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Special Section:

The Large Marsquake of Sol 1222

Seismic Scattering and Absorption Properties of Mars Estimated Through Coda Analysis on a Long-Period Surface Wave of S1222a Marsquake

Keisuke Onodera¹ , Takuto Maeda² , Kiwamu Nishida¹ , Taichi Kawamura³ , Ludovic Margerin⁴, Sabrina Menina³ , Philippe Lognonné³ , and William Bruce Banerdt⁵ 

Key Points:

- We modeled the scattering effect of the largest marsquake (S1222a) using radiative transfer theory on a spherical Mars
- The inversion revealed that the intrinsic and scattering quality factors below 0.1 Hz are 1,000–1,500 and 30–500, respectively
- We summarized the Martian quality factors derived so far and found that they are relatively Earth-like rather than Moon-like

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract On 4 May 2022, the seismometer on Mars observed the largest marsquake (S1222a) during its operation. One of the most specific features of S1222a is the long event duration lasting more than 8 hr, in addition to the clear appearance of body and surface waves. As demonstrated on Earth, by modeling a long-lasting and scattered surface wave with the radiative transfer theory under the isotropic scattering condition, we estimated the scattering and intrinsic quality factors of Mars (Q_s and Q_i). This study especially focused on the frequency range between 0.05–0.09 Hz, where Q_s and Q_i have not been constrained yet. Our results revealed that $Q_i = 1,000$ – $1,500$ and $Q_s = 30$ – 500 . By summarizing the Martian Q_i and Q_s estimated so far and by comparing them with those of other celestial bodies, we found that, overall, the Martian scattering and absorption properties showed Earth-like values.

Plain Language Summary Since February 2019, NASA's InSight (Interior Exploration using Seismic Investigations, Geodesy, and Heat Transport) has been conducting quasi-continuous seismic observation for more than three years. The seismic data from Mars has contributed significantly to a better understanding of the interior structure and the seismicity of the red planet. On 4 May 2022 (1222 Martian days after landing), another key event occurred, called S1222a. The event showed the largest seismic moment release (magnitude 4.7) and extremely long duration (>8 hr) with intense seismic scattering. As demonstrated on Earth, the long-lasting scattered waves are useful for retrieving information about the structural heterogeneity within a planet. In this study, by applying the radiative transfer theory—which considers the energy transportation from the seismic source to the observation point—to Mars, we evaluated the energy decay rate due to seismic scattering and energy absorption by a medium. By comparing our results with those of other solid bodies, we found that the Martian scattering and absorption features were closer to the terrestrial ones than to the lunar ones.

1. Introduction

After almost three years of seismic observations on Mars, the seismometer installed by Interior Exploration using Seismic Investigations, Geodesy, and Heat Transport (InSight) detected a magnitude 4.7 class event on Sol 1222 (1222 Martian days after landing) labeled as S1222a (Kawamura et al., 2022).

InSight deployed two types of seismometers: the very broadband seismometer (VBB) covering from a 0.01–10 Hz frequency band, and the Short-Period seismometer (SP) covering from 1–50 Hz (e.g., Lognonné et al., 2019). Quasi-continuous observations since 2019 brought us new insights into the Martian seismicity and internal structure (e.g., Banerdt et al., 2020; Giardini et al., 2020; Khan et al., 2021; Knapmeyer-Endrun et al., 2021; Lognonné et al., 2020; Stähler et al., 2021).

As described by Kawamura et al. (2022), only VBB was operated on Sol 1222 due to the severe power supply conditions. This event is only available for VBB (the channel names are XB.ELYSE.02.[BHU, BHV, and BHW], for instance). The remarkable characteristics of S1222a are, in addition to clear P- and S-wave arrivals, the excitation of both Rayleigh and Love waves, which are rarely observed in other marsquakes (Kawamura et al., 2022; Kim et al., 2022). Figures 1a–1c show the spectrogram, the mean squared envelope (MS envelope), and the

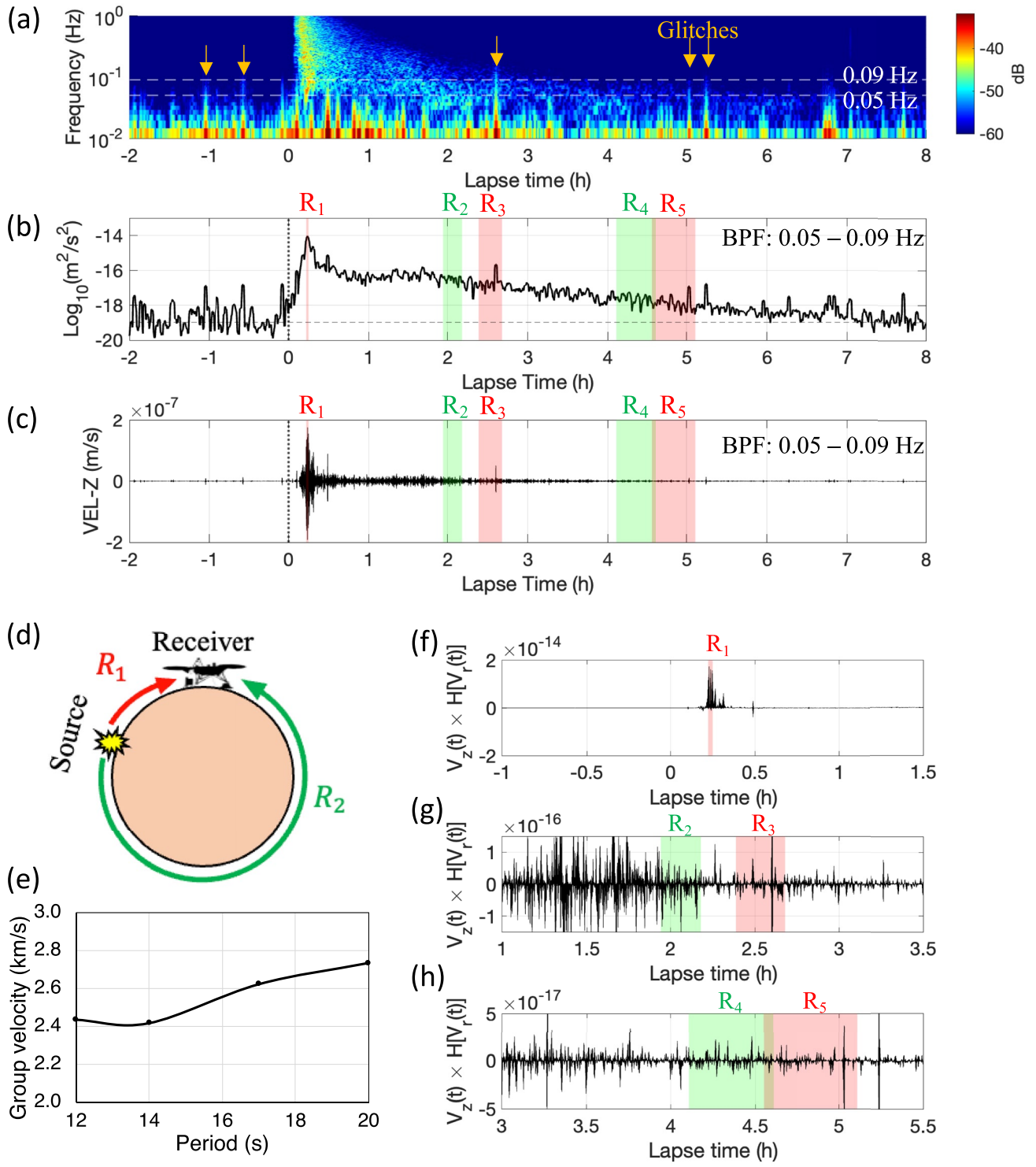


Figure 1.

waveform filtered at 0.05–0.09 Hz of the time series of S1222a, respectively. Interestingly, the low-frequency energy lasts approximately 8 hr from the arrival (e.g., Figure 1b). The gradual decrease from the energy peak is called the coda. In terrestrial seismology, it is known that the coda waves are generated due to the heterogeneous structures within a planet (e.g., Aki, 1969; Aki & Chouet, 1975).

In this study, to constrain the scattering and attenuation properties of the Martian lithosphere, we focus on the decay coda part at a frequency of 0.05–0.09 Hz, where Rayleigh wave is strongly excited, and the contamination of glitches is smaller than that of lower frequencies (<0.05 Hz). As these parameters have been poorly constrained at that frequency, our study fills the missing piece regarding the heterogeneous structures of Mars.

In the following, we will review the Rayleigh wave features of S1222a, introduce how to retrieve the scattering and attenuation parameters from the decay coda, and then show the inversion results. Finally, we compare the intrinsic and scattering attenuation properties between the Earth, the Moon, and Mars.

2. The Observed Rayleigh Wave and Its Multi-Orbital Phases

In Figures 1b and 1c, the left-most red-filled area shows the Rayleigh wave arrival (R_1), identified by Kawamura et al. (2022). The green and red-filled areas show the expected arrival times of Rayleigh wave traveling along the major arc (R_2) and the multi-orbital phases (R_3 , R_4 , and R_5). See Figures 1d and 1e and the caption for the description of the multi-orbital phases and their group velocity. At first glance, the phases following R_1 are not clearly seen in our target frequency range. To confirm whether such phases are present in the data, we performed a simple demonstration as described below.

If the Rayleigh wave component is excited, there must be a $\pi/2$ phase shift between the vertical and radial seismic records. In other words, the multiplication of the vertical ground velocity $V_z(t)$ and the Hilbert-transformed radial velocity $\mathcal{H}[V_r(t)]$ should return the one-sided signal during the arrival of the Rayleigh wave components (e.g., the positive signal for R_1 , R_3 , R_5 and the negative signal for R_2 and R_4). Figure 1f shows an example of Rayleigh wave detection. Around 0.2 hr lapse time (R_1 arrival), the positive one-sided signal lasts for approximately 10 min, indicating that the Rayleigh wave component arrives during this period. On the other hand, looking at Figures 1g and 1h, it is difficult to find Rayleigh wave-related phases because of the low signal-to-noise ratio. In other words, the scattering effect seems strong enough to attenuate both R_2 and the multi-orbital phases to the level of other incoherent signals, at least in our target frequency range (0.05–0.09 Hz).

3. Radiative Transfer Modeling on a Spherical Mars

In terrestrial seismology, the radiative transfer theory has been used to investigate the heterogeneous structures (e.g., Aki & Chouet, 1975; Sato, 1977; Wu, 1985). Recently, Menina et al. (2021) and Karakostas et al. (2021) applied this approach to Mars and estimated the scattering and attenuation properties. To further advance our understanding of this topic, we will investigate the scattering and attenuation properties at a lower frequency (<0.1 Hz) than before, utilizing the scattering features observed in S1222a.

In the following analysis, we consider a sphere with a Martian radius $R = 3,389.5$ km on the spherical coordinate system, where the seismic source (S1222a) and a receiver (InSight SEIS) are located on (3.0°S, 171.9°E) and (4.502°N, 135.623°E), respectively (Golombek et al., 2020; Kawamura et al., 2022). From a source to receiver, the distance along the minor arc θ and the forward azimuth ϕ are measured as shown in Figure 2a. According to Kawamura et al. (2022), $\theta = 37 \pm 1.6^\circ$ (~2,200 km) and $\phi = 281^\circ \pm 11^\circ$. The last scattering point—where the seismic wave radiated from the source encounters before the arrival at the receiver—is apart from the source with the distance and the forward azimuth being θ' and ϕ' . Under this geometry setting, let us consider the energy density of the fundamental-mode Rayleigh wave for (a) the direct wave component, (b) the single-scattered component, and (c) the multiple-scattered component to model the observed MS envelope. Here, we assumed the isotropic scattering considering past studies on terrestrial and lunar scattering (e.g., Onodera et al., 2022; Sato & Nohechi, 2001) and also the results for Martian coda analysis (Menina et al., 2021).

Figure 1. (a) Spectrogram of the very broadband seismometer vertical component. The horizontal axis represents the lapse time in hours from the origin time, and the vertical axis shows frequency. The orange arrows show the representative glitches seen in this time period. (b) Mean squared (MS) envelope at the low-frequency band. The deglitched waveform data (see the text) was bandpass filtered between 0.05 and 0.09 Hz, and the squared time series were smoothed with a time window of 100 s with 50% overlap. The red line tagged R_1 shows the R_1 arrival read by Kawamura et al. (2022). The red and green filled areas show the expected arrival times of the multi-orbital phases (R_2 , R_3 , ...) computed based on the group velocity shown in (e). The horizontal broken line shows the noise level estimated with the median value before the origin time, which is consistent with the representative noise level for this period of the sol (Figure S1 in Supporting Information S1). (c) The vertical-component waveform filtered between 0.05 and 0.09 Hz. The vertical lines and filled areas are the same as in (b). (d) Schematic diagram of Rayleigh wave propagation on a spherical Mars. R_1 refers to the Rayleigh wave propagating along the minor arc, and R_2 refers to that traveling along the major arc. The subscript number increases by two as the Rayleigh wave goes around Mars (i.e., R_3 , R_5 , ... for minor arc direction). (e) The group velocity dispersion curve as a function of period, computed based on the source and time information by Kawamura et al. (2022). (f–h) Time series of $V_z(t) \times \mathcal{H}[V_r(t)]$ at 0.05–0.09 Hz band for the time window of –1–1.5, 1–3.5, and 3–5.5 hr lapse time, respectively. The red and green areas show the expected arrival times of Rayleigh wave components as in (b) and (c).

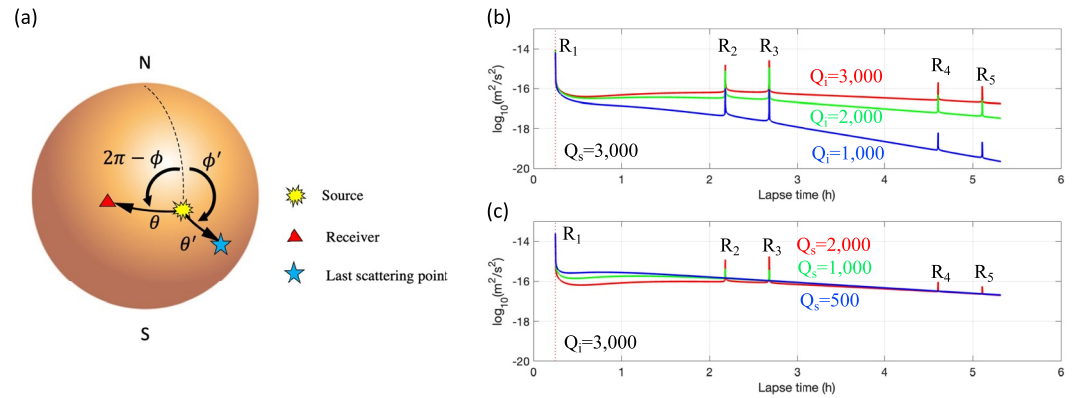


Figure 2. (a) Geometry of a source, receiver, and the last scattering point on a spherical body. (b) Comparison of theoretical MS envelopes for the different intrinsic quality factors ($Q_i = 1,000, 2,000,$ and $3,000$) with Q_s fixed to $3,000$. (c) Comparison of theoretical mean squared envelopes for the different scattering quality factors ($Q_s = 500, 1,000,$ and $2,000$) with Q_i fixed to $3,000$.

Following Sato and Nohechi (2001), the energy density of Rayleigh waves propagating along the minor and major arcs on a spherical planet can be written as:

$$E^0(\theta, \phi, t) = \frac{W\Phi(\phi)}{2\pi R^2 \sin \theta} \sum_{n=0}^{\infty} \left[\delta\left(\frac{Vt}{R} - \theta - 2\pi n\right) + \delta\left(\frac{Vt}{R} + \theta - 2\pi(n+1)\right) \right], \quad (1)$$

where t is the time, W is the scaled energy factor, V is the group velocity, and δ is the delta function. Φ denotes the radiation pattern of the source. Because of the large uncertainty in the focal mechanism with a single-spot observation, we assumed the isotropic radiation for Φ as:

$$\Phi = \frac{1}{2\pi}. \quad (2)$$

Normalizing the energy density with $W/4\pi R^2$ and introducing the intrinsic and scattering attenuation factors yields the scaled energy density of the direct wave component ϵ^0 :

$$\epsilon^0(\theta, t; \omega) = \frac{2\Phi}{\sin \theta} \sum_{n=0}^{\infty} \left[\delta\left(\frac{Vt}{R} - \theta - 2\pi n\right) + \delta\left(\frac{Vt}{R} + \theta - 2\pi(n+1)\right) \right] e^{-(Q_s^{-1} + Q_i^{-1})\omega t}, \quad (3)$$

where ω is the angular frequency, and Q_s and Q_i are the scattering and intrinsic attenuation factors, respectively.

As demonstrated for earthquakes (Maeda et al., 2006; Sato & Nishino, 2002; Sato & Nohechi, 2001), the energy density of single-scattered Rayleigh wave ϵ^S can be expressed as:

$$\epsilon^S(\theta, \phi, t; \omega) = \frac{\omega R}{\pi V Q_s} e^{-(Q_s^{-1} + Q_i^{-1})\omega t} \int_0^{2\pi} d\phi' \frac{\Phi n_s(\theta, t)}{\sqrt{(\sin \tau - \sin \theta \cos(\phi - \phi'))^2 + (\cos \theta - \cos \tau)^2}}, \quad (4)$$

where $\tau = Vt/R$, and the multiple orbit factor n_s is given by:

$$n_s(\theta, t) = \begin{cases} 0 & (\tau < \theta), \\ 1 & (\theta < \tau < 2\pi - \theta), \\ 2 & (2\pi - \theta < \tau < 2\pi + \theta), \\ 3 & (2\pi + \theta < \tau < 4\pi - \theta), \\ 4 & (4\pi - \theta < \tau < 4\pi + \theta), \\ \dots & \end{cases} \quad (5)$$

To calculate the multiple scattering term, we use the asymptotic form, which has been validated as a good approximation for earthquakes (Sato & Nishino, 2002). The energy density of the multiple scattering term e^M can be written as:

$$e^M(t; \omega) = \left(1 - e^{-\frac{\omega t}{Q_s}} - \frac{\omega t}{Q_s} e^{-\frac{\omega t}{Q_s}} \right) e^{-\frac{\omega t}{Q_i}}. \quad (6)$$

By combining all three terms above, we can theoretically draw the MS envelopes as follows:

$$E(\theta, \phi, t; \omega) = \frac{W}{4\pi R^2} [e^0(\theta, t; \omega) + e^S(\theta, \phi, t; \omega) + e^M(t; \omega)]. \quad (7)$$

Because the scaled energy factor W is unknown, we first focus on the relative decay trend of the MS envelope that allows us to constrain the Q values more easily (especially Q_i) and then estimate W using the preferable quality factors (See Sections 5 and 6).

To clarify how Q_i and Q_s affect the envelope shape, Figures 2b and 2c show examples of the theoretical envelopes. Q_i mostly controls the energy decay rate, and Q_s determines the peak intensity of Rayleigh waves.

4. Target Frequencies and Data Processing

We focus on the frequency range below 0.1 Hz, where the scattering and intrinsic quality factors have not been constrained yet. Especially we processed the data at the four frequencies: 1/12, 1/14, 1/17, and 1/20 Hz.

To reduce the contamination by glitches, we used the data denoised with the method proposed by Scholz et al. (2020). For preprocessing, we performed (a) detrending and demeaning, (b) applying pre-filtering between 0.005 and 9.5 Hz, and (c) correcting the instrumental response to convert the raw data into particle velocity. Then, the time trace was bandpass filtered using the fourth order Butterworth filter with the corner frequencies of $0.9f_c$ and $1.1f_c$, where f_c is the center frequency (1/12, 1/14, 1/17, and 1/20 Hz). As we focus on Rayleigh wave and stand on the approach by Sato and Nishino (2002), we used the vertical component of VBB in the analysis.

5. Inversion With Grid Search Method

In the inversion process, we used the MS envelope normalized with an average value between 1.5 and 4.5 hr lapse time for the respective frequency bands. In other words, we modeled the relative decay trend to obtain the scattering and intrinsic quality factors.

A grid search concerning the scattering quality factor Q_s and the intrinsic quality factor Q_i was conducted. We varied the Q_s and Q_i in a range of 200–4,000 and 500–5,000, respectively. The parameter ranges were equally divided into 20 on a log scale. The goodness of fit was evaluated with the summation of squared residual value σ , as follows:

$$\sigma_{j,k}(f_c) = \sum_{t_{\min}}^{t_{\max}} \left[\log_{10} \left(\frac{S^{\text{obs}}(t; f_c)}{S^{\text{trf}}(t; f_c)} \right) \right]^2, \quad (8)$$

where t_{\min} (= 1.5 hr) and t_{\max} (= 4.5 hr) define the time window for the fitting, S^{obs} and S^{trf} are the MS envelopes for the observation and the theoretical curve (scaled with the average value in the time window). The subscripts j and k in Equation 8 are for the varied Q_i and Q_s parameters. When $j = 1$ and $k = 1$, $Q_i = 500$ and $Q_s = 200$.

6. Estimated Intrinsic and Scattering Quality Factors and Scaled Energy Factor

Figure 3a presents the inversion results for the respective frequencies. The color map indicates the distribution of the residual values in the Q_i - Q_s parameter space. Figure 3b displays the best-fitted curves for each frequency band (all calculated curves can be found in Figure S2 in Supporting Information S1). Looking at the residual map, Q_i is well constrained, whereas any Q_s can provide good fits as long as Q_i is in the range of 1,000–1,500. As demonstrated in Figures 2b and 2c, Q_i mostly controls the gradient of the decay coda, whereas Q_s affects the peak intensity of Rayleigh wave and its multi-orbital phases. Thus, it is reasonable that Q_i is more easily constrained than Q_s .

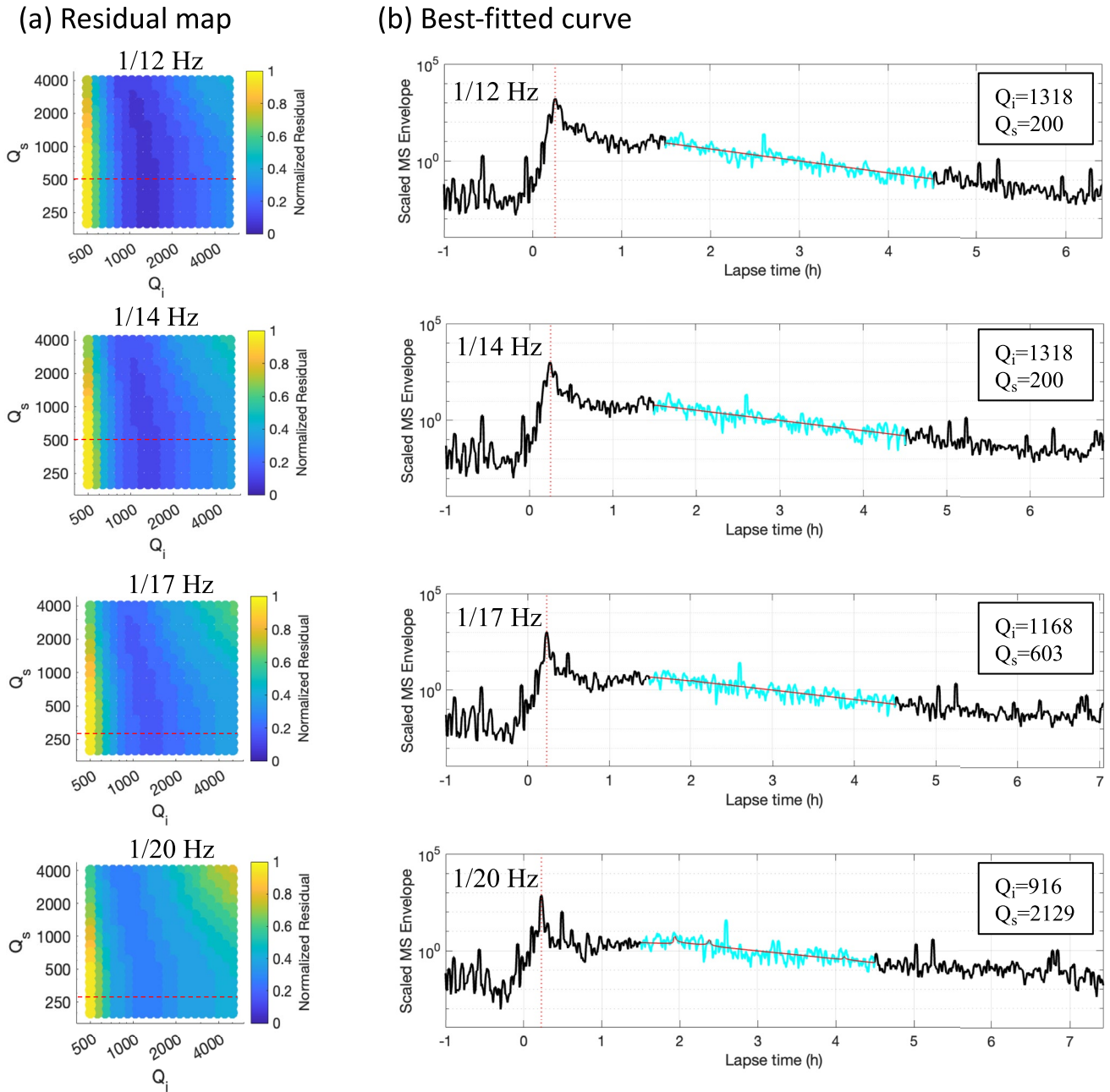


Figure 3. (a) Grid search results for the respective frequency bands. The horizontal axis shows the intrinsic Q_i and the vertical axis shows the scattering Q_s . The color map represents the summation of the squared residual (Equation 8), which is normalized with the maximum value. The red dashed line shows the upper limit of the scattering Q (See the text for the details). (b) The best-fitted curves superposed on the observations. For the fitting, the cyan profiles (1.5–4.5 hr window) were used out of the entire mean squared envelopes. The amplitude is normalized with the average value within the time window of 1.5–4.5 hr. The red profiles show the best-fitted curves. Note that the theoretical curves in red were move averaged in the same way as the observation in black.

To better constrain Q_s , we performed an additional analysis considering that R_2 and the multi-orbital phases were attenuated and could not be confirmed within our target frequency range (Section 2). Figure 4 shows the examples of parameter studies on Q_s with Q_i fixed to the best-fitted value in the previous inversion. In Figures 4a and 4b, comparing the first and the second rows gives us the upper limit of Q_s , which provides the smallest scattering intensity to hide the peaks of R_2 and the multi-orbital phases under the multiple scattering effects. In turn, Figures 4c and 4d provide us with the lower limit of Q_s , which is the smallest scattering intensity to diffuse the

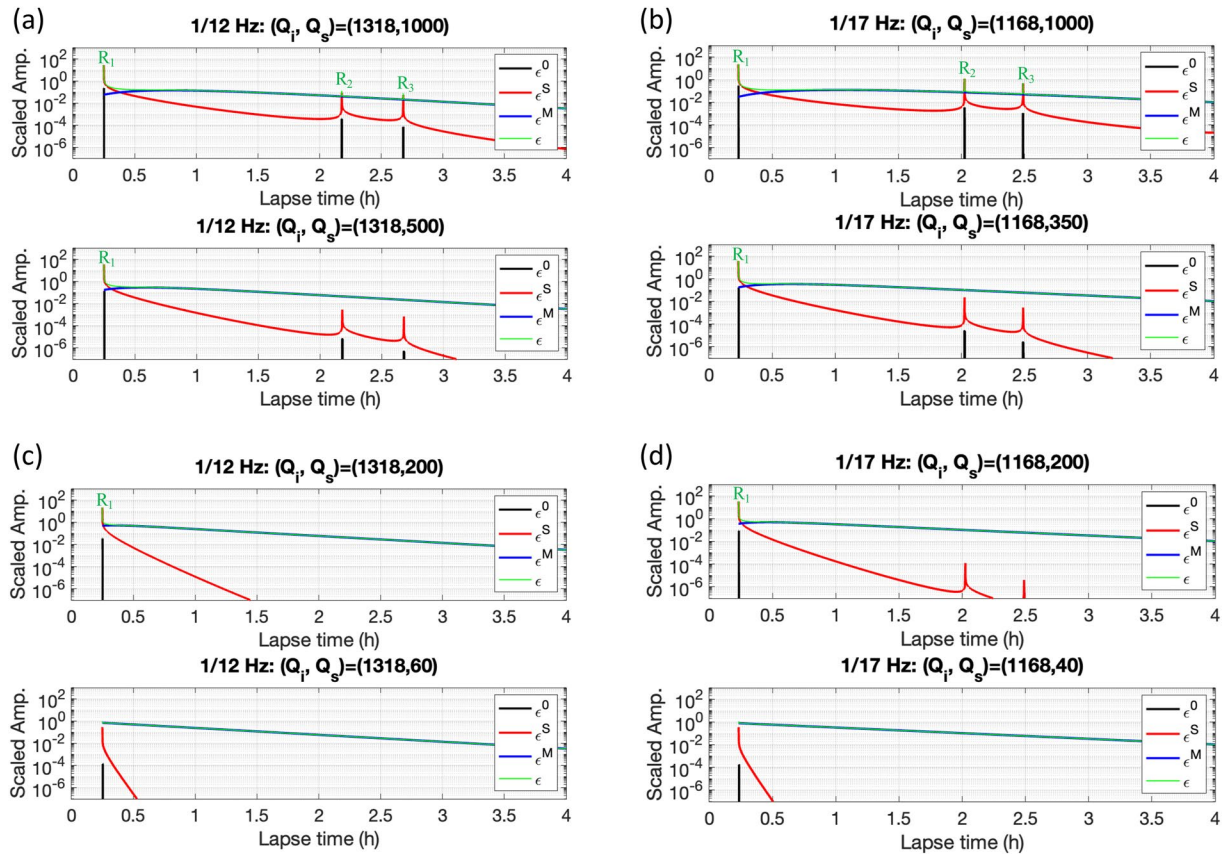


Figure 4. (a and b) Examples of parameter study results for estimating the upper limit of Q_s at 1/12 and 1/17 Hz. The black lines are the direct wave component, the red profile is the single-scattered component, the blue is the multiple-scattered component, and the green is the convolved profile. The first row is for $Q_s = 1,000$, where the multi-orbital phases can be seen. The second row is the case for the upper limit of Q_s , where the contribution of the multiple scattering is strong enough to bury R_2 and the multi-orbital phases. (c and d) Examples of parameter study results for estimating the lower limit of Q_s at 1/12 Hz and 1/17 Hz. The first row is for $Q_s = 200$, where the R_1 phase can be confirmed. The second row is the case for the lower limit of Q_s , where the contribution of the multiple scattering is strong enough to bury the R_1 phase.

R_1 peak completely. Consequently, we found that Q_s ranged from 60 to 500 for 1/12 and 1/14 Hz and from 30 to 350 for 1/17 and 1/20 Hz, respectively (Figure 4 and Figure S3 in Supporting Information S1). It appears that Q_s depends on the frequency. However, this cannot be concluded because both Q_s -ranges return similar residual values. Therefore, we conclude that the plausible Q_s range is 30–500.

Together with the estimated Q_i and Q_s , we evaluated the scaled energy factor W . As shown in Figure S4, we calculated the summation of residual for each frequency band in the same manner as in Equation 8 and found a preferable W value of $(8.5 \pm 1.5) \times 10^{-9} \text{ (m/s)}^2 \cdot \text{km}^2$. Overall, the observation obeys the synthetics. Yet, we found a convex feature (or energy excess) at around 1.5–1.6 hr (Figure 1b or Figure S4b in Supporting Information S1). We suppose this is associated with the arrival of R_1 overtone, which is not considered in our current model. Based on the arrival information of R_{1-1} (the first overtone of R_1 traveling along the minor arc) described by Kawamura et al. (2022), we computed the group velocity of R_{1-1} (3.3–3.5 km/s at 1/12–1/14 Hz) and found that the convex coincides with the arrival of R_{1-2} (the first overtone of R_1 traveling along the major arc) (1.5–1.6 hr). Thus, introducing the overtones in our model might give us a better fit to the observed MS envelope, which will be addressed in future studies.

7. Intrinsic and Scattering Quality Factors of the Earth, the Moon, and Mars

In this section, to compare the scattering and attenuation properties with the same criteria between the Earth, the Moon, and Mars, we review Q_i and Q_s derived thus far on each body. Because of a large uncertainty in the depth and thickness of the Martian scattering layer, a detailed discussion of the structures cannot be put forward.

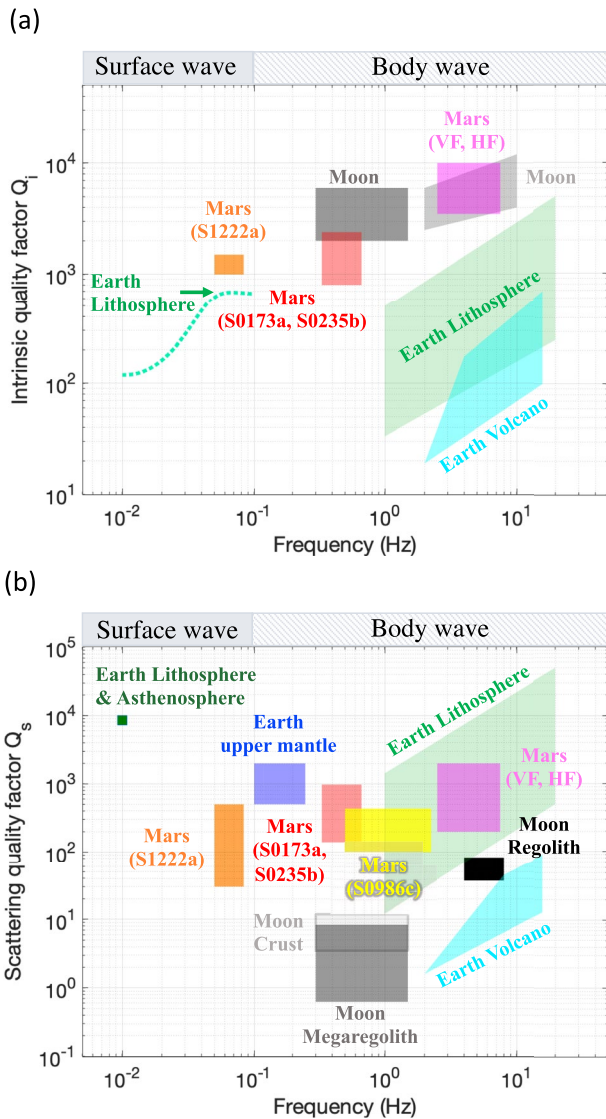


Figure 5. Comparison of (a) intrinsic quality factor and (b) scattering quality factor between the Earth, the Moon, and Mars. See Section 7 for the details.

Instead, we limit ourselves to showing the comparative figures for Q_i and Q_s against frequency and giving a preliminary interpretation.

7.1. Earth

Figures 5a and 5b show the intrinsic and scattering quality factors for the Earth, the Moon, and Mars, respectively, where the quality factors for body waves are displayed above 0.1 Hz, and those for surface waves are presented below 0.1 Hz.

The Earth's lithosphere Q_i and Q_s are estimated through the radiative transfer theory for isotropic single and/or multiple scattering models, using S-wave scattered waves of local earthquakes. The lithosphere's Q_i and Q_s for body waves in Figures 5a and 5b were taken from the recent reviews by Sato et al. (2012) and Sato (2019). Both quality factors show frequency dependence. Q_i ranges 30–500 at 2 Hz and 250–5,000 at 20 Hz. Q_i for surface waves was computed using Mineos (Masters et al., 2011) with the Preliminary Earth model (PREM; Dziewonski & Anderson, 1981). The upper limit (~ 700) corresponds to the lithosphere. The value decreases with decreasing frequency because Rayleigh wave at a lower frequency becomes more sensitive to the deeper part: the asthenospheric structure. The Q_s at 0.01 Hz ($\sim 10,000$) was estimated by Sato and Nohechi (2001) analyzing the Rayleigh wave and its multiple orbits as performed in this study.

Lee et al. (2003) and Lee et al. (2006) estimated the terrestrial mantle Q_s using ScS wave scattering. They inverted for the Q_s using the Monte Carlo method based on the radiative transfer theory with the PREM's velocity and attenuation structure. Around 0.1–0.2 Hz in Figure 5b, we plotted the upper mantle value.

The volcanic region is known to be one of the most heterogeneous regions on Earth. Previous studies evaluated the scattering parameters in various volcanic areas using body waves generated by artificial seismic sources. For example, Wegler (2003) evaluated the Q_i and Q_s at Vesuvius volcano in Italy, Yamamoto and Sato (2010) assessed the quality factors at Asama volcano in Japan, and Prudencio et al. (2015) investigated Stromboli volcano in Italy. The compiled parameter ranges are shown as the cyan areas in Figures 5a and 5b. When compared with the lithosphere, the volcanic area shows the smaller Q_i and Q_s , indicating the strong scattering and high attenuation rate.

7.2. Moon

The latest lunar intrinsic and scattering quality factors were evaluated by Blanchette-Guertin et al. (2012), Gillet et al. (2017), and Onodera et al. (2022).

Blanchette-Guertin et al. (2012) investigated the energy decay of the various types of moonquakes (such as deep moonquakes, shallow moonquakes, natural impacts, and artificial impacts) at different frequency bands and systematically assessed the decay time and coda Q (Q_c). Under the intense scattering conditions, Q_c can be regarded as the S-wave Q_i (e.g., Yoshimoto & Jin, 2008). Assuming their Q_c estimation as Q_i , we show the corresponding Q_i range as dark and light gray areas in Figure 5a. Q_i ranges from 2000 to 6000 in the middle frequency (0.3–1.5 Hz), and Q_i in the high frequency (2–10 Hz) takes a value of 2,500–6,000 at 2 Hz and 4,000–12,000 at 10 Hz.

Regarding the scattering quality factors (black and gray areas in Figures 5b), Gillet et al. (2017) estimated the global Q_s by introducing the spherically layered geometry in the diffusion model. In Figure 5b, the crustal value (3.5–12) is presented as the light gray area. Nakamura (1976) evaluated the diffusivity of the regolith

(surface fine and porous layer) as $(6.2 \pm 0.2) \times 10^{-3} \text{ km}^2/\text{s}$. It should be noted that we divided his estimation by 4 because the diffusivity in Nakamura (1976) was defined differently from that ordinarily used. Using the corrected diffusivity, we estimated the regolith's Q_s as 37–83 at 4–8 Hz (the black region in Figure 5b). For the megaregolith—the fractured structure due to continuous meteoroid impacts, Onodera et al. (2022) evaluated $Q_s = 0.6\text{--}8.3$ in the middle frequency (the dark gray area in Figure 5b) in a forward approach using full 3D seismic wave propagation simulation.

7.3. Mars

The initial estimation of the diffusivity and intrinsic attenuation were carried out by Lognonné et al. (2020) using both teleseismic events (S0173a and S0235b) and a regional marsquake (S0128a). As the results for S0128a are integrated with those of Menina et al. (2021), we briefly review the scattering parameters for S0173a and S0235b. Based on the radiative transfer modeling proposed by Margerin (2017), Lognonné et al. (2020) investigated the two teleseismic events. They estimated the diffusivity (200–700) and intrinsic quality factor (800–2,400) at around 0.5 Hz. Here, we converted the diffusivity into the scattering Q (140–977). The red areas in Figures 5a and 5b correspond to their estimations.

Following the initial outcomes by Lognonné et al. (2020), Menina et al. (2021) evaluated the scattering and attenuation properties at higher frequencies (>2.4 Hz) using Very High Frequency (VF) and High Frequency (HF) events. They took over the approach of Lognonné et al. (2020) and estimated Q_i and Q_s as 3,500–10,000 and 200–2,000, respectively (the magenta areas in Figures 5a and 5b). Recently, using the seismic waves generated by a meteoroid impact (S0986c), Garcia et al. (2022) gave an estimation of the crustal structure around the InSight landing site. We computed the diffusivity and scattering quality factor by referring to their supporting materials together with the diffusion model described by Strobach (1970). Consequently, we obtained $Q_s = 100\text{--}435$ at 0.5–2.25 Hz (yellow area in Figure 5b). At the low frequency (<0.1 Hz), this study provided the first estimation of Q_i and Q_s using the largest marsquake (S1222a) by applying the radiative transfer theory on a spherical Mars (orange area in Figures 5a and 5b).

7.4. Comparison of Three Solid Bodies

Comparing the Martian Q_i with those of the Earth and the Moon, we found that the absorption feature coincided with the lunar one at the high frequency, whereas it turned into a more Earth-like value at the middle and low frequencies. On the other hand, the Martian scattering quality factor is in accordance with the Earth's lithosphere. These results are consistent with the general marsquake features. The event lasts a few tens of minutes, which is longer than earthquakes but not as long as moonquakes (e.g., Lognonné et al., 2020; Onodera et al., 2022). Furthermore, the Martian scattering is not as intense as the Moon, which makes the seismic phases identifiable like earthquakes. According to the quantitative comparison in Figures 5a and 5b, we can preliminarily conclude that the Martian absorption and scattering properties are more Earth-like rather than Moon-like.

8. Conclusion

In this study, we investigated the properties of seismic scattering and intrinsic absorption on Mars. In previous studies, these parameters were not constrained at frequencies below 0.1 Hz. We provided initial estimations of the scattering and intrinsic Q at that frequency, focusing on the long-lasting surface wave coda observed in the S1222a marsquake. Using the radiative transfer theory on a spherical Mars, we succeeded in modeling the observed seismic coda features. As a result, we found $Q_i = 1,000\text{--}1,500$ and $Q_s = 30\text{--}500$, respectively.

Comparing the Martian quality factors derived so far with other solid bodies, we found that the overall scattering and absorption features of Mars appear similar to that of the Earth. Because the current estimation is building on only a small portion of the detected marsquakes, we hope that future works will update our results through more systematic and thorough analyses to better illustrate the heterogeneous structure inside the red planet.

Data Availability Statement

The SEIS data from the InSight mission used in this study can be retrieved through InSight Mars SEIS Data Service (2019) and InSight Marsquake Service (2022). A sample code for downloading data from the IRIS web server can be found at Onodera (2022).

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Erratum

In the originally published version of this article, the name of the second author, Takuto Maeda, was incorrectly published as Maeda Takuto. This error has been corrected, and this may be considered the authoritative version of record.