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Locating the largest event observed on Mars with multi-orbit surface waves

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Key Points:

- The M_W 4.7 S1222a event is the first marsquake large enough for multi-orbit surface wave location independent of a priori seismic velocity
- Using measurements of R1, R2, and R3 Rayleigh waves, we determine an epicentral distance consistent with that estimated from body waves
- Elliptical particle motion is observed for Rayleigh wave arrivals broadly consistent with the backazimuth identified from body waves

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Abstract

Prior to the 2018 landing of the InSight mission, the InSight science team proposed locating marsquakes using multiple orbit surface waves, independent of seismic velocity models, for events larger than $M_W 4.6$. The S1222a $M_W 4.7$ of May 4, 2022 is the largest marsquake recorded and the first large enough for this method. Group arrivals of the first three orbits of Rayleigh waves are determined to derive the group velocity, epicentral distance, and origin time. The mean distance of 36.9 ± 0.3 degrees agrees with the Marsquake Service (MQS) distance based on body wave measurements of 37.0 ± 1.6 degrees. The origin time from surface waves is systematically later than the MQS origin time by 20 seconds. Backazimuth estimation is similar to body wave estimations from MQS although suggesting a shift to the south. Backazimuth estimates from R2 and R3 are more scattered, but do show clear elliptical motion.

Plain Language Summary

Waves that move along the surface all the way around the planet of Mars can be used to figure out where a marsquake occurred without knowing in advance how fast the waves move through the planet, because we know how big the planet is. Before InSight got to Mars, we predicted that we would be able to see these waves if an event was big enough, and on May 4, 2022, we finally saw a marsquake large enough to test this approach. Based on the timing of the arrivals of these waves, we were able to figure out the distance and timing of the marsquake. The results agreed well with the approach we had been using for smaller events, giving us additional confidence in our tools for figuring out where marsquakes have happened.

1 Introduction

On May 4, 2022, the 1222nd sol of the InSight mission (Banerdt et al., 2020), the SEIS instrument (Lognonné et al., 2019) recorded the largest event of the mission to date, called S1222a (Kawamura et al., 2022). The moment magnitude of the event is estimated as $M_W 4.7$, meaning it is approximately 5 times larger in terms of seismic moment than the second largest observed event (S0976a, Horleston et al., 2022). The large moment release of this event has opened up a variety of new observations not possible with previous smaller events.

In particular, this event is the first that allows us to test a single station location method proposed before the launch of the mission that makes use of the observation of multiple orbit surface waves (Panning et al., 2015; Khan et al., 2016). Prior to the mission, there was *some* concern about how well the mission ~~would be able to~~ could locate events with a single station when the seismic velocity structure of Mars was not well-known in advance. While *a priori* models of the interior velocity structure were available before landing (e.g. Khan et al., 2018; Bagheri et al., 2019; Smrekar et al., 2019) and body wave location methods that depend on the initially unknown velocity structure have been *very* successful in locating events (Durán et al., 2022), proposing a method that did not directly depend on any knowledge of the velocity structure (beyond assuming the structure is spherically symmetric) allowed for a plan to verify locations based on body waves.

Multiple orbit surface waves have paths around the sphere of a planet that allow for multiple arrivals in the minutes and hours after the origin time of the event. For Rayleigh waves, recorded on the vertical and horizontal component in the great-circle plane connecting the source and receiver, we refer to these as R1, R2, R3, etc. R1 represents surface wave energy that takes the shortest distance around the planet (or minor arc) to the station, while R2 propagates away from the source 180 degrees away from the direction of R1 and takes the longer path around the planet (or major arc). R3 follows the minor arc, but has an additional full circuit around the planet compared to R1. If we

68 assume a spherically symmetric model of velocity structure, because R3 and R1 differ
 69 only by the complete trip around the planet, we are able to determine the velocity of sur-
 70 face wave propagation and therefore also the epicentral distance and origin time with-
 71 out knowing the velocity in advance (Panning et al., 2015). A **simple** set of 3 equations
 72 determines the 3 unknowns as

$$U = \frac{2\pi}{t_{R3} - t_{R1}} \quad (1)$$

$$\Delta = \pi - \frac{1}{2}U(t_{R2} - t_{R1}) \quad (2)$$

$$t_0 = t_{R1} - \frac{\Delta}{U}, \quad (3)$$

73 where ~~R1, R2, and R3~~ t_{R1} , t_{R2} , and t_{R3} are the arrival times of the multi-orbit Rayleigh
 74 waves (~~note that the travel times are written in italics, while the waves themselves are written with~~
 75 ~~out italics~~), U is the great-circle average group velocity of the Rayleigh wave (in radians
 76 per second measured on the great circle), and Δ and t_0 are the epicentral distance and
 77 origin time of the event, respectively. In addition to epicentral distance and origin time,
 78 the full event location also requires an estimation of the backazimuth, and this can be
 79 obtained from the elliptical particle motion of the Rayleigh waves (see section 3).

80 In order for this method to be used, however, an event needs to be large enough
 81 so that R3 can be observed. On Earth, R3 can be reliably observed at quiet stations by
 82 M_W 5.5-6, but Panning et al. (2015) argued that with the smaller radius of Mars, R3 should
 83 be reliably observable around M_W 4.6 on Mars for a vertical instrument noise of 10^{-9} m/s²/Hz^{1/2}
 84 in the surface wave bandwidth. With the estimates of martian seismicity available at the
 85 time, 1-10 events of M_W 5.3 were predicted over the course of the mission, and so it was
 86 expected that this method could be applied to several of the largest events observed by
 87 InSight. In reality, both the daily wind-induced noise that is much larger than 10^{-9} m/s²/Hz^{1/2}
 88 (e.g. Lognonné et al., 2020) and a seismicity generating mostly $M_W < 4$ events (Gia-
 89 rdini et al., 2020; Clinton et al., 2020; Brinkman et al., 2021; Jacob et al., 2022; Ceylan
 90 et al., 2022) has made this method impossible ~~until~~ for events prior to S1222a. This was,
 91 therefore, the first event that exceeded the pre-mission estimated magnitude threshold,
 92 and it provides an excellent test case for the method at last.

93 2 Measuring multi-orbit Rayleigh wave arrival times

94 Panning et al. (2015) and Khan et al. (2016) proposed a straightforward approach
 95 to picking the ~~R1-R3~~ t_{R1} to t_{R3} arrival times and demonstrated it using terrestrial and
 96 synthetic Martian data (called Method 1 in following figures), respectively. As illustrated
 97 in Figure 1, a series of narrow-band filters of the data (InSight Mars SEIS Data Service,
 98 2019) are performed on center frequencies spaced in 15% intervals. For each center fre-
 99 quency, zero-phase (i.e. two pass) 2nd-order Butterworth bandpass filtering with ~~2 cor-~~
 100 ~~ners and a 30% width~~ a width of 30% of the central frequency was performed with Obspy
 101 software (Krischer et al., 2015), and then the envelope was calculated, and picks were
 102 made in frequency bands where a clear peak was observable. In the frequency band be-
 103 tween 0.01 and 0.1 Hz, where we looked for surface wave energy, the raw data shows ev-
 104 idence of many glitches common to InSight data (e.g. Scholz et al., 2020; Kim et al., 2021;
 105 Ceylan et al., 2021). In particular, a large glitch arrives ~~very~~ close to the R3 arrival time,
 106 and so all measurements are made on deglitched data. Deglitching of the event data was
 107 carried out in two steps. First, we appliedwith the UCLA method (with more recent mod-
 108 ifications; see supplementary material) described in Scholz et al. (2020) on raw 20 sam-
 109 ples per second velocity channels BHU, BHV, BHW with an additional step to iden-
 110 tify glitches hidden in the event coda that show up as steps in displacement. ~~To test~~
 111 ~~for false identifications and missing glitches, the second step involved integration of the deglitched~~
 112 ~~velocity data to displacement. Unlike the majority of the noise, glitches are primarily either positive~~
 113 ~~or negative velocity pulses. Upon integration remaining glitches, both spurious and missed ones, then~~

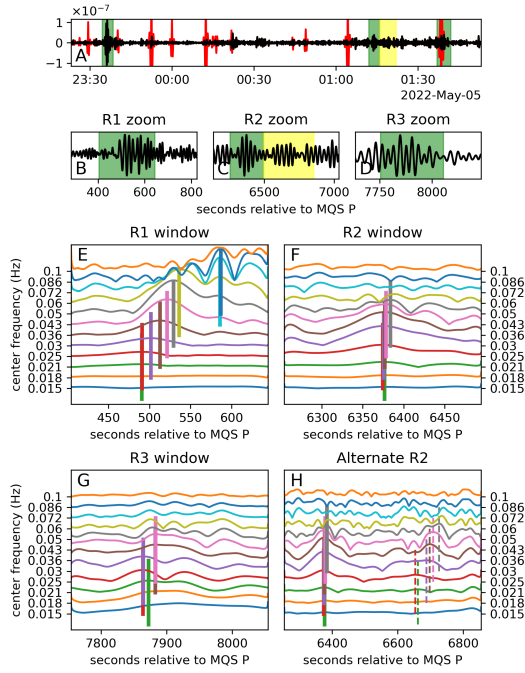


Figure 1. (A) 2.5 hours of raw (red) and deglitched (black) vertical component data starting with the MQS origin time of 23:23:06.57 UTC on May 4, 2022, bandpass filtered between 0.02 and 0.05 Hz. (B) Zoom into the R1 arrival window bandpass filtered between 0.02 and 0.09 Hz with the window for the [filter bankset of narrow-band filters](#) shown in panel D highlighted in green. (C and D) Zoom window showing R2 and R3 arrival times, respectively, filtered between 0.02 and 0.04 Hz. The green boxes highlight the windows for filter banks in panels F and G, while the yellow box indicates the additional R2 window considered in panel H. (E-H) Filter banks where the central frequency of each trace is shown on the left where all traces are band-passed within a window extending 30% from the central frequency. Picks for Method 1 are shown with vertical bars where the color indicates which frequency band the pick was made on. Dashed lines in (H) show the alternate R2 arrival time picks discussed in the text.

114 show up as sharp steps in the data. These were identified manually and removed by subtracting the
 115 corresponding glitch template. Several glitches were detected in the earthquake coda that were not
 116 detected in the higher frequency data, the coda amplitudes being so large (supplementary material)
 117 The glitch occurring at the time of R3 presented an initial difficulty in that the glitch template and
 118 the R3 signal are not orthogonal. Thus fitting the template and removing it runs the risk of removing
 119 some R3 signal. Ideally if a good synthetic were found a joint fit would be better. However with
 120 neither source nor path knowledge given the limitations of a one station recording this is not at this
 121 time practical.

122 Four different methods that differ primarily in the precise filter definition and pick-
 123 ing method are used for picking $R1-R3$ to be confident in the location determined,
 124 with Method 1 described above. Method 2 is a similar approach performed routinely by
 125 the Marsquake Service (MQS; Clinton et al., 2018) on half-octave wide frequency bands
 126 and uses the arrival times included in their standard catalog (InSight Marsquake Ser-

127 vice, 2022). Common picks for each of $R1-R3$ t_{R1} to t_{R3} are only possible ~~from 28 to 34~~
 128 ~~sfor periods between 28 and 34s~~. This method was tested and found to be effective in
 129 a pre-mission blind test (Clinton et al., 2017; van Driel et al., 2019). Method 3 is a mul-
 130 tiple filter technique implemented in the Computer Programs in Seismology (Herrmann,
 131 2013) to calculate the envelope energy on the vertical component of the seismogram, and
 132 the preferred arrival time corresponds to the maximum energy at different periods and
 133 time windows. For R1, picks are made for periods from 16.3 to 40.9 s, but picks for R1-
 134 R3 are only available for periods from 25.3 to 34.6 s. Method 4 derived arrival times at
 135 periods between 39 and 19s by applying the multiple filter technique (Dziewonski et al.,
 136 1969) in the implementation of Meier et al. (2004) to the vertical-component seismogram
 137 and, for each period, picking the amplitude maxima in time windows around the R1, R2
 138 and R3 phases.

139 While R1 shows clear dispersion, which can be used to model seismic structure along
 140 the minor arc as a function of depth, the picks for both R2 and R3 are visible over a much
 141 narrower frequency band, and show little or no dispersion. ~~Because of this lack of dis-~~
 142 ~~persion and the presence of other potential signals of similar amplitude near the pre-~~
 143 ~~ferred R2 observation, we also consider a second window for R2. An alternate possible set~~
 144 ~~of picks for R2 of a similar amplitude to the R2 we used, arriving~~The alternate R2 arrives roughly
 145 300 seconds later (Fig. 1G), ~~and~~ shows potential evidence of dispersion. However, this
 146 interpretation is not favored. The envelopes in this time window are complicated with
 147 multiple peaks, ~~and an R2 arriving that much later would suggest~~~~and this pick suggests~~ a lo-
 148 cation significantly closer (roughly 8 degrees) than that determined by MQS using the
 149 body wave timing (Kawamura et al., 2022). Additionally, the waveforms in different fre-
 150 quency bands do not show consistent elliptical polarization with no clear relationship to
 151 the backazimuth estimated from the MQS body wave polarization (Fig. 2D). For this
 152 reason, we use the R2 arrival times as shown in Fig. 1E.

153 Using the travel times estimated in narrow frequency band windows, we can use
 154 all frequency bands for which we can pick $R1-R3$ $t_{R1}-t_{R3}$ to estimate the epicentral dis-
 155 tance and origin time using equations 1-3. These results as well as the estimated great-
 156 circle average Rayleigh wave group velocity are shown for all four methods of picking group
 157 arrivals in Fig. 3. For each method, the standard deviation across the different frequency
 158 band estimates is shown ~~as 1 σ error bounds~~. The summary value is defined by the aver-
 159 age across the different picking methods and the standard deviation of those methods.
 160 For epicentral distance and origin time, these are compared with the MQS estimates from
 161 body wave observations shown with shading to indicate the 2σ uncertainty ~~bounds derived~~
 162 ~~from the best-fitting Gaussian to the non-Gaussian probability density function estimated with the~~
 163 ~~MQS approach~~~~defined by the MQS method, described in more detail in~~ Kawamura et
 164 al. (2022).

165 3 Rayleigh wave ellipticity and backazimuth estimation

166 In Panning et al. (2015), backazimuth estimation using Rayleigh wave energy on
 167 Earth events was performed using both a broadband window over all measured frequency
 168 bands, as well as averaging the narrow band backazimuth estimations with similar ac-
 169 curacy, although the broadband estimation showed slightly smaller mismatch across the
 170 events studied. For each prospective backazimuth in Fig. 2, we rotate a horizontal com-
 171 ponent such that motion along that backazimuth pointing towards the prospective source
 172 is positive. Correlation is calculated with the Hilbert transform of the vertical compo-
 173 nent, and should reach a maximum at the correct backazimuth. Note that this conven-
 174 tion for the horizontal component is the opposite of the radial component of the stan-
 175 dard seismological ZRT coordinate system which is defined positive in the direction from
 176 source to receiver, which would be negatively correlated with the Hilbert-transformed
 177 vertical component for standard retrograde elliptical Rayleigh wave particle motion. The
 178 narrowness of the correlation peak, however, was strongly dependent on the presence or

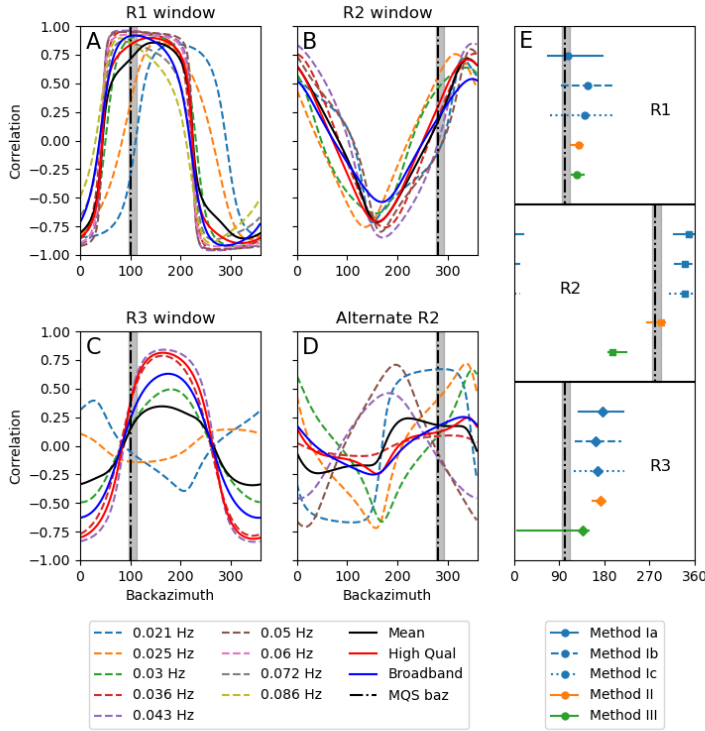


Figure 2. Backazimuth estimation for each Rayleigh wave arrival. For each backazimuth, correlation is calculated between the horizontal component positive in the direction of the proposed backazimuth and the Hilbert transform of the vertical component. Correlations are calculated on narrow band waveforms in time windows centered on the pick times shown in Fig. 1 with a width of 4 dominant periods. For the broadband waveforms, correlations are calculated over 200 second windows beginning at 450 seconds after the P arrival time for R1 (A), 6250 seconds for R2 (B), 7825 seconds for R2 (C), and 6550 seconds for the alternate R2 time (D). (E) Summary of backazimuth determined from R1, R2, and R3. Methods Ia-Ic are based on the results shown in panels (A)-(D) for the broadband, mean over the frequency bands, and average over the high quality measurements, respectively. Methods II and III are independent approaches described in the text. In all panels, the MQS backazimuth is shown with the dot-dash line with uncertainty shaded in gray.

179 absence of Love wave energy in the measurement window (Panning et al., 2015). While
 180 Love wave energy is seen for this event (Kawamura et al., 2022; Kim, Ceylan, et al., 2022;
 181 Li et al., 2022; Beghein et al., 2022), it arrives in a non-overlapping time window with
 182 the Rayleigh energy analyzed here, and so estimated correlation peaks are generally quite
 183 broad (Fig. 2). In Fig. 2E, we show three backazimuths from this correlation-based method
 184 (Methods Ia-Ic), which correspond to the correlation computed over broadband data,
 185 the average over all narrow-band data, and only over ‘high-quality’ data. Note that we
 186 number the different approaches to back-azimuth estimation with Roman numerals to
 187 differentiate from the different surface wave arrival estimations numbered with Arabic
 188 numerals. High-quality data excludes measurement windows which do not have clear peaks
 189 or have multiple peaks of similar amplitude in the enveloped data (see table in supple-
 190 mentary material for specific frequencies identified as lower quality). In each case, the
 191 range of possible backazimuths shown in the figure Fig. 2 represent the range with cor-
 192 relation above 80% of the maximum value. We also show estimates for two additional
 193 methods. Method II is based on the maximization of the ground-motion amplitudes on
 194 the Z and R components around the arrival time of the Rayleigh waves for different fre-
 195 quencies. The preferred back-azimuths are derived from the maximum of the Z*R/T co-
 196 efficient, which is computed from seismogram envelopes. This method has a 180 deg un-
 197 certainty, which is resolved by assessing the phase shift between the Z and R components,
 198 obtained from their maximum cross-correlation. The definitive back-azimuth of each Rayleigh
 199 wave is the median obtained from the frequencies for which Rayleigh energy is observed
 200 and for which mainly retrograde motion is determined (phase shift > 0). See Carrasco
 201 et al. (2022) for details. Method III uses several independent approaches to obtain frequency-
 202 dependent polarization and backazimuth estimates of surface wave arrivals. This method
 203 has been previously implemented to extract seismic signals that are strongly elliptically
 204 polarized and traveling along the great circle path, leading to the first detection of Rayleigh
 205 waves on Mars (Kim, Banerdt, et al., 2022). See Kim, Ceylan, et al. (2022) for details.

206 The broadband estimation of the correlation for R1 (Method Ia), as well as Meth-
 207 ods II and III peak very close to the MQS backazimuth determined using body waves (solid
 208 blue line in Fig. 2A), but the averages over the narrowband estimates (Methods Ib and
 209 Ic) have a very broad peak that reach a maximum value 30-40 degrees to the south of
 210 the MQS estimate. With the much lower signal to noise ratio (SNR) for R2, the back-
 211 azimuths are more variable between methods with Methods Ia-Ic shifted significantly to
 212 the north, while Method III is shifted to the west, but the methods do bracket the pre-
 213 dicted azimuth from the MQS body wave event azimuth. On the other hand, the poten-
 214 tial alternate R2 time, which shows a little more dispersion more apparent dispersion than
 215 the preferred R2 arrival, does not show strong correlation peaks indicating elliptical
 216 particle motion, and the weak peaks that are observed show no consistency between dif-
 217 ferent frequency bands. This strongly supports that this window does not contain the
 218 major R2 energy, and thus should not be used for location or structure estimation. Fi-
 219 nally, the R3 backazimuth estimates are shifted to the south for all five methods con-
 220 sidered, but signal-to-noise ratio SNR is fairly low for this observation, and the fact that
 221 elliptical motion does seem to be resolved in all methods at least gives credence to in-
 222 terpreting this arrival as R3. It is, however, important to note that this event S1222a oc-
 223 curs during the noisy season on Mars, and therefore the signal-to-noise ratio SNR for R2
 224 and R3 are low. Both ellipticity and backazimuth estimations are more challenging and
 225 can be biased in this situation as wind effects can mimic the elliptical motion of Rayleigh
 226 waves or even generate surface waves at different azimuths (e.g. Stutzmann et al., 2021),
 227 and this. This may contribute to both the offset of these backazimuth estimates from the
 228 MQS backazimuth as well as the scatter between the different methods.

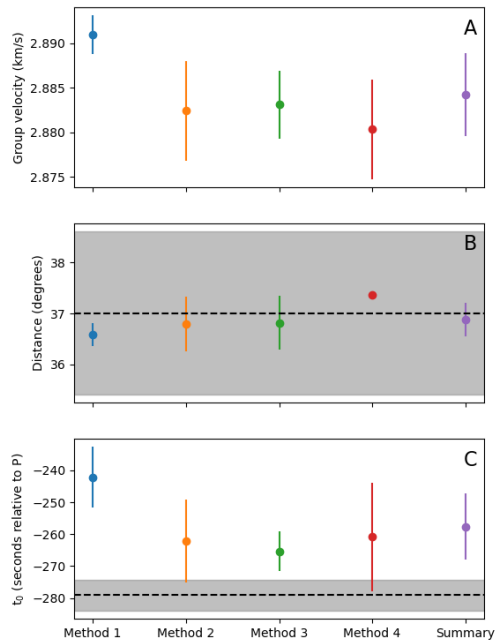


Figure 3. For each of the four methods employed, the average value and standard deviation across the individual narrow band frequencies measured is shown for the group velocity (A), epicentral distance (B), and origin time (C) calculated from equations 1-3. Dashed black lines represent the MQS estimated epicentral distance and origin time (Kawamura et al., 2022), while the grey shaded box represents the 2σ error bounds estimated based on the best-fitting Gaussian to the non-Gaussian uncertainties estimated by the MQS location procedure from Kawamura et al. (2022).

4 Results

The epicentral distance determined for all the sets of surface wave arrival times is 36.9° with a standard deviation of 0.3° . Note that this standard deviation represents only the variation of distance estimates based on different surface wave measurement approaches, and likely underestimates the total uncertainty in distance which should also include additional uncertainty due to 3D variation in seismic velocity, or possible biases in the measured surface wave arrival times due to effects such as interference with removed glitches. This estimate is in good agreement with the body-wave based MQS value. All surface wave estimates but one are within the 2-sigma uncertainty bounds obtained by the MQS ($37^\circ \pm 1.6^\circ$) (Kawamura et al., 2022), while the MQS estimate agrees within one standard deviation with the mean surface wave epicentral distance calculated across different methods.

The backazimuth estimated from the R1 broadband measurement of 108° is consistent with the MQS backazimuth uncertainty bounds ($96^\circ - 112^\circ$). When taking into account the full location obtained using the surface wave based distance estimate and the backazimuth determined from the R1 broadband measurement, the surface wave epicentral location agrees with the MQS estimate within a degree which is well within the 2-sigma uncertainty bounds. However, if the average over the high quality narrow band estimates is used instead (which provided similar accuracy for the Earth data analyzed in Panning et al. (2015)), the 32 degree mismatch in backazimuth calculation (108 for the broadband vs. 140 for the average over high quality narrow band estimates) leads to an absolute location mismatch of 18.5 degrees outside the 2-sigma uncertainty bounds of the MQS estimate, which is unsurprising as 140 degrees is outside the 2-sigma error bounds of the MQS backazimuth value (109 ± 14.9 degrees) is outside the uncertainty bounds estimated by the MQS. When combining the distance and backazimuth estimates, the location using the broadband backazimuth estimate is offset from the nominal MQS location by $\sim 4^\circ$ (Fig. 4, magenta diamond), while backazimuth based on the average across measurements leads to location that differs from the nominal MQS location by $\sim 23^\circ$ (Fig. 4, cyan diamond) which is well outside the estimated uncertainty of the MQS location (blue dot and ellipse in Fig. 4).

The origin time determination for all surface wave methods is roughly 20 seconds later than the MQS origin time estimate. Some possible explanations for the mismatch between estimated origin time are considered in the Discussion section. An offset of origin time of 20 seconds is also quite consistent with the range of offsets observed for Earth events located with this method by Panning et al. (2015) which were generally offset from catalog origin times within ± 30 s. Additionally, that study showed that origin time offsets compared with catalog origin time often significantly exceeded the standard deviation of origin time estimates across different frequency bands, so the lack of overlap of the standard deviations in Fig. 3C with the MQS t_0 should not be surprising.

5 Discussion

The results show very close agreement in distance estimation between the MQS body wave determination and that derived from the multi-orbit surface waves, which do not depend at all on a priori velocity models, beyond the assumption of spherical symmetry. This provides important validation of the MQS method that has been utilized for many events now and performed quite well. The MQS body wave method's success includes accurately providing location estimates for impacts within 300 km of the lander in order to target HiRISE images showing new craters (Garcia et al., 2022) as well as larger, more distant impacts with craters detected by the CTX camera aboard MRO (Posiolova et al., 2022). However, the difficulty in matching backazimuth between P- and surface waves shows that the latter may be affected by off-great-circle propagation due to three-dimensional (3D) structure, particularly as this path does cross the dichotomy

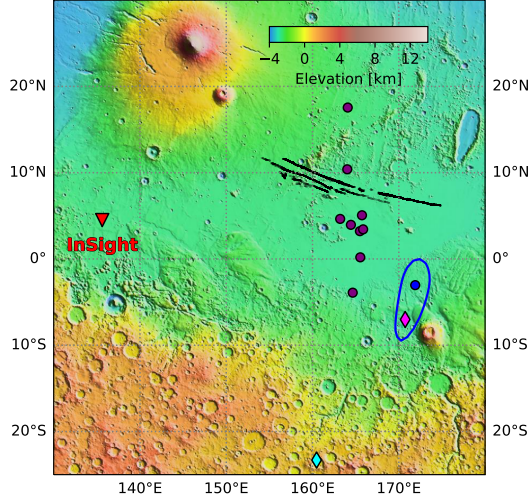


Figure 4. Estimated locations of S1222a from MQS (Kawamura et al., 2022, blue circle with uncertainty shown with blue ellipse), based on the multi-orbit distance estimation and the backazimuth estimated from the broadband polarization of R1 (magenta diamond), and based on the backazimuth estimated from the average of the correlation functions across the high-quality narrow band frequency estimates (cyan diamond). Purple dots show other events located by MQS. Figure is adapted from Kawamura et al. (2022).

280 between the northern and southern hemispheres of Mars at a relatively shallow angle.
 281 R2 and R3 backazimuths also show apparent offsets from the MQS backazimuth, but
 282 these are in general much more poorly resolved due to lower SNR (e.g. Kim, Ceylan, et
 283 al., 2022). The t_0 mismatch may also be related to 3D structure. For example if the R1
 284 path were a little slower than the great-circle average group velocity, one might expect
 285 that the R1 would arrive a little late, and thus a t_0 estimated from equation 3, would
 286 be correspondingly late. ~~Given that R1 only runs over 10% of the circumference of the planet,~~
 287 ~~it is plausible that its group velocity is least representative of the global average.~~ If we look at
 288 measured arrival times near 0.03Hz, and we assume the MQS location and origin time
 289 is correct and all surface wave propagation is along the great circle path, the velocity
 290 of R2 is $\sim 0.7\%$ faster than R1. However, the great-circle average velocity calculated as
 291 the path-length weighted average of the R1 and R2 velocities is $\sim 0.4\%$ slower than the
 292 great-circle averaged velocity computed from the difference between t_{R3} and t_{R1} , sug-
 293 gesting that we cannot simply explain the difference between estimated origin times
 294 through assuming the MQS origin time is correct and all differences in the surface
 295 wave estimation is due to different minor arc and major arc velocity. Likely the true
 296 explanation relates to some combination of differences in minor and major arc velocity,
 297 offsets in true distance and origin time within the uncertainties of the MQS estimates,
 298 and possible small biases in the estimates of $t_{R3}-t_{R1}$, as may happen due to interfer-
 299 ence from glitches or other causes. ~~However, in order to match the great-circle average velocity,~~
 300 ~~the R2 path would need to be faster, and therefore we would expect R2 to arrive a little earlier than~~
 301 ~~predicted from the MQS location. It actually also arrives later than predicted from the MQS origin~~
 302 ~~time and the great-circle average velocity, though, although perhaps the off-great-circle propagation~~
 303 ~~possibly suggested by the azimuth estimations along both arcs could contribute to the late arrivals.~~
 304 ~~This means that shifting the picks of R2, where there are some arrivals of similar amplitude before~~
 305 ~~or after the picks we went with in this study cannot resolve the offset between MQS origin time, and~~
 306 ~~that estimated from surface waves.~~

6 Conclusion

Consistent with pre-mission expectations on observability of surface waves circling Mars, the $M_W 4.7$ S1222a marsquake was large enough to make observations of multiple-orbit Rayleigh waves. These were used to apply a location method that does not depend on *a priori* velocity structure, and the recovered distance [and broadband backazimuth estimate](#) agree well with the standard MQS body-wave based approach, providing additional verification of the location approach used for the bulk of events observed in the InSight mission.

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Open Research

All raw waveform data is available through the InSight Mars SEIS Data Service @ IGP, IRIS-DMC and NASA PDS. (InSight Mars SEIS Data Service, 2019). All processed data and processing codes used in this study are available through https://github.com/mpanning/R1R2R3_data_codes (doi to be provided before manuscript is finalized).

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