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1 **Energy envelope and attenuation characteristics of**
2 **High Frequency (HF) and Very High Frequency (VF)**
3 **Martian events**

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19 The authors acknowledge there are no conflicts of interest recorded.

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20 **Abstract**

21 Since its deployment at the surface of Mars, the SEIS instrument of the InSight
22 mission has detected hundreds of small magnitude seismic events. In this work, we
23 highlight some features of two specific families: High-Frequency (HF) and Very-High-
24 Frequency (VF) events. We characterize the shape of the energy envelopes of HF
25 and VF events with two parameters: (1) The delay-time t_d between the onset and
26 the peak of the dominant arrival; (2) The quality factor Q_c which quantifies the en-
27 ergy decay rate in the coda. We observe that the envelope of HF and VF events is
28 frequency-independent. As a consequence, a single delay-time suffices to characterize
29 envelope broadening in the 2.5 - 7.5 Hz band. The typical coda decay time is also
30 frequency-independent as attested by the close to linear increase of Q_c with frequency.
31 Finally, we use elastic radiative transfer theory to perform a series of inversion of
32 seismogram envelopes for the attenuation properties of the Martian lithosphere. The
33 good fit between synthetic and observed envelopes confirms that multiple scattering
34 of elastic waves released by internal sources is a plausible explanation of the events
35 characteristics. We quantify scattering and attenuation properties of Mars and high-
36 light the differences/similarities with the Earth and the Moon. The albedo, i.e. the
37 contribution of scattering to the total attenuation, derived from VF events is very high
38 which we interpret as a signature of a mostly dry medium. Our results also suggest a
39 stratification of the scattering/attenuation properties.

40 **1 Introduction**

41 InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat
42 Transport, Banerdt et al., 2020) has deployed on Mars a complete geophysical payload
43 including a seismometer. Since the start of its operation, the SEIS (Seismic Experi-
44 ment for Interior Structure) seismometer (Lognonné et al., 2019, 2020) recorded several
45 hundreds of seismic events (Giardini et al., 2020). These events have been classified
46 into two main families: high-frequency and low-frequency, depending on whether their
47 frequency content is dominant above or below 1 Hz (Clinton et al., 2021). Among all
48 the events reported by the Mars Quake Service (MQS), the majority belongs to the
49 high frequency family, which is further divided into High-Frequency (HF) and Very-
50 High Frequency (VF) event types. In the HF group, we include specific events with
51 most of their energy in a narrow frequency band around 2.4 Hz, for which the term
52 “2.4 Hz events” has been coined (Clinton et al., 2021). The frequency content of rela-
53 tively rare events called “Broadband” covers the range 0.1 - 2.5 Hz. They are excluded
54 from our analysis. The main seismological characteristics of HF and VF events (e.g.
55 tentative location, temporal distribution) have been presented in detail in van Driel et
56 al. (2021). A brief account of their findings is reported hereafter. HF and VF events
57 are characterized by two temporally separated arrivals with a gradual beginning, a
58 broad maximum and a long coda lasting up to 16 minutes. They can be clearly distin-
59 guished from events of type low-frequency and broadband, whose spectra fall off above
60 1 and 2.5 Hz, respectively and who have clearly separated impulsive P- and S-arrivals,
61 similar to teleseismic earthquakes. The morphology of HF and VF seismograms is
62 reminiscent of moonquakes and high-frequency crustal earthquakes with some notable
63 differences (Lognonné et al., 2020; van Driel et al., 2021). Compared to moonquakes,
64 the dominant arrivals are more impulsive, the envelope broadening is less pronounced
65 and the coda duration (typically 10 minutes) is shorter. For comparison, Latham et
66 al. (1970) and Nakamura et al. (1982) analyzed seismic signals collected during the
67 Apollo missions (1969-1977) and reported observations of long ringing codas lasting up

68 to 2 hours. Latham et al. (1972) and Nakamura (1976) related these characteristics to
69 the strong scattering in the heterogeneous upper lunar crust. In contrast with crustal
70 earthquakes, HF and VF events do not exhibit clearly polarized first arrivals and their
71 coda duration is much longer. The accrued duration of the coda is likely a conse-
72 quence of both the low noise level on Mars and the slower energy decay as compared
73 to Earth. **van Driel et al. (2021) provide convincing evidence that HF and**
74 **VF events result from the propagation of seismic waves in a low-attenuation,**
75 **strongly scattering medium. In this work, we pursue the investigation of HF**
76 **and VF events by characterizing in details their envelope shape and by in-**
77 **verting for the scattering/attenuation properties of Mars using full seismo-**
78 **gram envelope modeling in 3-D.**

79 It is well established that multiple-scattering hampers the identification and anal-
80 ysis of ballistic body-wave phases (Sato et al., 2012). As a consequence, traditional
81 methods used in terrestrial seismology can become impractical when the near-surface
82 is strongly heterogeneous. This is the case on the Moon, due to the presence of the
83 megaregolith, but also in volcanic areas on Earth (Mayeda et al., 1992). Fortunately,
84 a large amount of information on the properties and structure of the scattering lay-
85 ers can be extracted from the detailed analysis of seismogram envelopes. The overall
86 shape of the envelopes can be described by two parameters. The first one is the peak
87 delay, i.e., the delay time from the onset to the peak intensity of S-waves. It is a conve-
88 nient tool to quantify the effects of strong diffraction of the waves in a heterogeneous
89 medium. Takahashi et al. (2007) gave convincing examples of the path dependence of
90 the peak delay in northern Japan. They found that large peak delays are correlated
91 with strong scattering due to the medium inhomogeneity. The second parameter is
92 the coda quality factor Q_c , which quantifies the rate of decay of the coda. Q_c has
93 been widely used in lithospheric or crustal attenuation studies (Aki & Chouet, 1975;
94 Mitchell, 1995; Sato et al., 2012).

95 Besides attenuation estimation based on Q_c measurements, several methods were
96 proposed to evaluate directly the contributions of scattering and absorption to the
97 total attenuation (e.g. Jacobson, 1987; Korn, 1990; Fehler et al., 1992). The Multiple-
98 Lapse Time Window Analysis of Fehler et al. (1992) and Hoshiya (1993) is probably
99 the most popular method in terrestrial seismology and has been applied in a variety
100 of contexts. However, it requires a relatively good epicentral distance coverage, a
101 condition that is not fulfilled on Mars or on the Moon. For this reason, time delay
102 and coda quality factor have remained popular in planetary seismology. Blanchette-
103 Guertin et al. (2012) proposed conceptual models of scattering stratification in the
104 Moon based on measurements of these two parameters. Their work was continued by
105 Gillet et al. (2017) who developed a method based on the diffusion model to retrieve
106 the scattering attenuation profile of the Moon from time delay and Q_c measurements.
107 They found that porosity and fractures could extend deeper than the crust-mantle
108 boundary (up to 80 - 100 km below the surface), as proposed in Lognonné et al.
109 (2003) and in agreement with gravimetric estimates from the GRAIL mission (Zuber
110 et al., 2013).

111 While mathematically convenient, the diffusion model is only a scalar approxi-
112 mation that describes the transport of the total seismic energy. It relies on the assump-
113 tion that seismic waves have been scattered so many times that P and S polarizations
114 emitted at the source can no longer be distinguished at the detection. The diffusion
115 model predicts simple seismogram envelopes characterized by a rise of the energy to
116 a maximum followed by a monotonous coda decay. While such an approximation is
117 well suited for moonquakes, it cannot be easily reconciled with the observation of two
118 pulses in HF and VF martian events. We will therefore employ an elastic radiative
119 transfer approach in this work. Transport equations for elastic waves have solid theo-
120 retical foundations (Weaver, 1990; Ryzhik et al., 1996) and can be conveniently solved
121 by Monte-Carlo simulations (Margerin et al., 2000; Shearer & Earle, 2004; Przybilla
122 et al., 2009; Gaebler et al., 2015; Sanborn et al., 2017).

123 Recently, Lognonné et al. (2020) used the radiative transfer equation to model
124 the full envelope of the first VF event detected by SEIS-InSight (S0128a). They in-
125 ferred first estimates of crustal diffusivity and intrinsic attenuation indicating that the
126 scattering strength is more Earth-like than Moon-like. The apparent intrinsic attenu-
127 ation was found to be very low as compared to the Earth, yet slightly higher than on
128 the Moon. van Driel et al. (2021) analyzed tens of HF and VF events and proposed a
129 conceptual model of long range propagation in a waveguide to explain their characteris-
130 tics. To support their model, they conducted a large number of numerical experiments
131 of wave propagation in a 2-D heterogeneous waveguide and proposed a stratification of
132 heterogeneity in the crust of Mars, with a strongly scattering layer in the first ten kilo-
133 meters of the planet. **In this work, we follow Lognonné et al. (2020) and in-**
134 **vert for the scattering and absorption properties of the Martian lithosphere**
135 **using a radiative transfer approach in a 3-D random elastic half-space. We**
136 **assume that the fluctuations of elastic parameters can be described (to sec-**
137 **ond order) by a Von Karman correlation function. As shown by Sato (2019),**
138 **this model provides a simple but realistic mathematical description of het-**
139 **erogeneity on a wide range of spatial scales.**

140 The paper is organized as follows. In section 2, we introduce the dataset. In sec-
141 tion 3, we present analyses of delay time and Q_c measurements. **For the latter pa-**
142 **rameter, we compare our results to previous measurements on Earth and on**
143 **the Moon.** In section 4, we present our forward modeling approach of the seismogram
144 envelopes and the inversion strategy. In section 5, we show that the envelopes of VF
145 events may be reasonably well explained by the multiple-scattering of elastic waves
146 in a heterogeneous half-space. The role of the model parameters is analyzed before
147 closing the paper with some conclusions.

2 Data description

The seismometer SEIS is equipped with both a three-axes Very Broad Band (VBB) instrument and a three-axes short-period (SP) instrument (Lognonné et al., 2019). These six sensors cover a broad seismic bandwidth, from 0.01 Hz to 50 Hz. Throughout the first year of the mission, considerable work was done on the data collected by SEIS to distinguish between seismic and non-seismic signals (Clinton et al., 2021; Ceylan et al., 2021). 465 potential seismic events were identified by the MQS (Clinton et al., 2021; InSight Marsquake Service, 2020) and we have used waveforms provided by the Mars SEIS Data service (Insight Mars SEIS Data Service, 2019a). Based on the spectral content, two families of events can be distinguished: low frequency and high frequency. The low-frequency family includes long period (LF) and broadband (BB) events. Most of the LF energy is at periods greater than 1s. They can be distinguished from (BB) events by the fact that they do not excite the 2.4 Hz resonances (Clinton et al., 2021). The high-frequency family is composed of so-called “2.4 Hz”, high-frequency (HF) and very high-frequency (VF) events. The 2.4 Hz events have narrow spectral content and were interpreted by van Driel et al. (2021) as small HF events. HF are most energetic in the 1 - 5.5 Hz frequency band with their spectra decaying rapidly at higher frequencies. VF events have energy up to at least 10 Hz, sometimes even much higher frequencies. The present study focuses on HF and VF events which, thanks to their good signal-to-noise ratio and broad frequency range are most interesting to place constraints on the high-frequency attenuation in Mars.

With the latest seismic event catalog, 75 event waveforms were available for analysis, composed of 52 HF events and 23 VF events (Clinton et al., 2021). Nevertheless, a large number of waveforms are contaminated by non-seismic signals such as donks. Ceylan et al. (2021) defined donks as brief high-frequency events of great intensity, resulting likely from the thermal cracking of the lander. We visually inspected all the waveforms and rejected those that were manifestly too contaminated to be usable for

175 coda analysis. Furthermore, we eliminated all the events with a coda duration inferior
 176 to 200 s with a signal-to-noise ratio greater than 2 at 2.5Hz. After application of these
 177 criteria 13 HF and 8 VF waveforms were retained for further analysis. They were
 178 collected from the VBB or SP sensors with acquisition frequencies of 20 samples per
 179 second (sps) or 100 sps, respectively. The arrival times of the primary and secondary
 180 arrivals were identified from the envelopes of the signals filtered in different frequency
 181 bands. The envelope of the signal is obtained by performing successively the following
 182 operations: filtering, squaring and smoothing with a moving average window of 20 s
 183 duration. The events are listed in Table 1.

184 To give a rapid overview of the high-frequency Martian seismic events, vertical
 185 component seismograms and spectrograms of a VF (S0334a) and an HF event (S0314b)
 186 are shown in Figure 1. Time windows of 10 s are used for spectrogram computations
 187 and the displacement waveforms are bandpass filtered at 3.5 Hz. Prior to the com-
 188 putations, the instrumental response of the VBB sensor has been removed from the
 189 signal. Note that besides the seismometers, SEIS is also composed of a tether connect-
 190 ing the sensor to the lander and a relaxation loop (LSA). The impact of these last two
 191 components on the recorded high-frequency ground motion is not perfectly known at
 192 the time of writing.

193 The HF and VF seismograms have an emergent character and a duration that
 194 typically exceeds 10 minutes. While both events strongly excite the 2.4 Hz reso-
 195 nances first reported in Lognonné et al. (2020) and Giardini et al. (2020), the HF
 196 event exhibits most of its energy between 1.5 and 5.5 Hz, while the spectral con-
 197 tent of the VF ranges from 1.5 Hz to the Nyquist frequency (10 Hz). On the hor-
 198 izontal components, this effect is even more pronounced and the displacement spec-
 199 trum of some of the most energetic VF events is rising above 4 Hz, as illustrated
 200 in Figure 2. **The origin of the difference between the spectra of VF and HF**
 201 **events is not understood yet. Simple earthquake scaling laws (e.g. Madariaga,**

202 **1976) suggest, for example, that VF events may exhibit larger stress drop than**
 203 **HF events. Nevertheless, such an interpretation requires that all path effects**
 204 **be removed from the spectra shown in Figure 2, an issue which we start to**
 205 **address in this paper.**

206 On each vertical component seismogram, two arrivals can be clearly identified,
 207 each followed by a long coda. Unsuccessful attempts at recovering the polarization
 208 information of the dominant arrivals suggest that the HF wavefield is almost entirely
 209 depolarized. These features are broadly consistent with the observations reported in
 210 Clinton et al. (2021). A number of non-seismic signals are also visible in Figure 1.
 211 Short, repetitive bursts of high-frequency energy can be discerned, that correspond
 212 likely to donks but sometimes also glitches that are associated with high-frequency
 213 precursors (Scholz et al., 2020). The permanent narrow band of energy visible at 1 Hz
 214 is caused by cross-talk between the temperature acquisition (at 1 sps) and the seismic
 215 channel (Zweifel et al., submitted; Compaire et al., 2021), termed tick-noise. While
 216 the most energetic quality B high-frequency events are of VF type, a large number of
 217 HF and VF events have small spectral amplitude and are prone to contamination by
 218 environmental and instrumental noise. This is a topic of concern and we shall carefully
 219 examine the impact of the noise on our measurements.

220 **3 Envelope characteristics of HF and VF events**

221 **3.1 Analysis of VF event S0734a**

222 In this section, we present a complete analysis of the VF event S0734a using
 223 20 sps data from the VBB sensor (see also Appendix A for an analysis based on
 224 100 sps SP data). **In the range of frequencies where the two datasets over-**
 225 **lap, we found good agreement between the results obtained from the VBB**
 226 **and SP sensors.** Our objective is to extract the main characteristics of the energy
 227 envelopes in different frequency bands. Before performing the measurements, we ap-

228 plied the following preliminary processing to the data: detrend using cubic splines,
 229 instrumental response correction and finally rotation to North East and Vertical com-
 230 ponents. In a second step, the energy envelopes are calculated as follows. The data
 231 are band-pass filtered, squared and smoothed. We applied Butterworth filters in suc-
 232 cessive frequency bands $[3f/4, 5f/4]$ centered around frequency $f \in \{2.5, 3.5, 4.5, 5.5,$
 233 $6.5, 7.5\}$ for VBB data (Lognonné et al., 2020) and $f \in [2.5, 19.5]$ with a step of 1
 234 Hz in the case of SP data. We used smoothing windows of 20 seconds to reduce the
 235 envelopes fluctuations. We normalized each envelope by dividing the (instantaneous)
 236 energy of the signal by the mean energy of the noise computed in a time window of 100
 237 s duration preceding the event start. The results are illustrated in Figure 3.a (for VBB
 238 data) and Figure A.1.a (for SP data) where we show the normalized energy envelope
 239 of the data in various frequency bands. The square root of these envelopes may readily
 240 be interpreted as the signal-to-noise (S/N) ratio of the event. At its maximum, the
 241 S/N ratio can be as large as 30 around 8.5 Hz and is typically above 10 from 2 Hz
 242 to at least 12 Hz. Note that this VF event carries energy almost up to the Nyquist
 243 frequency of the SP data (50 Hz).

244 Looking at the envelope shape in more details, we observe two wave packets sep-
 245 arated in time by approximately 80 s, each followed by a pronounced coda. **For com-**
 246 **parison, we show in Figure 4.a the result of applying the same processing to**
 247 **a regional event recorded on the Canadian shield. This event was chosen on**
 248 **the basis of its similarity with VF S0734a in terms of $(t_s - t_p)$ and coda du-**
 249 **ration. The main phases visible on the terrestrial seismogram are the refracted**
 250 **mantle waves P_n and S_n as well as the guided L_g waves. This last phase, which**
 251 **highlights the velocity discontinuity at the crust/mantle boundary on Earth,**
 252 **distinguishes the anatomy of a regional earthquake from the one of a regional**
 253 **marsquake. The L_g wavetrain is followed by a long coda whose decay prop-**
 254 **erties will be analyzed and compared to the ones of VF S0734a.**

255 In the next subsections we further examine the characteristics of the VF event
 256 by analyzing the coda quality factor Q_c and delay time t_d .

257 *3.1.1 Coda quality factor (Q_c) measurements*

Since the works of Aki & Chouet (1975), it is widely accepted that the temporal decay of the smoothed energy envelope of the coda may be parameterised as:

$$E(t) \propto \frac{1}{t^\alpha} e^{-\frac{\omega t}{Q_c}}, \quad (1)$$

258 where Q_c is the coda quality factor, ω is the central angular frequency of the signal and
 259 α is an exponent that depends on the model geometry. **In this work, we will con-**
 260 **sider both $\alpha = 0$ and $\alpha = 1$. The former choice facilitates the comparison**
 261 **with lunar measurements presented in Gillet et al. (2017), while the latter**
 262 **value has been traditionally adopted to study the coda decay at regional dis-**
 263 **tances on Earth (Mitchell, 1995). Note that in the case $\alpha = 0$, the Aki and**
 264 **Chouet formula is left invariant by a translation of the time origin so that**
 265 **quake location is not needed to measure Q_c . In the case $\alpha = 1$, we determined**
 266 **an approximate origin time t_0 for the marsquake event. Assuming constant**
 267 **velocities, we have $t_0 = t_p - (t_s - t_p)/(\gamma - 1)$ where the V_p/V_s ratio (γ) is as-**
 268 **sumed equal to 1.65 which is realistic for the near surface of Mars. We also**
 269 **tested $\gamma = 1.85$, without significant impact on the results.**

270 To measure Q_c , we perform a robust linear least-squares regression of
 271 the logarithm of the envelope of the summed energies of horizontal compo-
 272 nents, after correction by a factor t (t is the time elapsed since the event oc-
 273 currence) in the case $\alpha = 1$ (Aki & Chouet, 1975). The start time and end
 274 time of the coda windows used for analysis are listed in Table 1. For all the
 275 events analyzed, the duration of the coda window is of at least 100 s dura-
 276 tion with S/N greater than 2. The use of robust linear least-squares circum-

277 vents the difficulty of performing an accurate linear regression when the sig-
 278 nal is contaminated by outliers, in particular donks in the highest frequency
 279 range. Furthermore, for events located in the same range of epicentral dis-
 280 tance, we took care of selecting very similar time windows in order to min-
 281 imize possible selection biases. Examination of Figure 3.a on which we have
 282 superposed the results of the linear regression with $\alpha = 1$ on the data shows
 283 that the Aki and Chouet formula approximates the coda decay of marsquakes
 284 extremely well. As a consequence, the uncertainties on individual Q_c measure-
 285 ments are never larger than 1%. In Figure 3.a, it is worth noting that seismo-
 286 gram envelopes at different frequencies are almost parallel to one another in the
 287 coda. This property is reflected in the almost linear increase of the coda quality
 288 factor Q_c shown in Figure 3.b (see also Figure A.1.b for SP data). In the Fig-
 289 ure, the color bar indicates the average S/N ratio measured on the total energy of
 290 horizontal components. To confirm the almost linear trend visible in Figure 3.b,
 291 we performed a fit of the frequency dependence of Q_c using a parameterisation of
 292 the form $Q_c = Q_0 f^n$. **Based on linear least-squares applied to the logarithm**
 293 **of Q_c , we obtain $Q_0 = 440 \pm 14$ and $n = 1.08 \pm 0.02$ in the [2.5 Hz - 7.5 Hz]**
 294 **range for VBB data with $\alpha = 1$ (see Appendix A for the same analysis on**
 295 **SP data with similar results). In the case $\alpha = 0$, we find $Q_0 = 422 \pm 13$ and**
 296 **$n = 1.07 \pm 0.02$ with an equally satisfactory fit to the data. We note that the**
 297 **choice of α impacts the value of Q_0 but leaves n practically unchanged. The**
 298 **change in Q_0 is rather modest, typically less than 10% for VF S0734a. A vi-**
 299 **sual comparison between Figures 3.a and 4.a reveals a clear difference in the**
 300 **frequency-dependence of the coda decay between Mars and Earth (Canada).**
 301 **In the case of the regional earthquake, the ensemble of decay curves is fan-**
 302 **shaped, corresponding to a frequency exponent n lower than 1. Indeed, a lin-**
 303 **ear regression of Q_c measurements shown in Figure 4b indicates $Q_0 = 740 \pm$**
 304 **74 and $n = 0.49 \pm 0.05$. Coda decay properties of earth- and mars-quakes will**

305 **be further compared after analysis of all the selected high frequency events.**

306

307 ***3.1.2 Delay-time (t_d) measurements***

308 In random heterogeneous media, multiple scattering results in the broadening of
 309 energy envelopes with hypocentral distance (Saito et al., 2002; Sato, 1982). This phe-
 310 nomenon may be simply quantified by measuring the rise time from the onset to the
 311 peak of a given seismic arrival. To facilitate the comparisons with terrestrial seismol-
 312 ogy, we define the delay time on the secondary arrival as: $t_d = t_{max} - t_s$ where t_{max} is
 313 the arrival time of the energy maximum. In previous studies, delay-time measurements
 314 were successfully applied to characterize qualitatively the scattering properties of the
 315 medium in both the Earth and the Moon (e.g. Blanchette-Guertin et al., 2012; Gillet
 316 et al., 2017; Calvet & Margerin, 2013). Sophisticated delay time tomography based on
 317 multiple-forward scattering approximations have also been developed to map spatial
 318 variations of heterogeneity (Takahashi et al., 2007, 2009). The discussion that follows is
 319 mostly qualitative and will serve to highlight some differences between Mars, Earth and
 320 Moon. Pursuing our analysis of the VF event S0734a, we performed delay-time mea-
 321 surements (t_d) on the seismogram envelopes of the VBB data in the 2.5 – 7.5 Hz (**see**
 322 **Appendix A.c for an analysis at higher frequencies using SP data**). The re-
 323 sults are reported in Figures 3.c.

324 A rather striking feature of the results plotted in Figures 3.c is the absence of
 325 clear frequency dependence of the time-delay. This is particularly notable on the VBB
 326 data from 2 Hz to 8 Hz. Time delay of P-waves has received little attention on Earth
 327 (see however the work of Kubanza et al., 2007). In the case of the Moon, the diffuse
 328 character of the signal allows for the measurement of a single time delay, most likely
 329 related to S-waves. For these reasons, the discussion will be focused on the proper-
 330 ties of the secondary arrival. On Earth, t_d of S-waves has been shown to increase
 331 with frequency in various geological contexts (Takahashi et al., 2007; Calvet et al.,

2013). This property is usually understood as a consequence of strong forward scattering and should not be confused with the dispersion of velocities induced by attenuation (whether it is caused by scattering or absorption). For narrowly band-passed waves propagating in a heterogeneous medium, the effect of velocity dispersion on the envelope shape is usually very small compared to the multi-pathing effects induced by forward scattering (Sato, 1989). In the case where the randomness is described by Gaussian spatial correlations of the fluctuations (or more generally smooth random media), Markov's approximation predicts that t_d is independent of the central frequency of the waves. The frequency exponent inferred from Earth data is usually strictly positive and sometimes larger than 1, which is interpreted as the presence of small-scale fluctuations that are not captured by the Gaussian model (Saito et al., 2002; Takahashi et al., 2007). Note that in the case of the Canadian shield event, the level of scattering attenuation is presumably very low. In this example, the dominant mechanism at the origin of the peak delay is most likely the multiple reverberations of the guided waves in the crust.

In sharp contrast with the Earth, t_d is seen to decrease with frequency on the Moon (Gillet et al., 2017). There is no consensus explanation for this fact. But it is important to keep in mind that t_d is sensitive to both scattering and attenuation and the latter mechanism decreases the time delay (see Sato, 1989). **Attenuation does add some dispersion to the seismic velocities but since we are considering multiple-scattering of narrow-band signals, the effect is tiny.** Mars displays yet another behavior, somehow intermediate between Earth and Moon with apparently little frequency dependence of t_d for the second arrival. As a consequence, for each event we have estimated the mean value of t_d and its uncertainty based on a set of measurements on filtered data in the $[3f/4, 5f/4]$ band, where the central frequency increases from 2.5 Hz to 19.5 Hz by steps of 1 Hz. In Figure 5, we report our measurements of t_d as a function of the time difference ($t_s - t_p$) between the second and first arrivals, which

360 can be understood as a proxy for the hypocentral distance R . While multiple-forward
 361 scattering theory predicts that t_d increases like R^2 in smooth random media (Saito
 362 et al., 2002), the delay time of high-frequency martian events appears to be remark-
 363 ably independent on $(t_s - t_p)$. This property distinguishes Mars from Earth and Moon
 364 where the increase of t_d with hypocentral distance is clearly observed (Takahashi et al.,
 365 2007; Blanchette-Guertin et al., 2012). The deviation of martian HF events from the
 366 predicted theoretical behavior can have different origins: competition between scatter-
 367 ing and attenuation (absorption), contribution of large angle scattering neglected in
 368 Markov’s approximation or non-uniformity of scattering properties. These hypotheses
 369 will be evaluated in the light of envelope modeling in section 4.

370 **3.2 Comparison of HF and VF events characteristics**

371 The preliminary analysis of HF and VF events revealed significant differences in
 372 spectral content (see Figures 1-2). In this section, we propose to extend the comparison
 373 between the two groups of events by examining the coda quality factor and delay time
 374 of 13 HF and 8 VF events in the 2.5 - 5.5 Hz and 2.5 - 7.5 Hz frequency bands,
 375 respectively. We only use data collected on the VBB sensors with sampling rates of
 376 20 sps.

377 **3.2.1 Delay time**

378 Similar to the VF event S0734a (Figure 3), the delay-time (t_d) measured for
 379 each of the HF and VF events appears to vary little with frequency. The apparent
 380 differences in the measurements of t_d at different frequencies are likely the results of
 381 statistical fluctuations of the envelopes or contamination of the signal by donks. As a
 382 consequence, we define for each event the delay-time and its uncertainty as the mean
 383 and the standard deviation to one sigma of all the values measured on the filtered
 384 data in the $[3f/4, 5f/4]$ band with $f \in \{2.5, 3.5, \dots, 7.5\}$. Figure 5 (left) reports the
 385 delay-time as a function of $t_s - t_p$, taken as a proxy for the hypocentral distance. On

386 this Figure, there is no clear-cut difference between the VF and HF events, except
 387 that the latter show more variability. The lack of information on the back-azimuth
 388 of these events makes it impossible to determine whether this variability reflects a
 389 genuine path effect or if this is just a consequence of noise contamination. Indeed, the
 390 small amplitude of the HF events that we have analyzed makes them more sensitive
 391 to the noise conditions, as will be illustrated later.

392 **3.2.2 Coda quality factor**

393 Figure 5 (right) shows the dependence of the coda quality factor of HF and
 394 VF events at 3.5 Hz as a function of $(t_s - t_p)$. Dark and light colors correspond
 395 respectively to the choice $\alpha = 0$ and $\alpha = 1$ in formula (1). We observe again a much
 396 greater variability of Q_c among HF events. This observation has to be interpreted with
 397 some caution. While it suggests that some HF events sample a significantly higher Q
 398 region of Mars as compared to VF events, we will show in section 3.3 that the coda
 399 decay is extremely sensitive to the noise conditions. This is all the more true as the Q
 400 values (typically in the range 2000 - 9000 at 3.5 Hz) are particularly high. If we make
 401 abstraction of HF events, there appears to be an increase of the coda quality factor
 402 with hypocentral distance. Since the more distant events are likely to sample deeper
 403 parts of the medium as compared to the nearest one, this increase is suggestive of a
 404 possible stratification of attenuation properties with depth. This hypothesis will be
 405 further explored in section 5.

406 In preparation of section 3.3, we continue our exploration of HF and VF events
 407 with the analysis of Figure 6 which reports our measurements of Q_c as a function of
 408 the signal-to-noise ratio for central frequencies $f \in \{2.5, 3.5, \dots, 7.5\}$ Hz. S/N and its
 409 uncertainty were evaluated in a 200 s long window starting at the onset of the second
 410 arrival. As a consequence of their narrower spectral content, the coda quality factor
 411 of HF events could only be measured in the two lowest frequency bands (2.5 - 3.5 Hz).
 412 The difference between the two groups of events is apparent on both axes of Figure 6:

413 HF events show on average higher Q_c and lower S/N than VF events. The variability
 414 of Q_c for HF events at 3.5 Hz (Figure 5) is thus largely confirmed at 2.5 Hz. While
 415 this observation suggests that HF events sample on average higher Q regions of Mars,
 416 it is important to keep in mind the influence of the noise on the measurements. This
 417 point is further explored in the next subsection.

418 **3.3 Noise sensitivity analysis**

419 To understand the impact of the noise on envelope characteristics, we performed
 420 a simple sensitivity analysis by adding noise data to one the VF events (S0334a).
 421 We selected a noise window during Sol 333 at the exact local time of occurrence of
 422 S0334a. Before addition to the event signal, the noise amplitude was scaled by a factor
 423 $k \in \{0, 1, 2, 3, 4, 5\}$. Figure 7 shows the results of the noise addition to the signal of
 424 S0334a from 2.5 Hz to 7.5 Hz. As hypothesized above, the impact of the noise level
 425 on the coda quality factor is quite large. As the S/N ratio decreases by a factor 4, the
 426 quality factor increases by a factor almost 3 at 3.5 Hz. This very high sensitivity of Q_c
 427 to the noise level has two origins: (1) the S/N of the original signal is not very high
 428 (of the order of 10) and (2) The rate of decay of the coda is rather slow. By “slow”, we
 429 mean that the coda length is not very large compared to the typical decay time Q_c/ω at
 430 circular frequency ω . Hence, a small amount of noise can lead to an overestimation of
 431 Q_c . Comparing Figures 6 and 7, we recognize a somewhat similar pattern, suggesting
 432 that part of the variability of Q_c among HF events may be explained by their low
 433 S/N ratio. Finally, we remark that the impact of the noise on the coda decay of VF
 434 events at higher frequency (7.5 Hz), while slightly less pronounced than at 3.5 Hz, is
 435 still noticeable.

436 **3.4 Coda attenuation: Earth-Moon-Mars comparison**

437 To illustrate the variability of the coda decay on Mars, we show in Fig-
 438 ure 8 the values of Q_0 and n for 8 VF events analyzed in this study. HF are

439 not shown as their bandwidth is too narrow for meaningful comparison with
 440 Earth. Figure 8 confirms that the value of α mostly impacts Q_0 , but not n .
 441 Like in the case of VF S0734a, we find that the value of Q_0 typically increases
 442 by no more than 10% when substituting $\alpha = 0$ with $\alpha = 1$ in formula (1).
 443 To summarize our results, we perform an average over all events and find $Q_0 =$
 444 701 ± 188 and $n = 1.04 \pm 0.1$ for $\alpha = 1$ ($Q_0 = 644 \pm 156$ and $n = 1.038$ for $\alpha = 0$).
 445 The measurements with $\alpha = 1$ (resp. $\alpha = 0$) will be compared to Q_c values
 446 for Earth (resp. Moon). We remind the reader that $\alpha = 1$ is commonly used
 447 in coda attenuation studies at regional distances (Mitchell, 1995), while $\alpha =$
 448 0 has been adopted in the case of the Moon (Blanchette-Guertin et al., 2012;
 449 Gillet et al., 2017). In Figure 9, we have compiled a number of Q_c measure-
 450 ments performed in different geological environments on Earth together with
 451 data from the Moon and the results obtained in this study for Mars. Before
 452 discussing the Figure in more details, we note that while studies performed
 453 at regional distances on Earth make use of $\alpha = 1$ (e.g. Xie & Mitchell, 1990;
 454 Mitchell et al., 2008), a number local coda Q studies, particularly in tectonic
 455 areas on Earth, employ $\alpha = 2$. The latter value differs from the one used in
 456 this study. Since raising α by one unit increases Q_0 by less than 10% and does
 457 not affect n (for martian data), we believe that the comparison is neverthe-
 458 less meaningful.

459 With $Q_0 \approx 700$, the coda quality factor on Mars lies in the upper range
 460 of the values observed on Earth, particularly when compared to measurements
 461 reported for tectonically active regions (in blue in Figure 9) where Q_0 typ-
 462 ically varies from 100 to 400 (see Table 2 for references). It is only in cra-
 463 tons or shields (shown in green and yellow in Figure 9) that Q_0 exceeds 600
 464 and can in certain regions be as high as 1000 (Singh & Herrmann, 1983; C. R. Wood-
 465 gold, 1990; Xie & Mitchell, 1990; Singh et al., 2004; Mitchell et al., 2008). Fig-
 466 ure 9 clearly shows that the frequency dependence of Q_c on Earth is radically

467 different between tectonic areas and shields, with an approximately linear in-
 468 crease of Q_c for the former ($n \approx 1$), and a frequency exponent in the range
 469 0.1–0.5 for the latter (see also Romanowicz & Michell, 2015, for a review).
 470 In fact, there appears to be a systematic correlation between Q_0 and n on Earth,
 471 with high Q_0 generally associated with small n . This is for instance partic-
 472 ularly obvious on the Lg coda Q tomographies by Xie & Mitchell (1990) for
 473 Africa (see a number of other examples in Romanowicz & Michell, 2015). Fur-
 474 thermore, Q_c appears to saturate at high-frequency on Earth and only ex-
 475 ceptionally exceeds 3000 at 20 Hz (e.g. C. R. Woodgold, 1990; C. Woodgold,
 476 1994). No such saturation is seen in the VF events data.

477 On the Moon, Gillet et al. (2017) report coda Q_c values of 2400 at 0.5 Hz and
 478 possibly as large as 10000 at 7 Hz. From these observations, it appears that Q_0 on the
 479 Moon must be a factor 2 to 4 larger than on Mars, as already suggested in Lognonné
 480 et al. (2020). The frequency dependence is less well constrained due to the limited
 481 bandwidth of the seismic sensors deployed in the framework of the Apollo mission.
 482 Nevertheless, the values reported above suggest that the frequency exponent for Q_c
 483 on the Moon lies more likely in the range 0.4 - 0.6.

484 In summary, we see that Q_c on Mars is lower than on the Moon (at the same
 485 frequency) but increases more rapidly with frequency. The unique combination of
 486 high Q_0 with a frequency exponent $n \approx 1$ also distinguishes very clearly Mars from
 487 the Earth. The quasi-linear frequency increase of Q_c seen on VF events suggests that
 488 the coda decay is governed by a frequency independent attenuation time.

489 In the next section, we will focus on the highest quality VF events and infer
 490 the average scattering and absorption properties of the martian lithosphere from the
 491 multiple-scattering modeling of their envelope shape.

492 4 Seismogram envelopes modeling

493 In this section, we first present the theoretical approach and the inversion proce-
 494 dure to retrieve the scattering and attenuation properties of Mars from the modeling
 495 of seismogram envelopes of VF events. The method is illustrated on three VF events
 496 covering a broad range of hypocentral distances.

497 4.1 Radiative transfer model.

The envelope characteristics and the statistical properties of the signal of HF
 Martian events suggest that they are composed of seismic waves that have propagated
 in the multiple scattering regime. To describe the spatio-temporal distribution of
 seismic energy and the energy exchange between different modes of propagation, we
 use an approach based on the elastic radiative transport model in a half-space (Turner
 & Weaver, 1994; Ryzhik et al., 1996). We suppose that the first and second energy
 ‘packets’ observed during VF events correspond to multiply-scattered P and S waves
 emitted by a single impulsive source. To model the energy envelopes, we use the Monte-
 Carlo method to solve the following simplified set of transport equations (Margerin,
 2017):

$$\begin{aligned}
 (\partial_t + c^p \mathbf{n} \cdot \nabla) \rho^p(\mathbf{r}, \mathbf{n}, t) &= - \left(\frac{1}{\tau^p} + \frac{1}{t_i^p} \right) \rho^p(\mathbf{r}, \mathbf{n}, t) + \frac{1}{\tau^{pp}} \int_{4\pi} p^{pp}(\mathbf{n}, \mathbf{n}') \rho^p(\mathbf{r}, \mathbf{n}', t) d^2 \mathbf{n}' \\
 &\quad + \frac{1}{\tau^{sp}} \int_{4\pi} p^{sp}(\mathbf{n}, \mathbf{n}') \rho^s(\mathbf{r}, \mathbf{n}', t) d^2 \mathbf{n}' + S^p(\mathbf{r}, \mathbf{n}, t) \\
 (\partial_t + c^s \mathbf{n} \cdot \nabla) \rho^s(\mathbf{r}, \mathbf{n}, t) &= - \left(\frac{1}{\tau^s} + \frac{1}{t_i^s} \right) \rho^s(\mathbf{r}, \mathbf{n}, t) + \frac{1}{\tau^{ps}} \int_{4\pi} p^{ps}(\mathbf{n}, \mathbf{n}') \rho^p(\mathbf{r}, \mathbf{n}', t) d^2 \mathbf{n}' \\
 &\quad + \frac{1}{\tau^{ss}} \int_{4\pi} p^{ss}(\mathbf{n}, \mathbf{n}') \rho^s(\mathbf{r}, \mathbf{n}', t) d^2 \mathbf{n}' + S^s(\mathbf{r}, \mathbf{n}, t)
 \end{aligned} \tag{2}$$

498 where $\tau^{\alpha\beta}$ is the α to β scattering mean free time ($\alpha, \beta \in \{P, S\}$). In addition, we have
 499 introduced the following notations: t_i^α and c^α are the absorption time and the velocity
 500 of the mode α , $\rho^\alpha(\mathbf{r}, \mathbf{n}, t)$ is the energy density propagating in direction \mathbf{n} at time t
 501 and position \mathbf{r} of mode α . $S^\alpha(\mathbf{r}, \mathbf{n}, t)$ is the source term for mode α . The local angular

502 scattering pattern $p^{\alpha\beta}(\mathbf{n}, \mathbf{n}')$ is the probability that α energy propagating in direction,
 503 \mathbf{n}' is converted into β energy propagating in direction \mathbf{n} . Finally, $1/\tau^\alpha = \sum_\beta 1/\tau^{\alpha\beta}$
 504 is the total inverse scattering mean free time (of mode α). Note that the set of Eq.
 505 (2) can be reduced to a simple scalar diffusion equation for the total energy density
 506 $(\rho^p + \rho^s)$ in the limit of long propagation times ($t \rightarrow \infty$). To facilitate the comparison
 507 between Mars and the Moon, we will therefore quantify the strength of the scattering
 508 by computing the equivalent seismic diffusivity of the models of heterogeneity derived
 509 from the inversion of seismic envelopes. For a presentation of the formula for the
 510 diffusivity in a seismological context, the reader is referred to Turner (1998). To
 511 facilitate the comparison with the Earth, we will also quantify the scattering strength
 512 with the aid of the shear wave quality factor $Q_{sc} = \omega\tau^s$, where ω is the central
 513 frequency of the waves.

As demonstrated by scattering theory, the angular patterns $p^{\alpha\beta}$ are governed
 by the power spectrum of the random fluctuations as well as the possible correlations
 among the elastic parameters (Sato et al., 2012). In this work, we make the classical
 assumption that density and velocity are correlated as follows: $\delta c^p/c^p = \delta c^s/c^s$ and
 $\delta\rho/\rho = \nu\delta c^p/c^p$. This is known as Birch law in the literature. In this work, we adopt
 the classical value $\nu = 0.8$ for lithospheric rocks (Sato, 1984). The power spectrum of
 the elastic fluctuations Φ is assumed to be of Von-Karman type:

$$\Phi(m) = \frac{(2\sqrt{\pi})^3 \Gamma(\kappa + 3/2) \langle \epsilon^2 \rangle l_c^3}{\Gamma(\kappa) (1 + m^2 l_c^2)^{\kappa+3/2}} \quad (3)$$

514 where m is the wavenumber (of the fluctuations), Γ is the Gamma function, and $\langle \epsilon^2 \rangle$
 515 is the variance of the fluctuations. The two key parameters in Eq. (3) are the Hurst
 516 exponent κ and the correlation length l_c . The exponent κ controls the richness of
 517 the medium in small-scale fluctuations and l_c is the typical size of the largest het-
 518 erogeneities. A classical choice for κ is 0.5, corresponding to a correlation function of

519 exponential type. In this work, we will explore other forms of correlation corresponding
 520 to smoother media ($\kappa = 2$) besides the usual case $\kappa = 0.5$.

521 To complete the presentation of the model we discuss briefly the source term,
 522 absorption model and average wavespeeds. In view of the broad similarity of VF
 523 events with high-frequency earthquakes, it is reasonable to assume that they are of
 524 internal origin. In our model, the P/S energy ratio emitted at the source is therefore
 525 calculated from the radiation of a double couple and depends on the velocity ratio
 526 c^p/c^s to the fifth power (Sato et al., 2012). For lack of more precise information,
 527 we will assume that the dissipation of seismic energy is caused by shearing motions
 528 and is therefore entirely controlled by the rigidity. We therefore have the following
 529 relation: $t_i^p = \frac{3}{4}(\frac{c^p}{c^s})^2 t_i^s$, between the absorption times of P and S waves. As the seismic
 530 wavespeeds are not very well constrained except for the near surface (Lognonné et al.,
 531 2020), we will assume that $c^s = 1.7$ km/s, characteristic of the upper crust, and explore
 532 two possible values of the c^p/c^s ratio (1.65, 1.85). We also investigated a higher shear
 533 wave speed $c^s = 3.0$ km/s and obtained similar fits to the data, with somewhat lower
 534 scattering attenuation. We will come back to the role of c_s later in the discussion.

535 4.2 Inversion procedure

536 On Earth, the most common approach to retrieve the scattering and attenuation
 537 properties from seismogram envelopes is the Multiple-Lapse-Time-Window-Analysis
 538 (Fehler et al., 1992), where the smoothed spatio-temporal distribution of seismic energy
 539 is estimated from energy integrals for an ensemble of earthquakes in the vicinity of
 540 the station. This method cannot be readily transposed to Mars, due to the lack of
 541 seismicity at short hypocentral distance. In the case of the Moon, Gillet et al. (2017)
 542 developed an inversion method which uses only t_d and Q_c to characterize the shape of
 543 seismogram envelopes. Again, this approach is not readily applied to our data since
 544 VF events are composed of two major energy arrivals. We therefore decided to perform

545 a direct inversion of the full seismogram envelope of horizontal components using the
 546 transport equations (2) for the forward model.

547 The inversion seeks to retrieve only two parameters: the scattering mean free
 548 time (τ^s) and the absorption time of S waves (t_i^s). It is very important to note that
 549 all the scattering parameters of Eq. (2), i.e. $\tau^{\alpha\beta}$ and $p^{\alpha\beta}$ are entirely determined by
 550 τ^s once ω (central circular frequency), l_c (correlation length) and κ (Hurst exponent)
 551 are fixed. Because the envelope shape does not vary much between 2.5 and 8.5 Hz,
 552 we decided to perform the inversion at 6 Hz to optimize the S/N ratio. Since the
 553 correlation length l_c is unknown, we explored a broad range of values ranging from
 554 a few tens of meters to a few kilometers. For the Hurst exponent, two possibilities
 555 were considered: $\kappa = 0.5$ (exponential medium) and $\kappa = 2.0$ (smooth Von-Karman
 556 medium). The best results were obtained with the later choice as illustrated below.

To quantify the agreement between data and model, we apply a simple least-
 squares criterion to the difference of the logarithms of the observed and modeled energy
 envelopes:

$$\chi^2 = \int_0^{t_e} \left[\log \left(\frac{E^o(t)}{N^o} \right) - \log \left(\frac{E^m(t)}{N^m} \right) \right]^2 dt \quad (4)$$

557 where E denotes the energy and the integral is computed from the signal onset to
 558 the return to the noise level at time t_e . The use of the logarithm in the definition
 559 of χ^2 is important to give similar weights to the two main arrivals and the coda in
 560 the inversion process. In Eq. (4), the symbols $N^{o,m}$ denote energy integrals that are
 561 used to cross-normalize the synthetic and observed envelopes, where the subscripts
 562 o, m refer to observations and model, respectively. This is the same idea as the coda
 563 normalization method (Aki & Chouet, 1975; Rautian & Khalturin, 1978), where source
 564 and site effects are removed by normalizing the amplitude of the signal by the energy
 565 level of the coda at long lapse-time. In our applications, we used a window of 50 s
 566 durations at the end of the coda (i.e. between $t_e - 50$ s and t_e).

567 To minimize χ^2 , we employ an iterative optimization approach based on the
568 Levenberg-Marquardt algorithm as implemented in the GNU Scientific Library (Galassi
569 et al., 2017). To guide the inversion process, the method requires the computation of
570 the sensitivity of the synthetic envelope to a perturbation in the model parameters.
571 Rather than the scattering and absorption times, we employ the attenuations $1/\tau^s$
572 and $1/t_i^s$ for the parametrization, as is naturally suggested by the form of Eq. (2).
573 Therefore, in addition to solving Eq. (2), we use the differential Monte-Carlo method
574 of Takeuchi (2016) to compute the partial derivatives of the energy envelopes with
575 respect to the scattering and absorption attenuations. In general, a few iterations
576 suffice to converge to the minimum. The algorithm also provides uncertainties on the
577 best-fitting parameters based on the assumptions that the errors are Gaussian.

578 **5 Inversion Results**

579 Some representative results of the inversion procedure are shown in Figure 10
580 for the VF events S0734a (top), S0756a (middle) and S0421a (bottom). Assuming
581 a uniform shear velocity $c^s = 1.7$ km/s and $c^p/c^s = 1.85$ (resp. 1.65), the time
582 difference ($t_s - t_p$) indicates that these events are approximately located at 330 km
583 (resp. 390 km), 670 km (resp. 780 km) and 1510 km (resp. 1760 km) from the station,
584 respectively. The agreement between the best-fitting radiative transfer models with
585 Hurst exponent $\kappa = 2$ and the data is rather satisfactory, particularly for the two
586 shortest hypocentral distances. It is worth noting that the amplitude ratio between
587 the two dominant arrivals is consistent with the hypotheses that shear dislocations are
588 at the origin of the VF events, and that all dissipation is due to shear. For the most
589 distant event, the quality of the fit degrades. We see in particular that the rise time of
590 the first arrival is too short and its coda decay too rapid. We will further comment on
591 this discrepancy below. In all the cases that we examined, the adimensional correlation
592 length $\omega l_c/c^s$ is larger than 1, which indicates that the scattering is predominantly in
593 the forward direction (see eg. Sato et al., 2012, for details). The most important

594 preliminary conclusion to be drawn from Figure 10 is that the numerical modeling
 595 supports a multiple-forward-scattering origin for the observed VF events waveforms
 596 (and most likely other high-frequency events). We will now discuss more precisely the
 597 outcome of the inversions by analyzing the sensitivity of our results to the c^p/c^s ratio
 598 and the Hurst exponent. Finally, we will argue that the inversion results suggest a
 599 possible stratification of attenuation properties in Mars.

600 **5.1 Role of the Hurst exponent**

601 In Figure 10, we compare the outcome of the inversions for the two Hurst ex-
 602 ponents: $\kappa = 0.5, 2.0$. For all the events that we investigated, we observed that the
 603 largest value of κ systematically yields the best fit to the data. This suggests that
 604 Earth is richer in small-scale heterogeneities than Mars. In more informal terms, we
 605 may say that the interior of Mars appears smooth as compared to the Earth. It is
 606 worth noting that the correlation length derived from the models decreases strongly
 607 as κ increases. This is an example of trade-off that needs to be resolved in future
 608 works. However, we would like to point out that there are indications in the data
 609 that κ could indeed be larger on Mars than on Earth. We have already noted that
 610 the envelope shape of the VF events is remarkably independent of the frequency. In a
 611 medium with uniform scattering properties, such a behavior can only be reproduced in
 612 the forward-scattering regime ($\omega l_c/c^s > 1$) for sufficiently large values of κ , typically
 613 of the order of 2 or larger (see Calvet & Margerin, 2013). The fact that the best fits
 614 are obtained for $\kappa = 2$ is therefore consistent with the overall characteristics of the VF
 615 seismogram envelopes across multiple frequencies.

616 **5.2 Impact of the c^p/c^s ratio.**

617 The ratio c^p/c^s in the interior of Mars is so far not very well constrained and
 618 it is important to examine how it may affect the fit to the data. The presence of
 619 porosity in the shallow part of the crust may reduce c^p/c^s of the host rock. In Figure

620 11, we examine the case $c^p/c^s = 1.65$ and compare it with the reference models with
 621 $c^p/c^s = 1.85$. The Hurst exponent is set to 2. Overall, the best-fitting models obtained
 622 in the two cases are very similar and agree reasonably well with the data, except for
 623 the largest hypocentral distance. This result confirms the consistence of the data with
 624 a multiple-scattering hypothesis. Reciprocally, we may argue that it is unfortunately
 625 not possible to put constraints on the c^p/c^s ratio in the crust from envelope shapes
 626 alone.

627 5.3 Variability of scattering and attenuation parameters

628 To give an idea of the variability of the scattering and attenuation properties
 629 inferred from the envelope shape of VF events, the inversion procedure was applied to
 630 seven of them (S0128a, S0264e, S0334a, S0421a, S0424c, S0734a, S0756a) at a central
 631 frequency of 6 Hz with $c^p/c^s = 1.85$ and $\kappa = 2$. Figure 12 compiles the results of
 632 the inversion for the diffusivity (left), the scattering quality factor of S waves (center)
 633 and the intrinsic quality factor of S waves (right). We see that the diffusivity ranges
 634 from 50 to 800 km²/s, which suggests that the scattering attenuation on Mars is much
 635 more Earth-like than Moon-like. For the smallest hypocentral distances, the results are
 636 compatible with previous findings by Lognonné et al. (2020), based on the analysis of
 637 S0128a. Note that changing the average shear wavespeed to $c_s = 3$ km/s increases the
 638 inferred diffusivity by a factor approximately equal to 2.8. This result is a direct conse-
 639 quence of the linear increase of the hypocentral distance with c_s . By a simple similarity
 640 argument based on the diffusion model, the increase of the diffusivity due to an increase
 641 of c_s is expected to be equal to the ratio of the shear wavespeeds squared $(3/1.7)^2 \approx 3.1$,
 642 which is not far from the value 2.8 reported above. As for the attenuation, with an
 643 intrinsic quality factor Q_μ ranging from 3500 to 10000, Mars is found to be much more
 644 Moon-like than Earth-like. The albedo of the martian lithosphere is extremely high,
 645 typically of the order of 0.9, in sharp contrast with the Earth where the albedo rarely
 646 exceeds 0.5. **Some notable exceptions are volcanic areas (e.g. Mayeda et al.,**

1992) but only at sufficiently low frequencies, typically less than 3Hz. Recently, Scheller et al. (2021) proposed that vast amounts of water could be trapped in the crust of Mars. This model may be compatible with our observations, provided that some parts of the crust remain mostly dry. That the upper crust could be dry in the equatorial region near InSight is in agreement with the study of Clifford et al. (2010). To put our measurements of Q_μ in perspective, we recall that experiments on basalt samples by Tittmann et al. (1980) have revealed that high Q values (typically higher than 2500) can only be achieved through the complete degassing of the material, including the removal of intra-crystalline water. The Q_μ values we report in the present work are in fact higher than the highest values obtained by Tittman (1977) after several degassing cycles in vacuum. Unless our understanding of the role of water in the attenuation of seismic waves is incorrect, an important conclusion of our study is that the waveforms of VF events are compatible with a mostly dry crust.

In Figure 12, the increase of D , Q_{sc} and Q_μ with hypocentral distance (or equivalently with the proxy $(t_s - t_p)$) is particularly clear. In Linear-Log scale, the dependence is approximately linear, which suggests an empirical dependence of the form $y = y_0 \exp((t_s - t_p)/\xi)$ where y stands for D , Q_{sc} or Q_μ . Indeed, this simple form is seen to fit the observations reasonably well. These results show clearly that, while it reasonably fits the observed seismogram envelopes individually, a uniform scattering model cannot explain simultaneously all the records. Furthermore, we observe that as the hypocentral distance increases, attenuation by scattering and absorption appear to decrease. Under the reasonable assumption that the sensitivity to deep structures increases with hypocentral distance, a natural explanation for the trend seen in Figure 12 is that there exists a stratification of attenuation properties inside Mars. More precisely, we may expect a rapid decrease of attenuation with depth. **Recent results by Knapmeyer-Endrun et al. (2021) indicate that, while this is not apparent from the seismogram envelopes of VF events, the crust of Mars is stratified. Determining the depth dependence of Mar-**

675 **tian attenuation taking into account the stratification of velocities in the litho-**
676 **sphere will undoubtedly be an important topic for future works.**

677 **6 Conclusions**

678 In this paper, we have investigated the envelope and attenuation characteristics
679 of high-quality high-frequency martian events recorded by the instrument SEIS in the
680 framework of the InSight mission. The main conclusion of our investigations is that
681 these events are compatible with the propagation of elastic waves radiated by internal
682 sources in a multiple-scattering medium. This statement is attested by the overall
683 good agreement between synthetic envelopes predicted by elastic radiative transfer
684 models and observed envelopes. Data analysis and modeling has also revealed some
685 outstanding features. (1) As compared to high-frequency quakes observed on Earth
686 or on the Moon, the envelope shape of high-frequency martian events is remarkably
687 weakly dependent on frequency. The coda decay is characterized by an almost constant
688 attenuation, reflected in the linear increase of the coda quality factor with frequency.
689 The delay-time is also very weakly frequency-dependent, in sharp contrast what is
690 observed on earthquakes and moonquakes waveforms. (2) Numerical inversions of
691 the seismogram envelopes of high-frequency martian events with an elastic radiative
692 transfer model show that the observations can be explained by multiple-scattering in
693 smooth models of heterogeneity with a correlation distance in the range 70 - 240 m and
694 a Hurst exponent $\kappa = 2$. The overall strength of the scattering is found to be Earth-like.
695 We also found that the attenuation parameters apparently increase with hypocentral
696 distance, which we interpret as a possible signature of a stratification of heterogeneity
697 in Mars (van Driel et al., 2021). (3) Finally, with a frequency-independent albedo of
698 about 0.9, we found that attenuation (dissipation of seismic energy) is very low in
699 Mars. This finding indicates that the high-frequency Martian events sample mostly
700 dry materials. This issue requires further investigation. In future works, we propose

701 in particular to develop stratified models of scattering and attenuation to test the
702 compatibility of our data with the presence of layers with high levels of dissipation.

703 **Data and Resources**

704 Seismic data used for this study were collected as part of the NASA InSight (In-
705 terior Exploration using Seismic Investigations, Geodesy and Heat Transport, Banerdt
706 et al., 2020) Mission to Mars using SEIS (Seismic Experiment for Interior Structure)
707 seismometer (Lognonné et al., 2019). They can be uploaded on the IRIS Data Man-
708 agement Center website (<https://www.iris.edu/hq/sis/insight>), the NASA PDS Geo-
709 science Node (InSight SEIS Science Team, 2019) and the IPGP SEIS Data portal
710 (InSight Mars SEIS Data Service., 2019).

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Tables

Table 1: List of events analyzed in this study. $t_{p,s}$: arrival time of primary, secondary arrival (expressed in Universal Time Coordinated). The coda start time is determined empirically and corresponds to the observation of steady decay long after the passage of the secondary wavetrain. The coda end time is determined by the S/N ratio (always greater than 2). The distance range corresponds to the assumptions $c_s = 3.0\text{km/s}$, $c_p/c_s = 1.85$ and $c_s = 1.7\text{km/s}$, $c_p/c_s = 1.65$.

Event	Type	Date	t_p	t_s	Coda start time	Coda end time	Distance range (km)
S0239a	HF	2019/07/30	14:16:59	14:21:46	14:23:06	14:25:36	[1243, 1881]
S0260a	HF	2019/08/21	05:11:21	05:15:53	05:18:43	05:22:33	[1180, 1785]
S0291c	HF	2019/09/22	03:46:14	03:49:58	03:52:38	03:54:18	[971, 1469]
S0304b	HF	2019/10/05	12:47:55	12:51:54	12:54:24	12:56:54	[1027, 1554]
S0308a	HF	2019/10/09	15:45:53	15:50:28	15:53:08	15:55:48	[1187, 1796]
S0314b	HF	2019/10/15	15:41:40	15:48:58	15:51:38	15:54:38	[1053, 1593]
S0319b	HF	2019/10/20	17:44:55	17:48:30	17:49:50	17:52:50	[1230, 1861]
S0327c	HF	2019/10/29	04:03:21	04:06:40	04:08:40	04:11:20	[859, 1300]
S0331a	HF	2019/11/01	08:40:32	08:44:15	08:46:55	08:49:55	[1054, 1594]
S0343b	HF	2019/11/14	11:59:43	12:04:49	12:06:49	12:09:09	[1321, 1998]
S0352a	HF	2019/11/23	18:18:46	18:22:56	18:24:36	18:27:16	[1208, 1828]
S0384b	HF	2019/12/26	13:10:25	13:13:22	13:16:02	13:18:42	[807, 1221]
S0392a	HF	2020/01/03	17:25:23	17:29:30	17:32:10	17:34:40	[1213, 1835]
S0128a	VF	2019/04/07	09:33:26	09:34:50	09:36:50	09:41:50	[363, 550]
S0263a	VF	2019/08/23	11:09:30	11:10:26	11:11:46	11:14:06	[240, 364]
S0264e	VF	2019/08/25	10:31:20	10:37:24	10:39:24	10:43:34	[1571, 2377]
S0334a	VF	2019/11/05	04:55:03	04:58:23	05:00:03	05:04:13	[863, 1308]
S0421a	VF	2020/02/02	17:38:08	17:44:56	17:47:16	17:50:16	[1762, 2667]
S0424c	VF	2020/02/05	17:29:56	17:35:32	17:37:32	17:41:22	[1450, 2194]
S0734a	VF	2020/12/19	10:14:00	10:15:21	10:17:01	10:19:31	[348, 527]
S0756a	VF	2021/01/11	01:12:07	01:15:07	01:17:27	01:21:37	[777, 1176]

Table 2: Geographical location and reference associated to the Q_c measurements shown in Figure 9.

Label	Location	Articles
1	Wakayama Shallow, Japan (40 - 45 s)	(KANAOKA & ITO, 1991)
2	Nagoya Shallow, Japan (50 - 60 s)	(KANAOKA & ITO, 1991)
3	Western Nagano, Japan	(Kosuga, 1992)
4	Kanto-Tokai, Japan (V. compo. average)	(Fehler et al., 1992)
5	Granada zone, southern Spain (90 s)	(Ibanez et al., 1990)
6	Southern Sicily, Italy (50 s)	(Giampiccolo et al., 2004)
7	Southern Apennines zone, Italy	(Bianco et al., 2002)
8	Konya region, India (40 s)	(Gupta et al., 1998)
9	Kachchh Basin, western India (50 - 80 s)	(Gupta et al., 2006)
10	Long Valley, California	(Mayeda et al., 1992)
11	Central California	(Mayeda et al., 1992),
12	Hawaii	(Mayeda et al., 1992)
13	Straits of Messina area, southern Italy (60 s)	(Tuvè et al., 2006)
14	Kothagudem, southern India	(Kumar et al., 2007)
15	Cuddapah, southern India	(Kumar et al., 2007)
16	Dharwar, southern India	(Kumar et al., 2007)
17	Singhbhum Odisha craton, eastern India	(Biswas et al., 2019)
18	Chotanagpur granitic gneissic terrain, eastern India	(Biswas et al., 2019)
19	Eastern Ghat mobile belt, eastern India	(Biswas et al., 2019)
20	Continental United States	(Singh & Herrmann, 1983)
21	New Brunswick, eastern Canada	(C. R. Woodgold, 1990)
22	Near Ottawa, eastern Canada	(C. R. Woodgold, 1990)
23	Adirondack Mountains, eastern Canada	(C. R. Woodgold, 1990)
24	near Val-d'Or, Quebec, eastern Canada	(C. R. Woodgold, 1990)
25	St. Lawrence River, eastern Canada	(C. R. Woodgold, 1990)
26	Indian shield	(Singh et al., 2004)
27	East European shield	(Mitchell et al., 2008)
28	Siberian shield	(Mitchell et al., 2008)
29	Arabian shield	(Mitchell et al., 2008)
30	Northwest of Africa	(Xie & Mitchell, 1990)
31	Northeast of Africa (Sahara)	(Xie & Mitchell, 1990)
32	Kalahari Craton	(Xie & Mitchell, 1990)
33	Brazilian shield	(De Souza & Mitchell, 1998)
34	InSight	Event S0734a ($\alpha = 0$)
35	InSight	Event S0734a ($\alpha = 1$)
36	InSight	VF events ($\alpha = 0$)
37	InSight	VF events ($\alpha = 1$)
38	Apollo mission (The Moon)	(Gillet et al., 2017)

998 **List of Figure Captions**

999 • **Figure 1** (a) Waveform filtered at 3.5 Hz (top) and spectrogram (bottom) of
 1000 the vertical component of the S0334 VF event recorded by the VBB sensor at
 1001 20 samples per seconds. The arrival times of the first and second arrivals are
 1002 denoted by t_p and t_s respectively and are indicated with red dashed lines. Time
 1003 $t = 0$ coincides with the onset of the first arrival. (b) Same as (a) for the HF
 1004 event S0314b.

1005 • **Figure 2** Spectral amplitude (m/Hz) as a function of frequency: (a) total spec-
 1006 tral amplitude, (b) vertical component spectral amplitude, (c) horizontal com-
 1007 ponents spectral amplitude for HF events (blue) and VF events (red). At each
 1008 frequency, the mean energy is measured on the vertical and horizontal compo-
 1009 nents in a time window of 200 s duration starting after the second arrival. The
 1010 RMS amplitude has been normalized by the bandwidth.

1011 • **Figure 3** Envelope characteristics of the VF event S0734a. The data were
 1012 collected on the VBB sensors with sampling rates of 20 sps. (a): Base 10
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 1014 time and fit of the coda decay (black dashed lines). The gray dashed line
 1015 indicates $S/N = 2$. The different colors correspond to different frequency bands
 1016 indicated in inset. The time $t = 0$ s correspond to the first arrival. t_p and
 1017 t_s refer to the arrival times of the first and second wave packets (red dashed
 1018 lines). The black dots show the arrival times of the energy maximum (t_{max}).
 1019 The magenta and purple dashed lines indicate the mean and standard deviation
 1020 of t_{max} in the 2.5 - 7.5 Hz band. (b) Frequency dependence of Q_c in the 2.5 -
 1021 7.5 Hz frequency band. The color bar indicates the S/N ratio measured on the
 1022 horizontal components. The dashed line shows the power-law fit $Q_c = 440f^{1.08}$
 1023 (f is the frequency). (c) Delay time ($t_d = t_{max} - t_s$) as a function of frequency.

1024 The magenta and purple dashed lines show the mean and standard deviation of
 1025 t_d in the 2.5 - 7.5 Hz band.

1026 • **Figure 4** Envelope characteristics of a regional event ($m_b = 4.0$) recorded by
 1027 a VBB seismometer (Streckheisen STS-1) on the 2007-07-16 at station FRB
 1028 (Iqaluit, Canada). The quake location is 65.11°N , 86.81°W , corresponding to
 1029 an epicentral distance of approximately 900km (information provided by IRIS-
 1030 DMC). (a)-(c): same as Figure 3 except for the power law fit $Q_c = 740f^{0.49}$.

1031 • **Figure 5** Horizontal envelope characteristics of 13 HF events (blue) and 8 VF
 1032 events (green). Left: delay-time measurements (t_d) as a function of traveltime
 1033 difference between second and first arrivals ($t_s - t_p$). Right: Q_c measurements as
 1034 a function of $t_s - t_p$ at 3.5 Hz. Dark and light colours correspond to the choice
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1036 • **Figure 6** Coda quality factor Q_c as a function of the mean signal-to-noise ratio
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 1041 duration after the direct S-wave onset. The black dashed line refer to $S/N = 2$.

1042 • **Figure 7** Noise sensitivity analysis applied to the VF event S0334a. Top: Coda
 1043 quality factor as a function of the signal-to-noise ratio (S/N) at 2.5 Hz (left)
 1044 and 7.5 Hz (right). S/N measured are calculated in a window of 200 s duration
 1045 starting at the second arrival onset. Noise data recorded at the same LMST
 1046 (Local Mean Solar Time) on Sol 333 has been added to the data. In inset, we
 1047 indicate the amplitude factor k applied to the noise prior to addition to the
 1048 signal ($k \in \{0, 1, 2, 3, 4, 5\}$).

- 1049 • **Figure 8** Q_0 and n computed as a function of $t_s - t_p$ for the 8 VF events
 1050 selected. Dark and light colours correspond to the choice $\alpha = 0$ and $\alpha = 1$ in
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- 1053 • **Figure 9** Coda attenuation Q_c^{-1} as a function of the frequency for different
 1054 regions on Earth (blue for tectonically active, green-yellow for cratons), the
 1055 Moon (grey) and Mars (with $\alpha = 0$ in red and $\alpha = 1$ in orange). The numbers
 1056 in inset refer to Table 2 where more details can be found on the geographical
 1057 locations for Earth data, as well as the references of the original publications.
- 1058 • **Figure 10** Radiative transfer modeling of the energy envelope of three VF
 1059 events: (a) S0734a, (b) S0756a and (c) S0421a VF. The dashed black lines
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 1061 6 Hz. The green and blue lines show the best-fitting radiative transfer models
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 1063 1.85 and $c^s = 1.7$ km/s.
- 1064 • **Figure 11** Radiative transfer modeling of the energy envelope of three VF
 1065 events: (a) S0734a, (b) S0756a and (c) S0421a VF. The dashed black lines
 1066 correspond to the energy envelope of the horizontal components filtered around
 1067 6 Hz. The red and blue lines show the best-fitting radiative transfer models
 1068 with $c^p/c^s = 1.65$ and $c^p/c^s = 1.85$, respectively. In these examples κ is set to
 1069 2 and $c^s = 1.7$ km/s.
- 1070 • **Figure 12** Inversion results for seven VF events. (a) Diffusivity (km^2/s), (b)
 1071 S-wave scattering quality factor and (c) S-wave absorption quality factor as a
 1072 function of $(t_s - t_p)$ for selected VF events. The dashed line shows the best fit
 1073 to the data assuming a law of the form $y = y_0 \exp(t_s - t_p)/\xi$.

Figures

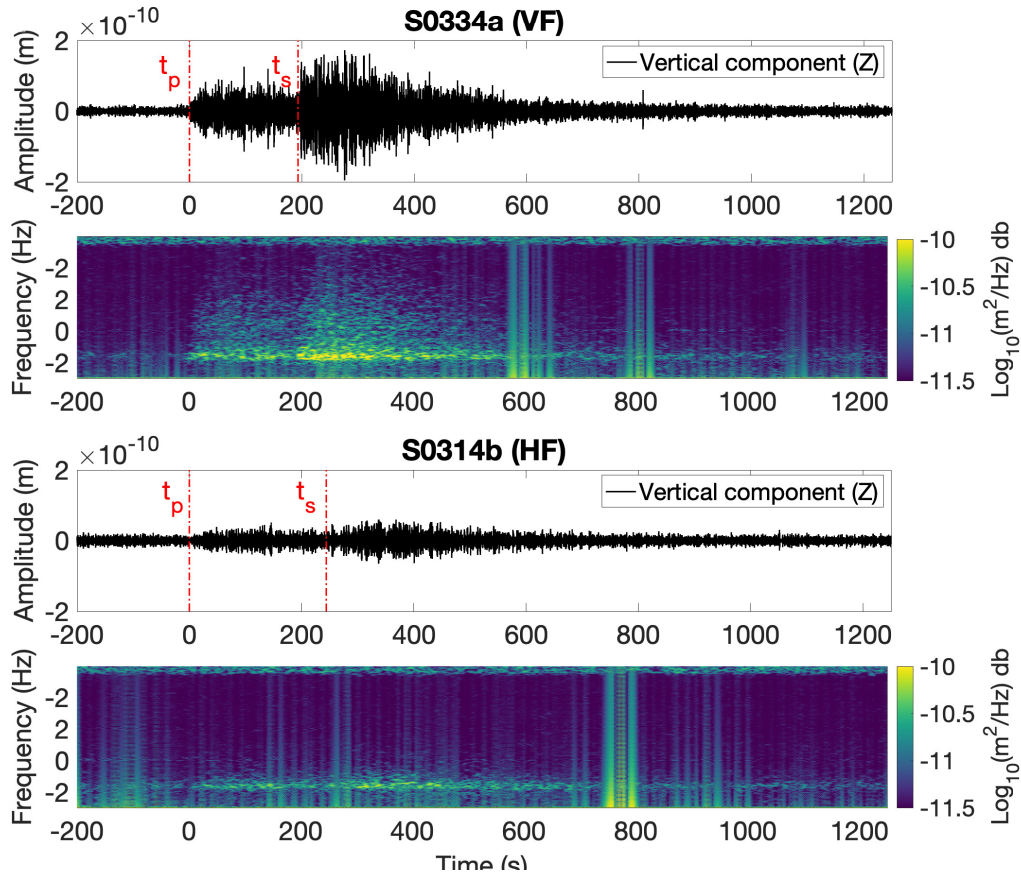


Figure 1: (a) Waveform filtered at 3.5 Hz (top) and spectrogram (bottom) of the vertical component of the S0334 VF event recorded by the VBB sensor at 20 samples per seconds. The arrival times of the first and second arrivals are denoted by t_p and t_s respectively and are indicated with red dashed lines. Time $t = 0$ coincides with the onset of the first arrival. (b) Same as (a) for the HF event S0314b.

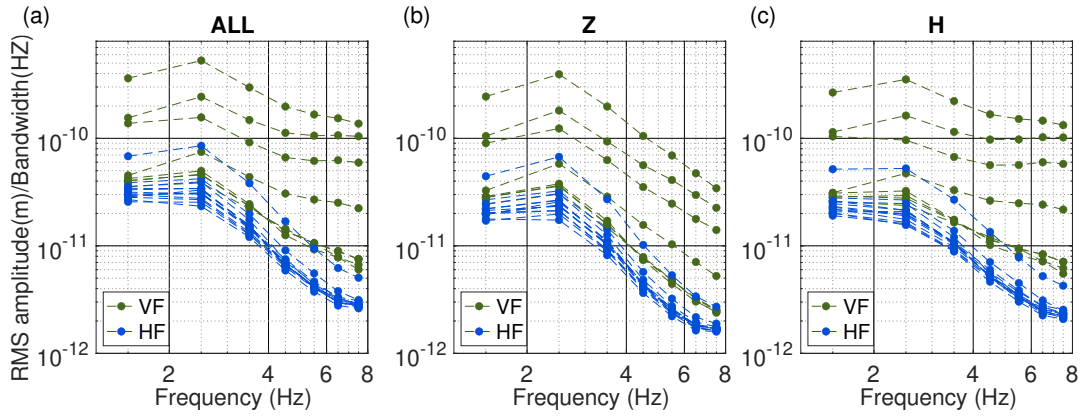


Figure 2: Spectral amplitude (m/Hz) as a function of frequency: (a) total spectral amplitude, (b) vertical component spectral amplitude, (c) horizontal components spectral amplitude for HF events (blue) and VF events (red). At each frequency, the mean energy is measured on the vertical and horizontal components in a time window of 200 s duration starting after the second arrival. The RMS amplitude has been normalized by the bandwidth.

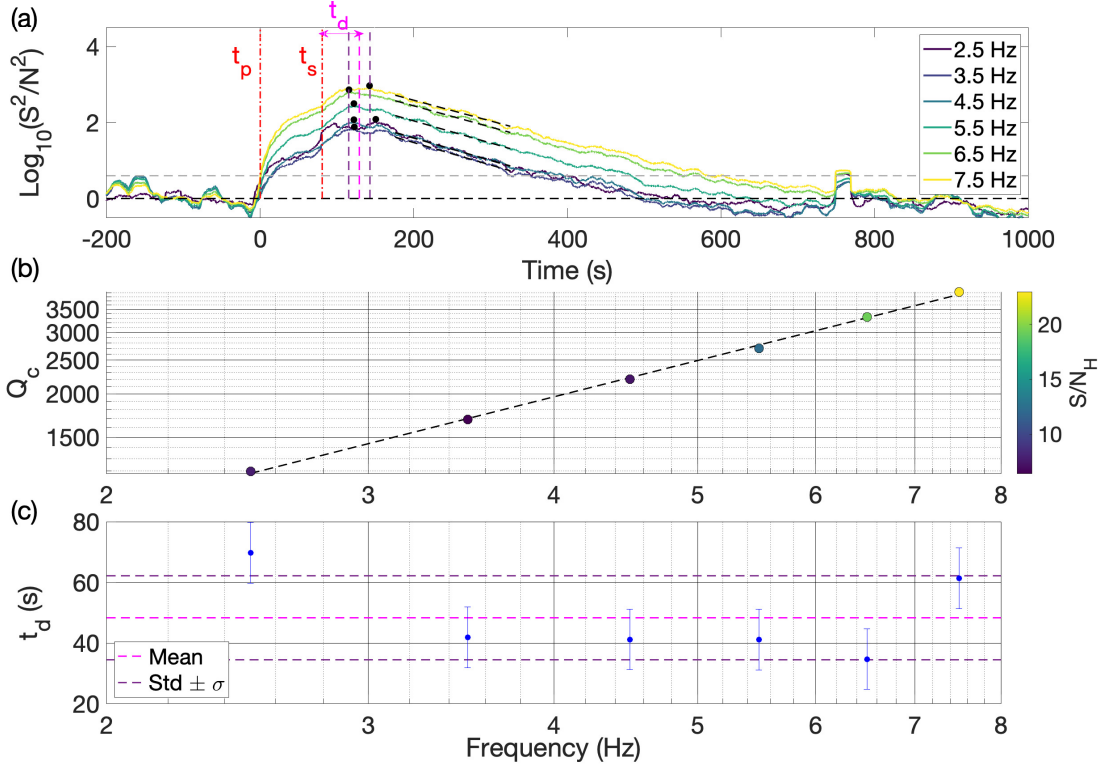


Figure 3: Envelope characteristics of the VF event S0734a. The data were collected on the VBB sensors with sampling rates of 20 sps. (a): Base 10 logarithm of energy envelopes normalized by the noise level as a function of time and fit of the coda decay (black dashed lines). The gray dashed line indicates $S/N = 2$. The different colors correspond to different frequency bands indicated in inset. The time $t = 0$ s correspond to the first arrival. t_p and t_s refer to the arrival times of the first and second wave packets (red dashed lines). The black dots show the arrival times of the energy maximum (t_{max}). The magenta and purple dashed lines indicate the mean and standard deviation of t_{max} in the 2.5 - 7.5 Hz band. (b) Frequency dependence of Q_c in the 2.5 - 7.5 Hz frequency band. The color bar indicates the S/N ratio measured on the horizontal components. The dashed line shows the power-law fit $Q_c = 440f^{1.08}$ (f is the frequency). (c) Delay time ($t_d = t_{max} - t_s$) as a function of frequency. The magenta and purple dashed lines show the mean and standard deviation of t_d in the 2.5 - 7.5 Hz band.

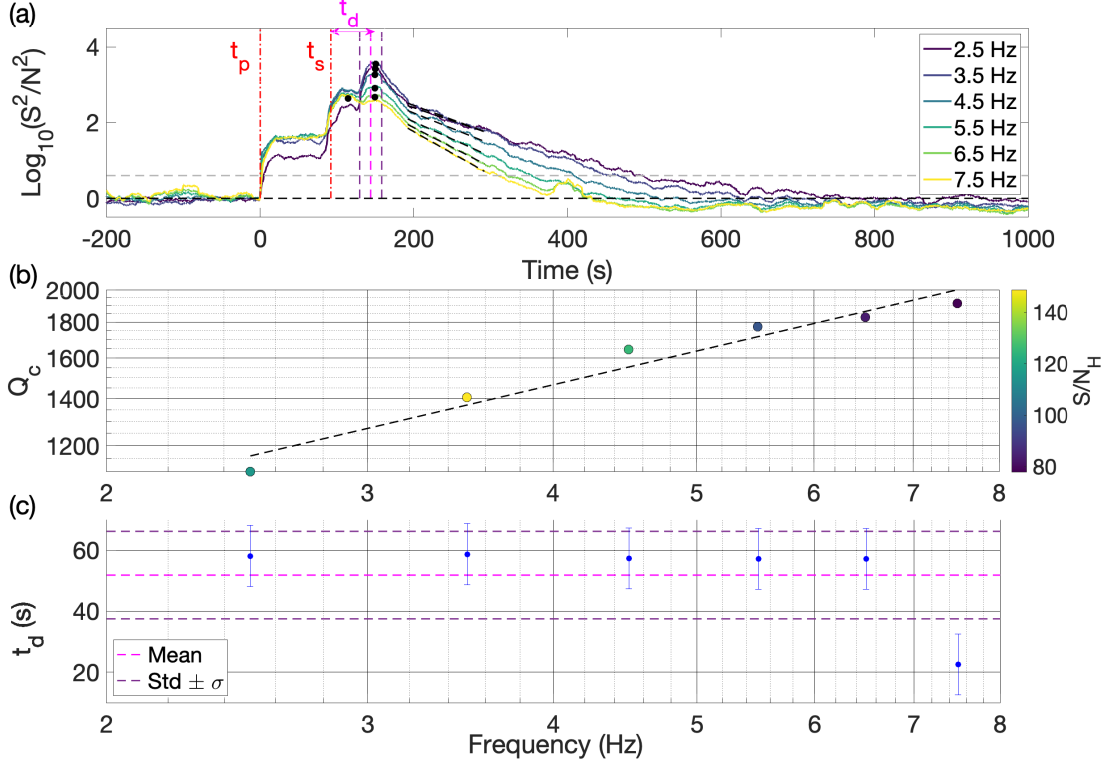


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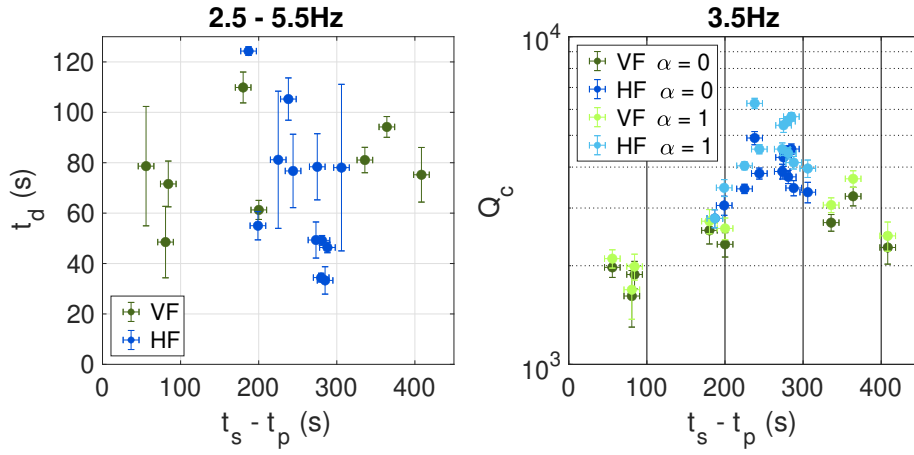


Figure 5: Horizontal envelope characteristics of 13 HF events (blue) and 8 VF events (green). Left: delay-time measurements (t_d) as a function of traveltime difference between second and first arrivals ($t_s - t_p$). Right: Q_c measurements as a function of $t_s - t_p$ at 3.5 Hz. Dark and light colours correspond to the choice $\alpha = 0$ and $\alpha = 1$ in Eq. (1), respectively.

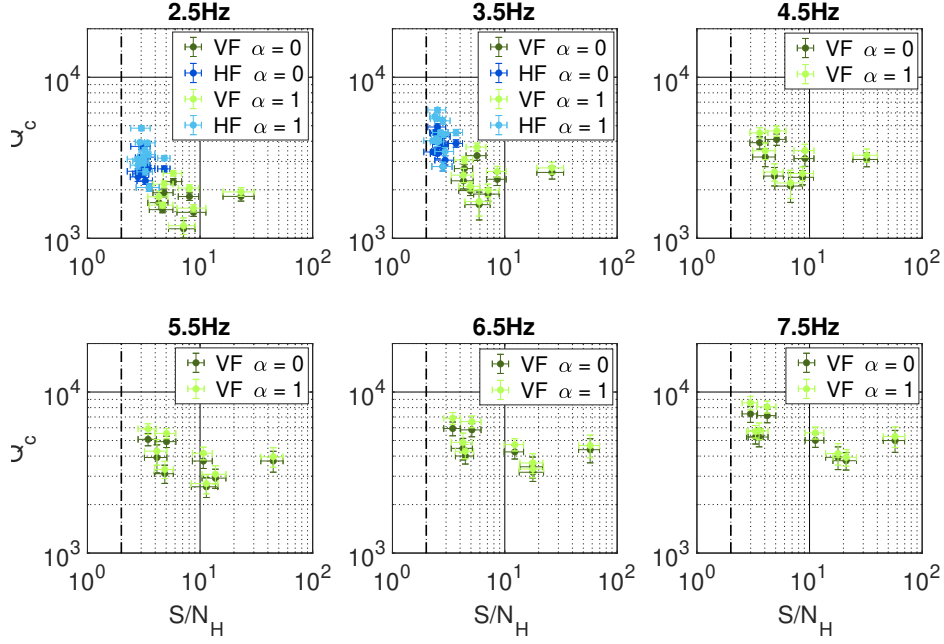


Figure 6: Coda quality factor Q_c as a function of the mean signal-to-noise ratio (S/N) in the 2.5 - 7.5 Hz frequency band for 13 HF events (blue) and 8 VF events (green). The measurements were performed on the horizontal components. Dark and light colours correspond to the choice $\alpha = 0$ and $\alpha = 1$ in Eq. (1), respectively. The mean S/N ratio is calculated in a window of 200 s duration after the direct S-wave onset. The black dashed line refer to $S/N = 2$.

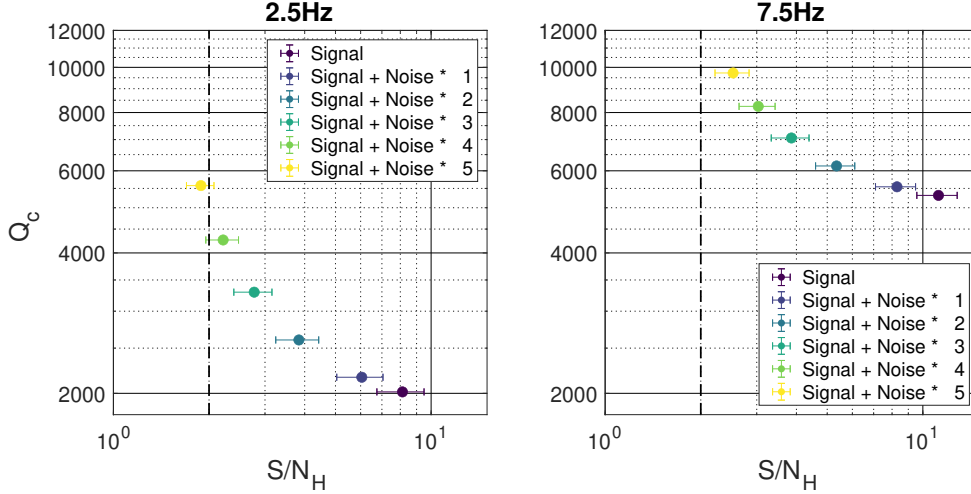


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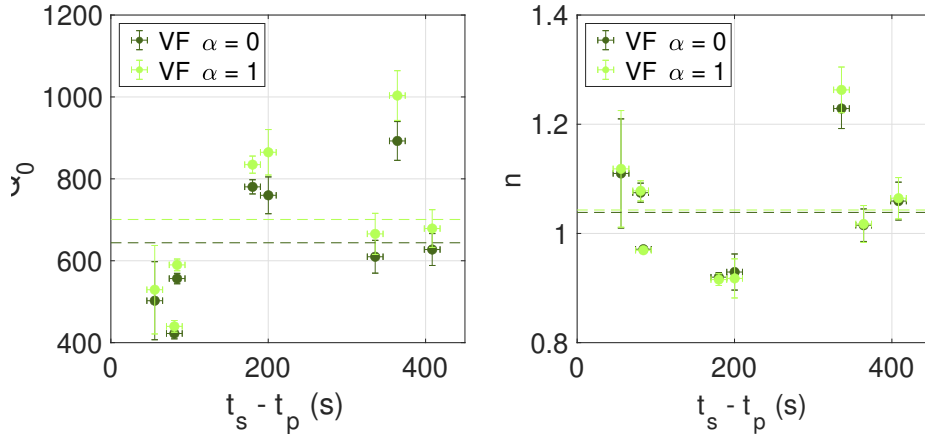


Figure 8: Q_0 and n computed as a function of $t_s - t_p$ for the 8 VF events selected. Dark and light colours correspond to the choice $\alpha = 0$ and $\alpha = 1$ in Eq. (1), respectively. The dashed lines refers to the mean values for $\alpha = 0$ ($Q_0 = 644$ and $n = 1.04$) and $\alpha = 1$ ($Q_0 = 701$ and $n = 1.038$).

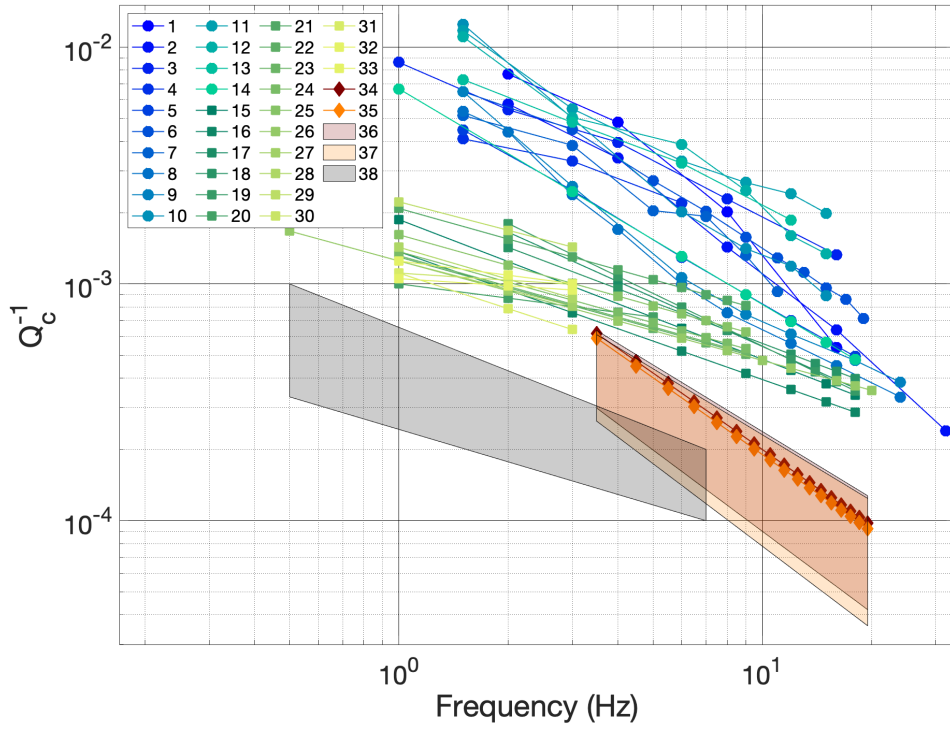


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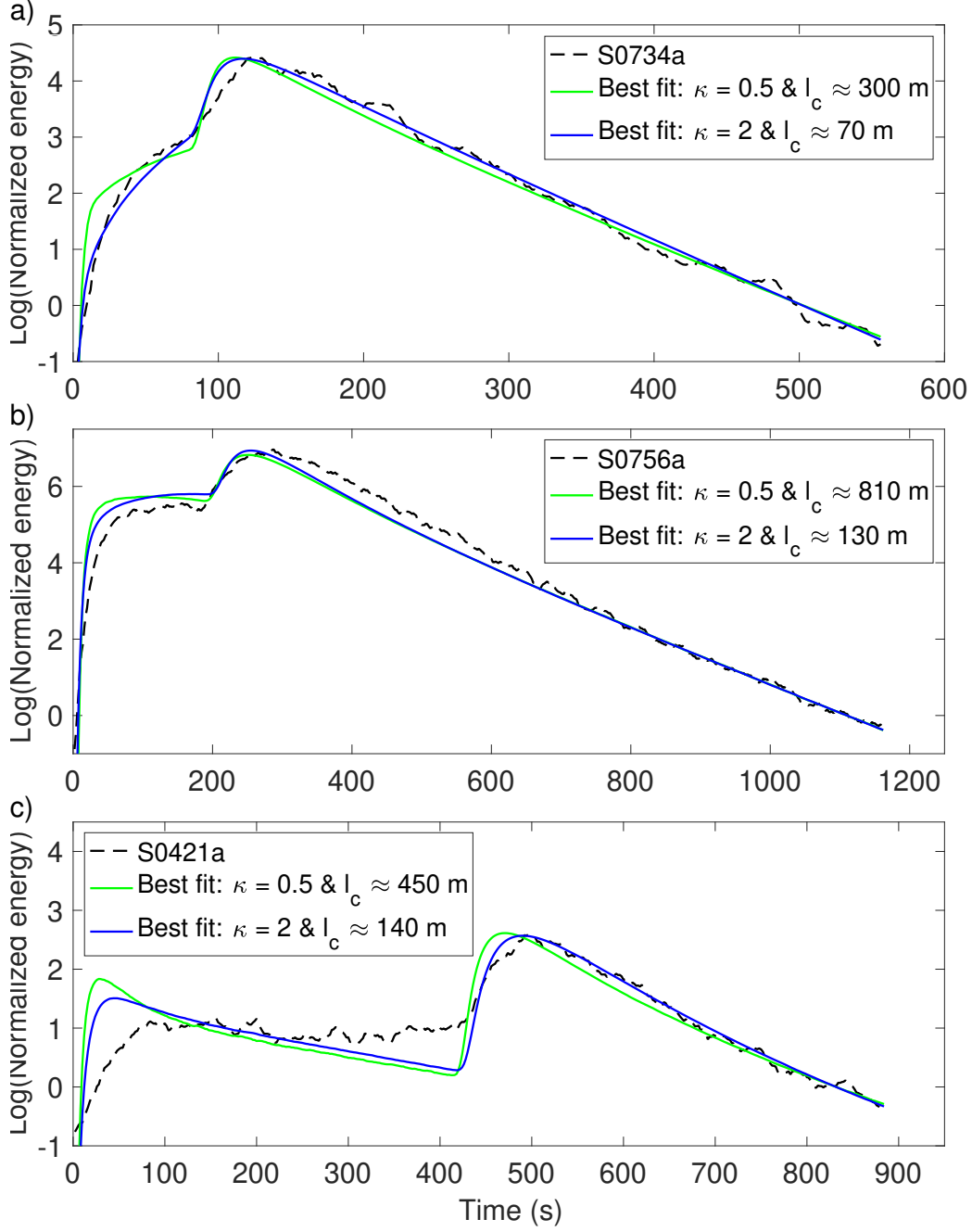


Figure 10: Radiative transfer modeling of the energy envelope of three VF events: (a) S0734a, (b) S0756a and (c) S0421a VF. The dashed black lines correspond to the energy envelope of the horizontal components filtered around 6 Hz. The green and blue lines show the best-fitting radiative transfer models with $\kappa = 0.5$ and $\kappa = 2$ respectively. In these examples the c^p/c^s ratio is set to 1.85 and $c^s = 1.7\text{km/s}$.

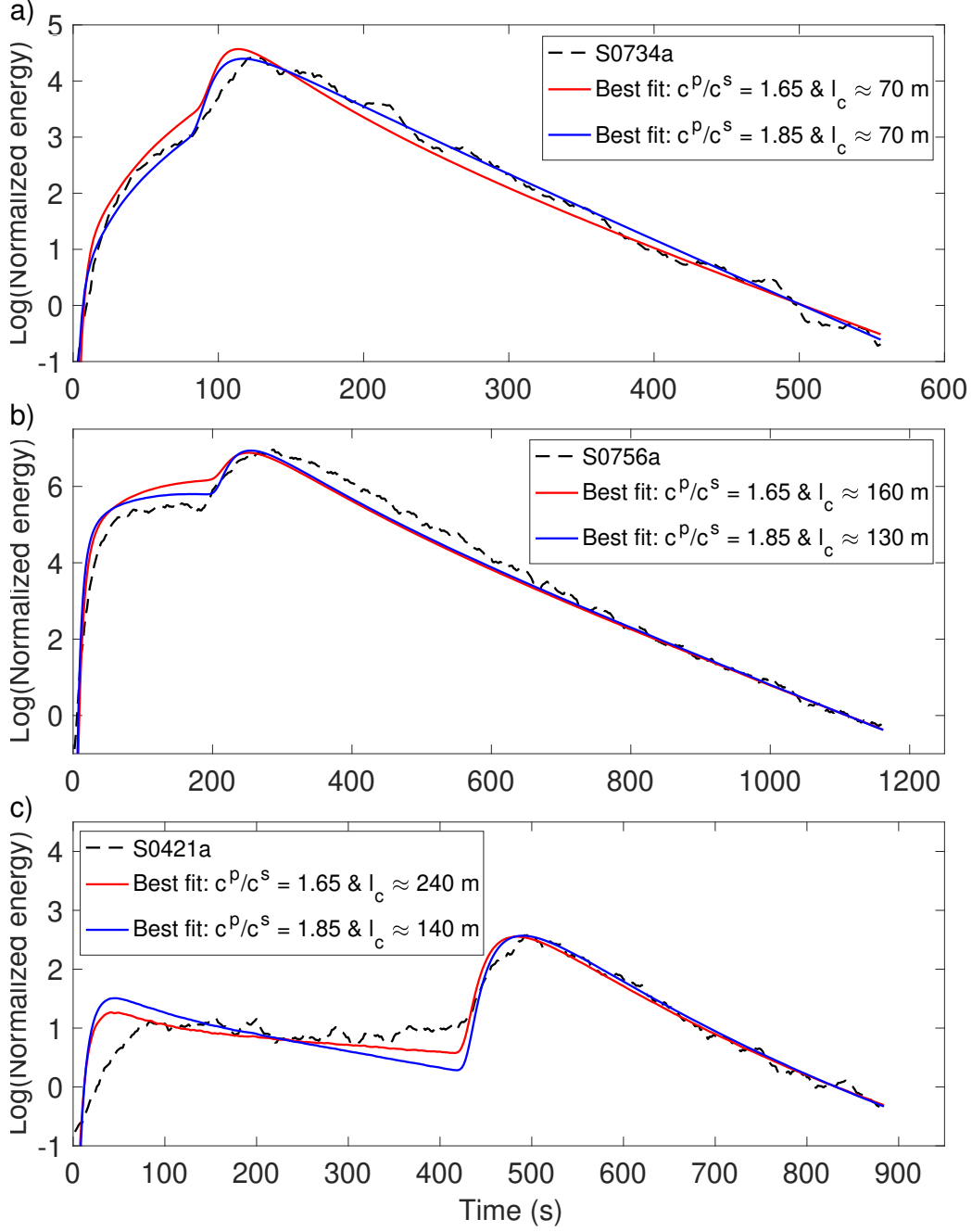


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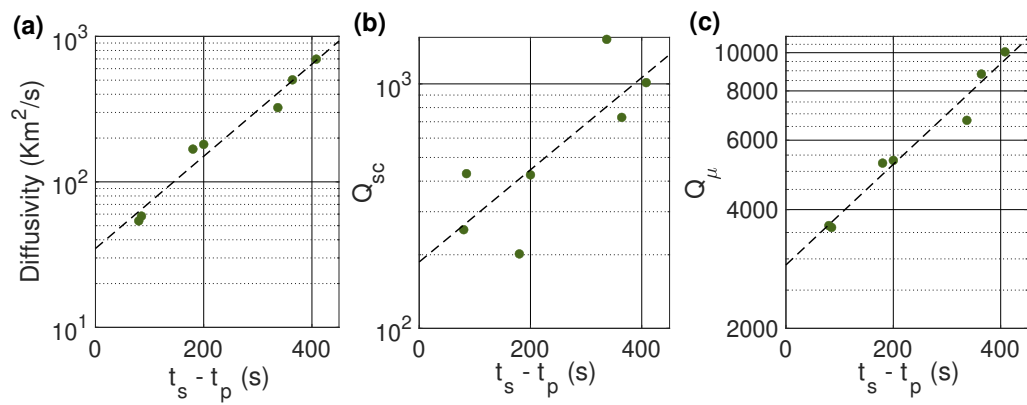


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1075 **Appendices**

1076 **A Envelope analysis of VF event S0734a using SP data**

1077 In this appendix, we show the envelope characteristics of VF event S0734a as
 1078 seen by the SP sensor in the 3 - 20 Hz frequency band. Figure A.1 complements
 1079 Figure 3 presented in the main body of the text. For frequencies higher than 10 Hz,
 1080 we note some contamination of the envelopes by short transients (donks), which occur
 1081 permanently and independent of seismic events (Ceylan et al., 2021). They entail
 1082 fluctuations in the measurements of the time delay, as reflected in Figure A.1c. Data
 1083 from the SP seismometer allow us to confirm the close to linear increase of the coda
 1084 quality factor observed on the VBB, as well as the very weak frequency dependence
 1085 of the peak delay time. We found $Q_0 = 476 \pm 9$ and $n = 1.05 \pm 0.02$ for $\alpha = 1$ (
 1086 $Q_0 = 431 \pm 7$ and $n = 1.06 \pm 0.02$ for $\alpha = 0$), which is in reasonable agreement with
 1087 the measurements performed on the VBB in the 2.5 - 7.5 Hz band.

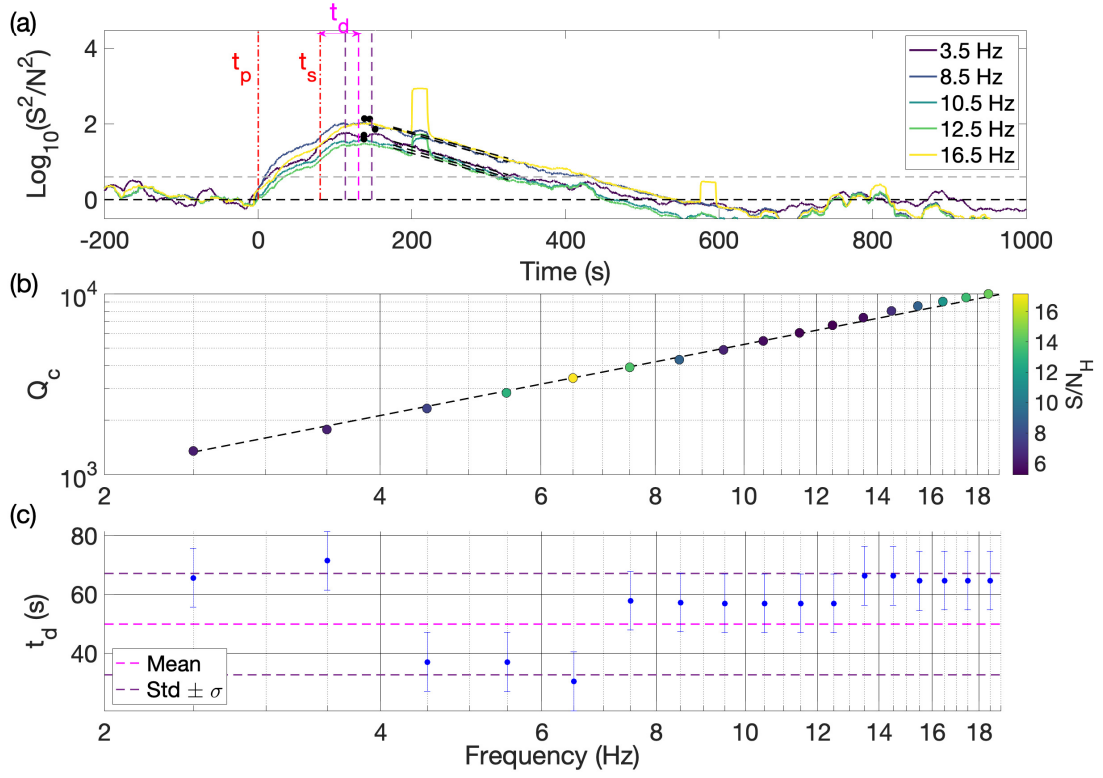


Figure A.1: Envelope characteristics of the VF event S0734a event. The data were collected by the SP sensors with sampling rates of 100 sps. (a) same as Figure 3. (b) same as Figure 3.b except for the power-law fit $Q_c = 476f^{1.05}$ (f is the frequency). (c) Same as Figure 3.