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# Joint Inversion of Receiver Functions and Apparent Incidence Angles to Determine the Crustal Structure of Mars

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# S1222a - the largest Marsquake detected by InSight

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## Key Points:

- InSight detected on May, 4, 2022 a  $M_W^{Ma} 4.7$  marsquake, S1222a, which is the largest seismic event detected so far.
- The exceptional signal-to-noise allows multiple phases to be identified, with a rich collection of surface waves.
- S1222a was located 37 degrees southeast of the InSight landing site and close to the Martian dichotomy boundary.

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**Abstract**

NASA’s InSight has detected a large magnitude seismic event, labelled S1222a. The event has a moment magnitude of  $M_W^{Ma} 4.7$ , with 5 times more seismic moment release compared to the second largest even. The event is so large that features are clearly observed that were not seen in any previously detected events. In addition to body phases and Rayleigh waves, we also see Love waves, minor arc surface wave overtones, and multi-orbit surface waves. At long periods, the coda event exceeds 10 hours. The event locates close to the North-South dichotomy and outside the tectonically active Cerberus Fossae region. S1222a does not show any evident geological or tectonic features. The event is extremely rich in frequency content, extending from below 1/30 Hz up to 35 Hz. The event was classified as a broadband type event; we also observe coda decay and polarization similar to that of very high frequency type events.

**1 Introduction**

NASA’s Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) mission has achieved almost continuous seismic monitoring of Mars since early 2019 (Banerdt et al., 2020; Lognonné et al., 2020). Since May 2022, the local background seismic noise has increased due to the typical atmospheric disturbance observed during the Martian autumn and winter, and the power situation had deteriorated to the point that InSight’s SEIS (Seismic Experiment for Interior Structure) instrument (Lognonné et al., 2019) was about to begin to be periodically switched off. In this challenging situation, SEIS recorded the largest marsquake ever detected during the mission lifetime to date. On May 4<sup>th</sup>, at 23:23:07 UTC, also known as the 1222<sup>nd</sup> Martian day (sol) since InSight landed, a magnitude  $M_W^{Ma} 4.7$  marsquake shook the red planet. The aim of this paper is to describe in detail the main characteristics of the event and provide initial context for further research.

To uncover the internal structure of Mars, InSight was equipped with a suite of geophysical instruments and seismic sensors; SEIS is one of the key scientific instruments of the mission (Banerdt et al., 2020; Lognonné et al., 2019; Lognonné et al., 2020). Since the deployment, SEIS has been monitoring Martian seismicity for more than 1350 sols (each sol is approximately 24h39m). SEIS consists of two seismometers, the Very Broadband (VBB) seismometer and the Short Period (SP) seismometer designed to cover the different frequency bands. InSight also has a series of environmental monitoring sensors known as the Auxiliary Payload Sensor Suite (APSS). APSS includes meteorological sensors (pressure, wind and thermal sensors) and a magnetometer (Banfield et al., 2019, 2020; Johnson et al., 2020). SEIS data are strongly contaminated by environmental, spacecraft and instrumental noise (Ceylan et al., 2021; Scholz et al., 2020; Kim, Davis, et al., 2021). In the nominal configuration, InSight simultaneously observes both seismic signals and environmental noise, which allows seismologists to distinguish between true seismic events and environmental noise injection (Clinton et al., 2021; Charalambous et al., 2021). However, this was no longer possible since Sol 789 due to power limitations that required shut down of some of the scientific payload. The two solar panels that are used to power the spacecraft and the instrument have steadily accumulating Martian dust and the power generation has degraded significantly. Thus, for the last 600 sols, SP and APSS were only occasionally powered on and only the VBB has been powered on continuously, with sampling at 20 Hz. Neither the SP nor APSS were turned on during S1222a. VBB was operating in high-sampling-rate mode and it was possible to also retrieve 100 Hz for the event. SEIS data is archived and released by InSight Mars SEIS Data Service and the data is available to the science community with 3 months delay (InSight Mars SEIS Data Service, 2019).

Using InSight seismic data, various Martian seismic velocity models were proposed (Giardini et al., 2020; Lognonné et al., 2020; Stähler et al., 2021; Khan et al., 2021; Knapmeyer-

Endrun et al., 2021; Kim, Lekić, et al., 2021; Drilleau et al., 2021, 2022). MQS uses the suite of models proposed in Stähler et al. (2021) to locate seismic events. This approach was proven to be highly plausible after the remarkable precision we achieved for detected impacts whose locations were confirmed using orbital imaging (Garcia et al., 2022; Posiolova et al., 2022). Back azimuths are obtained based on the method described in Zenhäusern et al. (2022). This method provides a more rigorous and systematic estimation of the polarization compared to the former approach described in Böse et al. (2017), not least since it combines observations from both P and S arrivals. Its efficacy was also demonstrated through analyses of ambient noise (Stutzmann et al., 2020). Event depths are challenging to define using only a single station where depth phases are rarely identified, so MQS assigns a fixed depth of 50 km to all events.

## 2 Event Overview

Figure 1 and Table 1 show the general characteristics of event S1222a and the context of the background environmental noise. Waves from the event first reached InSight shortly before 4AM Local Mean Solar Time (LMST) on Mars. S1222a occurred in mid-autumn at the landing site, a season with high seismic noise due to persistent winds. Broadband noise injection from wind was observed constantly before and during the event as evidenced by the presence of clear lander resonances (Dahmen et al., 2021; Charalambous et al., 2021). In addition to the environmental noise, InSight data suffers from glitches which are likely due to thermal-induced shocks within the instrument or the lander (Scholz et al., 2020). Glitches are 1-sided pulses that can be modelled by the instrument response to a step in acceleration, and hence appear as near-critically damped 20s signals, that are rich in all frequencies. The signals regularly corrupt the seismic signal and obscure phase interpretation (Kim, Davis, et al., 2021). Despite the very high amplitude seismic signals, strong glitches are present throughout S1222a. To avoid misinterpretation of seismic phases with glitches, analysis of the data is performed on both raw data as well as deglitched data following the methods described in Scholz et al. (2020).

Despite the high background noise, the seismic energy of the event strongly exceeds the noise level (Figure1(d)). The event is rich in frequency content and for many minutes following the energy onset, signal far exceeds the noise level from below 30 seconds to 35 Hz. Comparing the seismic spectra to the background noise, the signal to noise ratio is as high as 40 dB at  $\sim 30$  seconds and 60 dB at  $\sim 1$ Hz (Figure1(d)). Following the MQS convention, since there is very significant energy below 2.4 Hz, the event is cataloged as a Broadband (BB). This event is remarkable in many ways - low-frequency energy persists for approximately 10 hours (Figure1(b)). While the high frequency energy above 1 Hz attenuates far more rapidly ( $\sim 20$  min) than the long period, the resonance at 2.4 Hz continues to ring for an additional ( $\sim 20$  min). Previously, no broadband event included energy above 10 Hz, yet in S1222a energy is clearly present up to 35 Hz and is strongest on the horizontal components at high frequencies - behaviour that otherwise is only observed in Very High Frequency (VF) events. The event spectrum is so broad and large it spans all previously known event types.

The peak amplitude of the signal reaches  $2.8 \times 10^{-5}$  m/s on the instrument-response-corrected radial components. On the oblique components of the raw data, the value is  $2.4 \times 10^{-5}$  m/s, equivalent to 2.2 millions counts. It is noted that this is 26% of the  $2^{23}$  count limit of the 24-bit EBOX digitiser (Zweifel et al., 2021). SEIS was remarkably close to saturation during this event.

### 2.1 Phase Identification

Two energy packets can be clearly identified that are interpreted as P and S body waves, as has been done for other Low Frequency family events (Clinton et al., 2021; Ceylan et al., 2021)(Figure1(e)). The onset of each packet is picked as the first arrival of each

122 phase. The P coda has almost constant amplitude across the minutes before the S ar-  
 123 rival. After the arrival of the stronger S phase, energy gradually decays which is a typ-  
 124 ical characteristic of the High Frequency family of marsquakes (Figure1(e)).

125 In addition to the routinely identified body phases, surface waves are clearly vis-  
 126 ible in the S-wave coda (Figure1(a,b,c)). To date, the only surface waves identified on  
 127 Mars have been fundamental Rayleigh waves that were observed in 2 other events, S1000a  
 128 and S1094b (Kim et al., 2022). In the case of S1222a, a much richer set of surface waves  
 129 are observed. Both fundamental Rayleigh and Love waves (R1 and G1 respectively), and  
 130 first overtones (R1.1 and G1.1), can be identified. Further, major arc R2 and multi or-  
 131 bit R3, although weak, can be identified, and there are suggestions of later multi-orbit  
 132 arrivals (x4, x5). All the phase arrival picks that were made by MQS are summarized  
 133 in Table 1. We will describe in detail in the following the phases that we identified.

### 134 **2.1.1 Body Waves**

135 The first clear arrival visible in the data is an impulsive P wave. The P arrival was  
 136 picked in the time domain which is only possible for events with a high signal-to-noise  
 137 ratio, such as 14 quality A events. 1.5-10 seconds filtered data were used to identify the  
 138 downward motion of the P arrival with an uncertainty of 0.5 seconds. In Figure 2 we can  
 139 see a clear impulsive and broadband P arrival between 3 Hz - 10 s, though above 3 Hz  
 140 there is a distinct delay in arrival time that increases linearly with frequency, possibly  
 141 the effect of scattering at higher frequencies. The P arrival is glitch free though a large  
 142 glitch is observed within the P coda (obvious glitches are indicated in the timeseries shown  
 143 in Figure 1(e,f)). Polarisation analysis (see below) shows that this phase is strongly and  
 144 persistently polarised. A stronger second envelope of energy arrives approximately 3.5  
 145 min later, consistent with an S phase arrival. The polarisation is persistent and differ-  
 146 ent to the P-wave, allowing us to label it as a S-phase (Figure3). The impulsive S ar-  
 147 rival can also be identified in the time series, for the MQS phase pick we used data fil-  
 148 tered between 1.5 and 10 seconds, and assigned a 2 seconds uncertainty. As in the case  
 149 for P wave, the S wave also shows an impulsive broadband arrival though is similarly de-  
 150 layed at higher frequencies. A large number of significant glitches are present in the S-  
 151 wave coda, though they are not clearly visible in the raw time series since the signal am-  
 152 plitudes are so high - they are revealed if the signal is integrated to displacement.

153 Both the P and S wave coda include high frequency energy that reaches up to  $\sim 32.5$   
 154 Hz with signal to noise ratio larger than 10(Figure 2). In order to be consistent with  
 155 other broadband events in the catalogue, MQS also identified y1 and y2 arrivals which  
 156 correspond to the arrival times of the high frequency portion of the energy and are picked  
 157 using the energy envelope at the 2.4Hz resonance (Ceylan et al., 2021). As expected, ar-  
 158 rivals are very similar to the P and S arrivals, lying within the error bars, as shown in  
 159 Table 1. As for other VF events, S1222a has stronger horizontal energy at high frequen-  
 160 cies and the horizontal energy persists to higher frequencies while the vertical energy de-  
 161 cays quickly (Figure 1(c),(d))(van Driel et al., 2021; Menina et al., 2021; Karakostas et  
 162 al., 2021).

### 163 **2.1.2 Surface Waves**

164 Almost no other marsquake had energy above the noise below 10s. At periods from  
 165 about 10-30 seconds, S1222a exhibits dispersive signals which are a strong indication of  
 166 surface waves. Surface waves were first reported for two large impacts where the surface  
 167 source efficiently excited surface waves (Kim et al., 2022). The polarised P-wave allows  
 168 us to rotate the signal into radial and transverse components, aiding our interpretation.  
 169 For S1222a, on the vertical and radial components, we see a clear Rayleigh wave between  
 170 at least 10 and 35 seconds period, starting about 4.5 minutes after the S arrival (Figure??).  
 171 As shown in Table 1 and visible in Figure1(c), the signal shows clear dispersion where

172 phase arrivals are delayed towards the high frequencies. Furthermore, we can also iden-  
 173 tify a first overtone arriving before the fundamental mode. The overtone is shifted to-  
 174 wards the higher frequencies and the dispersive signal is detected in the period range of  
 175 3 - 15 seconds. As expected for the overtone, the two signals show similar dispersion. In  
 176 addition to the Rayleigh wave, on the transverse component, a Love wave was detected  
 177 for the first time on Mars for S1222a at 23:33:38.2, which is about 2 minutes after the  
 178 S arrival. The Love wave arrives about 2.5 minutes before the Rayleigh wave and almost  
 179 at the same time as the Rayleigh wave overtone.

## 180 2.2 Multi-orbit Surface Waves

181 S1222a not only enabled us to identify Love waves for the first time on Mars, it also  
 182 provides us with opportunities to explore further subsequent surface waves. In Figure  
 183 1(a), where we plot a 12 hour spectrogram in acceleration, we see energy significantly  
 184 higher than the background noise at 01:15(UTC). The signal shows a weak dispersion  
 185 but this is difficult to confirm with the low signal to noise ratio. The energy is followed  
 186 by another packet of energy about 20 minutes later. This signal is overlapping with a  
 187 significant glitch but is clearly visible after the deglitching (Figure1(f)). These signals  
 188 are only visible in the vertical component and this makes it difficult for us to investigate  
 189 the polarization of these signals. However, given the dispersive feature of the signal, we  
 190 concluded that these are the R2 and R3 phases and their picks are also provided in Table1.  
 191 Similar multi-orbit phases were not identified for Love waves which is reasonable given  
 192 the higher noise level on the horizontal components, where Love waves should be most  
 193 visible. This is the first time that we have identified and catalogued R2 and R3.

## 194 2.3 Distance Analysis

195 As done throughout the mission, we used P and S arrivals and a suite of reference  
 196 seismic velocity models (Stähler et al., 2021) to find the most probable location (mod-  
 197 ified after (Böse et al., 2017)). This provides a distance consistent with all the other events  
 198 in the catalog (Ceylan et al., 2021) and we are confident that this gives us a reasonable  
 199 distance after the detection of confirmed impacts (Posiolova et al., 2022). This gave us  
 200 37 degrees for the distance. We refrain from using fundamental and overtone surface wave  
 201 arrival times here since our methods are not yet calibrated for these phases.

202 Our pre-landing plan was to use R1/2/3 to locate marsquakes with a single sta-  
 203 tion. This method was described in various pre-landing papers but was not used to date  
 204 given the lack of R2/R3 detection (Panning et al., 2015; Böse et al., 2017; van Driel et  
 205 al., 2019). Given that this is our first detection of R2 and R3, we tested this method to  
 206 locate the marsquake and compared with the distance obtained from the body waves.  
 207 With R1/2/3, we obtained 35.4 degrees which is consistent and overlaps with the value  
 208 obtained with body waves within the range of the errorbar. While S1222a enabled us  
 209 to at last confirm our pre-landing concept, we did not include this as the preferred lo-  
 210 cation for consistency with other events in the catalog.

## 211 2.4 Back-azimuth Analysis

212 Figure 3(a) shows the result of the back azimuth analysis for body waves by us-  
 213 ing the eigenvector method described in Zenhäusern et al. (2022) and adopted by MQS  
 214 from catalog V12. Data here includes a linearity filter to accentuate body wave energy,  
 215 which is defined as  $F_e = (1 - \epsilon)^2$ .  $\epsilon$  is the ellipticity of the signal and is 0 for a recti-  
 216 linear and 1 for a circular signal (for details see Zenhäusern et al. (2022)). The P energy  
 217 observed between 1/10-1/2 Hz, the window MQS uses to determine LF family polariza-  
 218 tion, has a polarization that peaks at 101 degrees. This value is consistent over a wide  
 219 frequency band, from 1/10 to 2 Hz and time window (shown in yellow in Figure 3(a)).  
 220 As is normal for marsquakes, high frequency energy is intensely scattered. The incident



221 angles of about 70-80 degrees (shown in orange in the figure) are observed at 1/5-1/2  
 222 Hz. Such vertical polarization supports our identification of the P wave. When we fo-  
 223 cuse on the S wave, we also see coherent energy around a similar frequency band as the  
 224 P wave which clearly has a different back-azimuth of about  $0^\circ$ , about  $90^\circ$  shifted from  
 225 the P polarization, and having a low inclination angle of about  $20^\circ$ . Both are consistent  
 226 with an S-wave.

227 Figure 3(b) shows the same polarization analyses, but without linearity filter, in  
 228 order to accentuate surface wave energy. Indicated in the figure both the fundamental  
 229 Rayleigh (green ellipse) and Love (light blue ellipse) wave energy are indicated. The Rayleigh  
 230 wave is visible with a high ellipticity signal. The back azimuth obtained from the Rayleigh  
 231 wave is similar but offset to that obtained from body waves and is estimated to be about  
 232  $120^\circ$ . The Love wave has horizontal polarization as expected from a typical Love wave.  
 233 In contrast to the Rayleigh wave, it has a low ellipticity, meaning the signal is linear. From  
 234 both body waves and surface waves, we have a self-consistent set of polarization. To be  
 235 consistent with the MQS catalogue, the preferred back azimuth is  $101^\circ$  ( $96^\circ$ - $112^\circ$ ).

## 236 2.5 Location of S1222a

237 Combining the distance and the back azimuth, the event can be located at  $3.0^\circ$ S,  
 238  $171.9^\circ$ E (Figure 3(c), Table 1). The uncertainty ellipse is indicated in the figure, dom-  
 239 inated by the relatively wide uncertainty in backazimuth. The event appears to lie about  
 240  $10^\circ$  to the south to the farthest Eastern extent of Cerberus Fossae, by a considerably mar-  
 241 gin the most seismically active region on Mars (Giardini et al., 2020; Perrin et al., 2022;  
 242 Rivas-Dorado et al., 2022; Zenhäusern et al., 2022; Stähler et al., 2022). The majority  
 243 of located seismic events locate within this region (Ceylan et al., 2022) and a clear link  
 244 between surface fault system and source mechanisms is suggested (Brinkman et al., 2021;  
 245 Jacob et al., 2022). S1222a locates in a region closer to the North-South dichotomy (Smith  
 246 et al., 2001). Unlike the Cerberus Fossae region, the epicenter of S1222a shows no ev-  
 247 ident tectonic features. In addition, no new crater of appropriate size has been detected  
 248 in orbital images taken of the location error ellipse, thus far. Further investigation should  
 249 be done with higher resolution imagery (e.g. MRO HiRISE).

## 250 2.6 Magnitude Evaluation

251 Following the methods described in (Böse et al., 2021), we obtained magnitudes  
 252 for this event, which are summarized in Table 1. We assigned 3 types of magnitude de-  
 253 pending on the frequency band and the method that we use to define the magnitude. The  
 254 first,  $M_{w,spec}^{Ma}$  was defined using the body wave spectrum and fitting this with omega square  
 255 model. We obtained  $4.7 \pm 0.2$  for the magnitude which is larger by 0.5 compared to the  
 256 second largest event (S0976a,  $M_{w,spec}^{Ma}=4.2\pm 0.3$  (Horleston et al., 2022)). This was viewed  
 257 as the reference magnitude among the obtained magnitudes and was used to calculate  
 258 the seismic moment. This magnitude is by far the largest of all the cataloged marsquakes  
 259 and the seismic moment release of this single event is comparable to all other events in  
 260 the marsquake catalog combined. The other two magnitudes were calculated from body  
 261 wave amplitudes for P and S filtered at 2-6 seconds period. The body wave magnitude  
 262 ( $m_b^{Ma}$  and  $m_b^{SMa}$ ) was obtained for P and S amplitude respectively and we obtained 5.3  
 263 and 5.8. The difference in the obtained magnitude can be explained by the high corner  
 264 frequency compared to other marsquakes (Stähler et al., 2022).

## 265 2.7 Spectral analysis

266 S1222a shows one of the richest frequency contents ever seen within marsquakes  
 267 with a significantly wider frequency band that range from  $1/30$  Hz to 35 Hz, compared  
 268 to previously detected events. Both P and S arrivals have broadband energy covering  
 269 frequencies as low as  $\sim 0.02$  Hz up to  $\sim 35$  Hz (Figure 1(c), Figure 2). The noise starts

270 to increase below  $\sim 0.4$  Hz and becomes dominant at  $\sim 0.01$  Hz. The S wave extends over  
 271 a wider frequency band, covering both lower and higher frequencies compared to the P  
 272 wave. At high frequencies above 1 Hz, the P and S waves have similar spectral shapes  
 273 that almost overlap with each other.

274 When we compare spectra from the vertical and horizontal components, we see clear  
 275 enhancement for horizontal components (Figure 1(c)). While the spectrum of the ver-  
 276 tical component decays rapidly with frequency, the horizontal components show almost  
 277 flat or slightly decaying spectra. This is a typical characteristic observed for VF type events.  
 278 Such a feature was not observed for other BB type events. At frequencies higher than  
 279 1 Hz, we see a characteristic peak centered around 2.4 Hz. The resonance at 2.4 Hz is  
 280 widely known and was reported in previous studies (van Driel et al., 2021; Dahmen et  
 281 al., 2021; Hobiger et al., 2021). The high corner frequency of the event is unusual for other  
 282 relatively large marsquakes, specifically those observed in Cerberus Fossae (Stähler et  
 283 al., 2022), and suggests that the event occurs outside this fault system, which is consis-  
 284 tent with the location we obtained.

### 285 3 Discussion

#### 286 3.1 Possible Aftershock

287 About 34 hours after S1222a, a small VF event was detected (S1223a). While this  
 288 was a much weaker event compared to S1222a ( $M_W^{\text{Ma}}=2.9$ ), the event was carefully ex-  
 289 amined given the possibility of it being an aftershock of S1222a. S1223a clearly lacks long  
 290 period energy compared to S1222a, thus it is cataloged as a VF event and not a BB event.  
 291 This is unlikely for an aftershock but this might be due to the large difference in the mag-  
 292 nitudes of the two events. Due to strong environmental noise injection at the time of S1223a,  
 293 the time differences between the P and S arrivals were constrained through comodula-  
 294 tion from weather-sensitive lander resonances (Charalambous et al., 2021) and indicate  
 295 similar time delays for both events (3 minutes 20 seconds and 3 minutes 34 seconds). As  
 296 is often the case for VF events, no polarization can be assigned.

#### 297 3.2 Additional Multi-orbit Phases

298 S1222a is so large that beyond the multi-orbit R3 phase arrival there are hints for  
 299 further phase arrivals, which are labelled in Figure 1 and Table 1 as x4 and x5. The pre-  
 300 landing expectation was that locations could be made using any combination of body  
 301 phases and surface waves. In the pre-launch blind test (Clinton et al., 2017; van Driel  
 302 et al., 2019), source locations were tested using body waves and R1/R2/R3. Further multi-  
 303 orbit phases were not considered or its utilisation was not tested (Panning et al., 2015;  
 304 Böse et al., 2017). However, for S1222a, we were able to identify some increases in en-  
 305 ergy on the vertical component at around the expected time windows for R4 and R5.  
 306 The signal to noise ratio is low and we were not able to see any clear phase of disper-  
 307 sion in the data, leaving some uncertainties in their identification as R4 and R5. Thus,  
 308 we included these signals in the catalog as x4 and x5, using the indicator x, which MQS  
 309 uses for unknown phases. While we would like to leave future studies to confirm this,  
 310 we believe that these arrivals are possible candidates for R4 and R5.

### 311 4 Conclusion

312 We reported in this study the general characteristics of S1222a, the magnitude 4.7  
 313 marsquake located  $37^\circ$  distance from the SEIS seismometer, which is by far the largest  
 314 event detected during the InSight mission to date. Both body waves and a rich suite of  
 315 surface waves can be identified, including both fundamental and first overtone Rayleigh  
 316 and Love waves, and multi orbit Rayleigh waves. As recorded at InSight, the event in-  
 317 cludes energy ranging from below 1/30 Hz up to 35Hz. In the context of the marsquake



318 catalog event types, the low frequency component ( $<2.4\text{Hz}$ ) resembles broadband type  
319 events whereas the higher frequency component is characteristic of very high frequency  
320 events. Such an event may provide us with a clue to understand the different types of  
321 marsquakes and their origins. The event is located close to the the North/South dichotomy  
322 of Mars and outside the well-known Cerberus Fossae region where many of the major  
323 seismic events are located. These features require further investigation and the event will  
324 serve as an unique example to uncover the mysteries of Martian seismicity.

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### 338 **Open Research**

339 All raw waveform data is available through the InSight Mars SEIS Data Service  
340 @ IPGP, IRIS-DMC and NASA PDS. (InSight Mars SEIS Data Service, 2019).



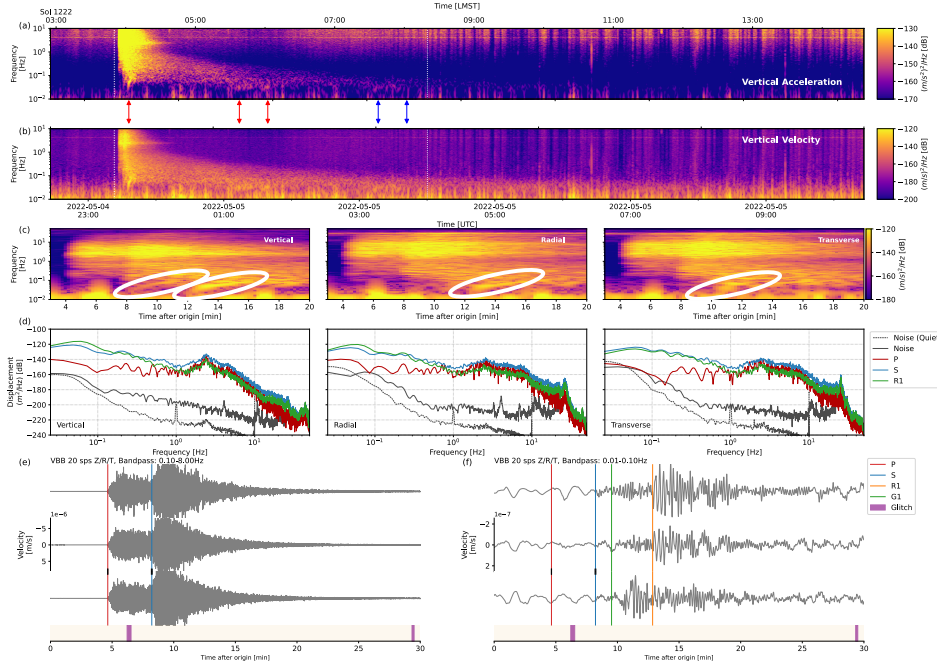


Figure 1: Event summary for S1222a. (a) 12 hour spectrogram in acceleration on the long period signal of the event. 20Hz deglitched data was used for the plot. Time window of 200 second with 90% overlap was used. The 3 red arrows below indicate R1/2/3 arrivals from the MQS catalog and the 2 blue arrows correspond to the x4 and x5 arrivals. The white dotted line is the origin time and the event end time from the catalog. (b) 12 hour spectrogram in velocity including the high frequency energy. The same time window and overlap as (a) was used. (c) 3 axes velocity spectrogram zoomed in to the event and expanded to the full frequency band width. 100 Hz deglitched data were used for the plot. Time window of 100 seconds and overlap of 90% were used. The signal (d) Spectra of P, S and R1 energy of the event compared with pre-event noise and the noise level of a quiet period during the mission (noise curve of Sol 0235 were taken). To calculate P and S spectra, spectral time windows in the MQS catalog were used. For the noise, we also referred to the noise window in the catalog. For the noise level of the quiet season, we took noise window of marsquake S0235b. (e) Seismograms filtered between 0.1-0.8 Hz. The red and the blue lines refer to P and S arrival times identified by MQS. Glitches identified by MQS are indicated in purple in the bottom.(f) Seismograms filtered between 0.01-0.1 Hz. The red and blue lines refer to P and S arrival times identified by MQS. Arrival times of fundamental Rayleigh and Love waves are shown in orange and green. For the surface waves the earliest arrival of all the frequency bands are shown in the figure. For (c)-(f), the signal were rotated to vertical, radial and transverse component using the back-azimuth we obtained (Table1)

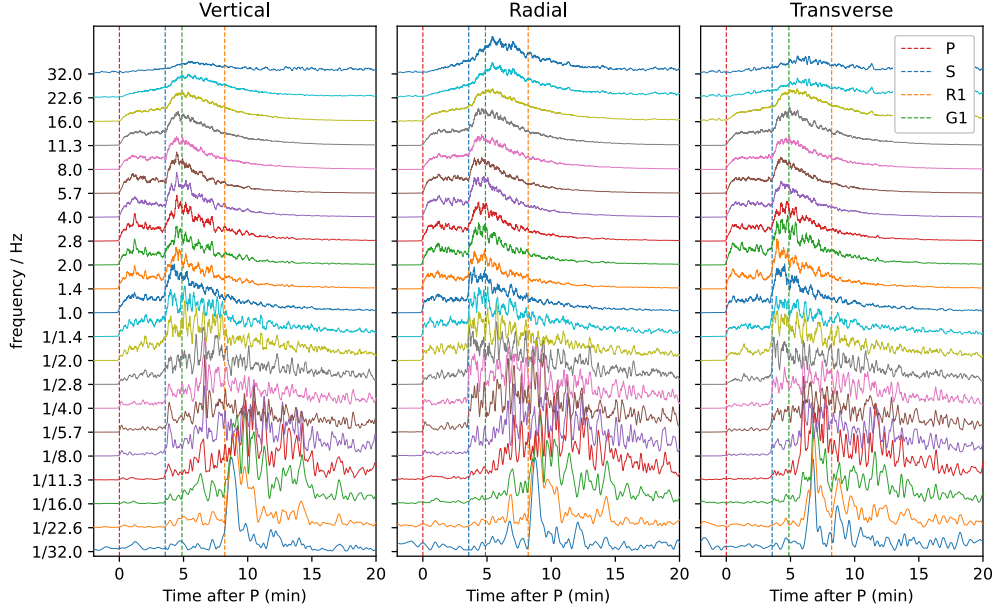


Figure 2: Filterbanks of S1222a. To create the filterbanks, both 20 Hz and 100 Hz data were used. Frequencies above 10 Hz used 100 Hz channels and were deglitched using the `seisdeglitch` tool (<https://pss-gitlab.math.univ-paris-diderot.fr/data-processing-wg/seisglitch>). The low frequencies below 10 Hz used 20 Hz continuous VBB channels and were deglitched with the method developed in UCLA (see Scholz et al. (2020) for further details) which achieves more efficient deglitching but is not applicable to 100 Hz data. The deglitching was tailored specifically for the event and was more efficient in removing glitches within the P and S code. Each trace shows the filtered envelope smoothed with 10 second time window. Each trace is bandpass-filtered at the frequencies shown in the y-axis. The filters are half an octave wide on each side. Body (P and S) and surface wave (Rayleigh and Love) arrivals are indicated with vertical dashed lines.

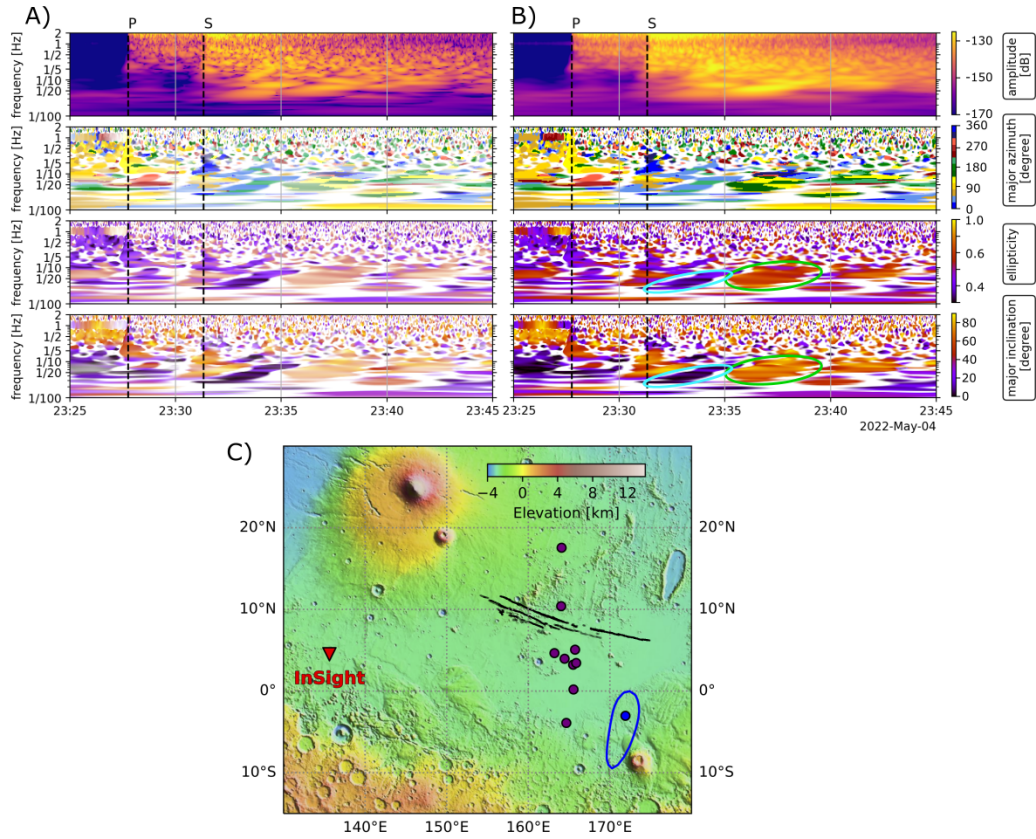


Figure 3: Polarisation and location of S1222a. (a) Data filtered to enhance linear, polarised signals. (b) Data filtered to enhance only polarised data, no linearity filter. Love and Rayleigh waves with overtones are visible after the S wave pick. For both (a) and (b): Back Azimuth of S1222a obtained from eigenvector methods (Zenhäusern et al., 2022) using de-glitched data; time-frequency depiction of (top row) amplitude, (second row) azimuth, (third row) ellipticity, and (bottom row) inclination. (c) Shown are quality A event locations (purple dots) and the InSight location (red triangle). The location of S1222a is marked by the blue uncertainty ellipse with a blue dot to show the preferred location. The Cerberus Fossae graben are marked with black lines. Updated from (Zenhäusern et al., 2022). The map background uses Mars Orbiter Laser Altimeter elevation data (Smith et al., 2001).

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