian autumn and winter winds proving particularly noisy. During the early months of the mission the Insight science team began to wonder whether there was any seismicity on Mars at all. In retrospect, we now understand that InSight landed in late winter where wind noise covers all seismic events. But the Martian spring and summer allow extended atmospherically quiet observation periods, especially in the Martian night-time. Further, the occurrence rate of higher frequency events during the first Martian year actually ceased before the wind noise became too strong to detect it [17].

The extended mission provided us with a second Martian year of data and part of a third, but curiously has also given an increased occurrence rate compared to the first year of operations [4]. The reason for this is as yet unknown. We can rule out potential observational bias of manual picking with the work of Dahmen et al., [18] where independent machine learning techniques have been applied to the dataset to help suppress atmospheric noise. The MQS catalogue shows a 66% increase in the number of HF family events during the second Martian year, the machine learning catalogue shows an 88% increase.

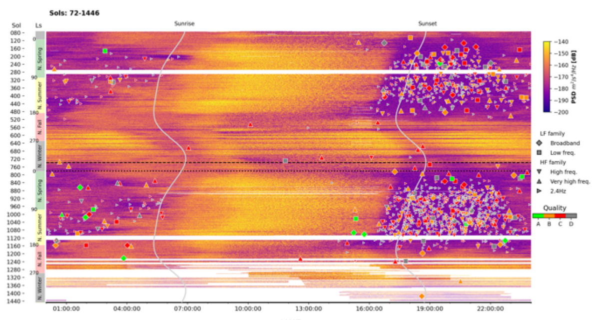

**Figure 1:** Daily spectrogram of the very broadband vertical component stacked from sol 72 to sol 1446. Catalogued seismic events, except for superhigh frequency events, are superposed.

**Mars Magnitudes:** Magnitudes are computed for all events that have an estimated distance. Several scales are used based on the P- and S-wave peak amplitudes for LF and BB events and the maximum amplitude around 2.4 Hz for the HF family events. The magnitude relations were first derived by Bose et al [19] using synthetic seismograms produced for a set of pre-launch Martian models that can be found in Ceylan et al [20]. These relations were updated in Giardini et al [21] and then again by Bose et al [22] using real data from the 485 marsquakes that occurred up to October 2020. These revised relations are now used for all events within the marsquake catalogue.

**Data Release:** The mars seismic data and marsquake catalogue have been released every three months with a three-month delay, through IRIS, the PDS and the InSight Mars SEIS Data Service [23]. The latest catalogue is v13 [3]. A final release will be made on April 1st, 2023.

**Conclusions:** The seismicity of Mars is fascinating, and our understanding of its origins is evolving with every quake we analyze. The extended mission has given us data from impacts and events with surface waves. The marsquake catalogue created by the Marsquake Service will allow researchers for generations to access this incredible dataset and all that it holds about the secrets of Mars and its interior.

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