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Autocorrelation of the ground vibrations recorded by the SEIS-InSight seismometer on Mars.

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Key Points:

- Autocorrelation functions of SEIS ambient vibrations and seismic events are computed and validated by inter-comparison
- The stability of autocorrelations at 2.4Hz resonance favor an excitation by a diffuse seismic wavefield
- Various arrivals are observed in autocorrelation functions and interpreted as seismic reflections on internal discontinuities

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32 Abstract

33 Since early February 2019, the SEIS seismometer deployed at the surface of Mars
34 in the framework of the InSight mission has been continuously recording the ground mo-
35 tion at Elysium Planitia. In this work, we take advantage of this exceptional dataset to
36 put constraints on the crustal properties of Mars using seismic interferometry (SI). To
37 carry out this task, we first examine the continuous records from the very broadband seis-
38 mometer (SEIS-VBB). Several deterministic sources of environmental noise are identi-
39 fied and specific pre-processing strategies are presented to mitigate their influence. Ap-
40 plying the principles of SI to the single-station configuration of InSight, we compute, for
41 each Sol and each hour of the martian day, the diagonal elements of the time-domain cor-
42 relation tensor of random ambient vibrations recorded by SEIS. A similar computation
43 is performed on the diffuse waveforms generated by more than a hundred Marsquakes.
44 A careful signal-to-noise ratio analysis and an inter-comparison between the two datasets
45 suggest that the results from SI are most reliable in a narrow frequency band around 2.4Hz,
46 where an amplification of both ambient vibrations and seismic events is observed. The
47 average autocorrelation functions (ACFs) contain well identifiable seismic arrivals, that
48 are very consistent between the two datasets. Interpreting the vertical and horizontal
49 ACFs as, respectively, the P- and S- seismic reflectivity below InSight, we propose a sim-
50 ple stratified velocity model of the crust, which is mostly compatible with previous re-
51 sults from Receiver Function analysis. Our results are discussed and compared to recent
52 works from the literature.

53 Plain Language Summary

54 The correlation of seismic records is the basis of seismic interferometry methods.
55 These methods use seismic waves, either from ambient vibrations of the planet or from
56 quakes, that are scattered in the medium in order to recover information about the struc-
57 ture between two seismic sensors. The method is implemented to compute the auto-correlation
58 functions of the three components of the ground motion recorded by the SEIS seismome-
59 ter. The comparison of the results obtained from earthquake data to the ones obtained
60 from ambient vibrations demonstrates that the ambient seismic vibration is clearly above
61 the self-noise of SEIS during early night hours around a specific frequency (2.4Hz). The
62 seismic vibrations appear to be amplified at this frequency by an unknown mechanism.
63 Some seismic energy arrivals appear consistently in the auto-correlation functions, at spe-
64 cific propagation times, independent of the data sets and processing parameters tested.
65 These arrivals are interpreted as vertically propagating seismic waves which are reflected
66 on top of crustal layers. Their propagation times can be used to constrain a model of
67 Mars crustal structure.

68 **1 INTRODUCTION**

69 NASA’s InSight (Interior Exploration using Seismic Investigations, Geodesy and
 70 Heat Transport) mission landed on November 26, 2018 near the Martian equator in Ely-
 71 sium Planitia (Banerdt et al., 2020). The seismological records provided by the main in-
 72 strument -SEIS (Seismic Experiment for Interior Structure)- constitute a dataset of un-
 73 precedented quality for planetary seismology. The seismometer sensitivity and the ex-
 74 tremely low amplitude of the ambient ground vibrations make the martian seismic sig-
 75 nals very different from those collected on Earth (Lognonné et al., 2019, 2020). Not all
 76 the features of the ground velocity records can be interpreted as seismic signals, and all
 77 the details of the InSight mission system have to be taken into account to correctly in-
 78 terpret the data. Among these, we mention the lander-related noise, the electrical noise,
 79 the atmospheric noise and all the mechanical resonances that are temperature depen-
 80 dent (Murdoch, Mimoun, et al., 2017; Murdoch, Kenda, et al., 2017; Lognonné et al., 2020;
 81 Garcia et al., 2020). Henceforth, we refer to these as “environmental noise”.

82 Planetary bodies like the Moon or Mars have a much lower seismicity-rate com-
 83 pared to Earth due to the absence of plate tectonics. As a consequence, the scarcity and
 84 low amplitude of seismic sources can be an issue for seismological applications. Fortu-
 85 nately, the last twenty years have seen the rapid development of new processing meth-
 86 ods which allow seismologists to extract meaningful seismological signals from passive
 87 records of random vibrations generated by natural processes such as winds, earthquakes,
 88 etc. (Nakata et al., 2019). These methods are often referred to collectively as “seismic
 89 interferometry”. They are based on the close relation between the mean correlation func-
 90 tion C_{AB} of diffuse seismic wavefields recorded at any two stations A and B and the Green’s
 91 function G_{AB} between A and B (Lobkis & Weaver, 2001; Campillo & Paul, 2003). We
 92 recall that the Green’s function is the seismic response recorded at A due to an impul-
 93 sive source operating at B . Because seismic wavefields are rarely perfectly diffuse, the
 94 signal reconstructed by cross-correlating random seismic signals is referred to as “Em-
 95 pirical” Green’s function as it will in general deviate from the exact Green’s function of
 96 the medium (Weaver & Lobkis, 2005). We will also adopt this terminology.

97 Seismic interferometry has been applied with success to Lunar seismic data (Larose
 98 et al., 2005). These authors demonstrated the possibility to virtually reconstruct prop-
 99 agating Rayleigh waves by cross-correlating ambient vibrations recorded on an array of
 100 geophones deployed in the framework of the Apollo Lunar Seismic Profiling Experiment.
 101 Using the dispersion properties of surface waves, they were able to put constraints on
 102 the shear wave speed profile in the Lunar regolith, thereby gleaning new insights from
 103 an already prolific dataset (Garcia et al., 2019; Nunn et al., 2020). The experimental con-
 104 ditions of InSight are more specific in the sense that only a single (6-axis) sensor is at
 105 our disposal. In this situation, the most direct observables are Auto-Correlation Func-
 106 tions (ACF). This is by no means a severe limitation. Indeed, it is known since the works
 107 of Claerbout (1968), that the reflection response of a stack of layers located beneath a
 108 single seismometer can be retrieved from its transmission response. In other words, if
 109 the medium is illuminated from below, computing the ACF of the transmitted wavefield
 110 is essentially equivalent to virtually activating a source at the location of the seismome-
 111 ter and recording the seismic response. The results of Claerbout (1968), valid for a 1D-
 112 horizontally layered medium, have been extended to 3D-inhomogeneous media by Wapenaar
 113 (2003), based again on a perfect illumination of the structure. Following the pioneering
 114 works of Claerbout (1968) and Wapenaar (2003), a number of studies reported the suc-
 115 cessful passive reconstruction of the crustal reflection response from the AC of field data
 116 acquired on Earth (Tibuleac & von Seggern, 2012; Ito & Shiomi, 2012; Gorbato et al.,
 117 2013; Kennett et al., 2015; Saygin et al., 2017; Phạm & Tkalčić, 2017; Oren & Nowack,
 118 2017; Romero & Schimmel, 2018) and on the Moon (Nishitsuji et al., 2016).

119 Suemoto et al. (2020) were the first to extract propagating signals from AC of am-
 120 bient vibrations recorded by SEIS. They considered high frequencies and short propa-

121 gation times. They observed stable phases on the ACF of the Vertical, East and North
 122 components of the seismic wavefield. From this observation, they deduced the presence
 123 of a very shallow interface underneath InSight. More recent works by Deng and Levan-
 124 der (2020) focused on the deep seismic structure of Mars. Their results will be discussed
 125 and compared to ours in section 4. In the present work, we apply the seismic interfer-
 126 ometry method to two types of diffuse wavefields -ambient vibrations and the diffuse part
 127 of seismic events- and investigate the possibility to retrieve the deep vertical reflection
 128 response of the Martian crust beneath InSight. In section 2, we describe the particular
 129 features of the continuous records of SEIS-VBB and the various types of seismic events.
 130 In section 3, we present a pre-processing strategy to mitigate environmental noise and
 131 compute empirical Green’s function (EGF) by correlating records of both ambient vi-
 132 brations and diffuse seismic events. We show excellent agreement between the two datasets
 133 in a specific frequency band. Based on these results, some simple layering models below
 134 InSight are proposed in section 4, and compared to previous results from the literature.
 135 Section 5 summarizes our main findings and proposes directions for future works.

136 2 DATA

137 2.1 Overview of the SEIS instrument

138 SEIS is the main instruments of the InSight mission (Banerdt et al., 2020). It is
 139 a six axes seismometer composed of three Very Broad Band (VBB) sensors sensitive to
 140 frequencies between 0.01Hz and 10Hz and three Short Period (SP) sensors sensitive to
 141 frequencies between 0.1Hz and 50Hz (Lognonné et al., 2019, 2020). The three VBB sen-
 142 sors are installed in a vacuum sphere as a first thermal protection. The sphere and the
 143 three SP sensors rest on a three-legged levelling system (LVL) that couples with the Mar-
 144 tian ground. The whole constitutes the sensor assembly (SA). The SA is connected to
 145 the lander via the tether. A relaxation loop (LSA) has been installed at the junction be-
 146 tween the SA and the tether. Thus, when the tether contracts or expands under the ef-
 147 fect of temperature the movement is not transmitted to the SA. SEIS was deployed on
 148 the Martian surface with the robotic arm of the InSight lander on December 19, 2018.
 149 It is covered by the Wind and Thermal Shield (WTS) since February 2, 2019 (Lognonné
 150 et al., 2020). SEIS is continuously recording ground motion at the InSight’s landing site.
 151 We summarize the acronyms relevant to this study in Table 1. The orientations of the
 152 six sensors of SEIS in the Martian geographical system are extracted from SEIS data-
 153 less information and provided in Table 2. More information on the location and orien-
 154 tation of the various instruments is provided by Golombek et al. (2020). In this study
 155 we focus our analysis on the frequency band below 10Hz and chose to use VBB data at
 156 20 sample-per-second (sps) (InSight Mars SEIS Data Service, 2019).

Table 1. Summary of acronyms used in the text.

Nomenclature	
VBB	Very Broad Band
SP	Short Period
SA	Sensor Assembly
WTS	Wind and Thermal Shield
LVL	Leveling System
LSA	Load Shunt Assembly

Table 2. Azimuth (Az) and Dip (angular deviation from horizontal) defining the spatial orientation of the 6 sensors composing the SEIS instrument.

SEIS sensors	
VBB Channel	Sensor orientation (degrees)
U	135.1 Az, -29.4 Dip
V	15.0 Az, -29.2 Dip
W	255.0 Az, -29.7 Dip
SP Channel	Sensor orientation (degrees)
1	285.0 Az, -89.9 Dip
2	105.2 Az, 0 Dip
3	345.3 Az, 0 Dip

157 2.2 Raw continuous signal

158 The continuous records of SEIS present several features that have been described
159 in Lognonné et al. (2020) and Ceylan et al. (2021). We briefly summarize the main char-
160 acteristics here. We show in Figure 1.A a spectrogram of raw records of the VBB-V axis
161 at 20 samples-per-second (sps) between Sol 183 and Sol 190. The time windows with high-
162 est energy correspond to sunlight periods. The clear difference between daytime- and nighttime-
163 records is due to atmospheric processes. As described in Lognonné et al. (2020), atmo-
164 spheric noise entails elastic deformations induced by pressure effects on the ground, tilt
165 of the lander under wind, and lander vibrations under wind. The changes in the speed
166 and turbulent flow of the wind are the main drivers of the SEIS background signal. Next,
167 we remark that certain narrow frequency bands are noticeably more energetic than oth-
168 ers. Careful examination reveals the excitation of resonances whose central frequency
169 exhibits a daily modulation. Some of these resonances are clustered in the frequency do-
170 main between 3.2Hz and 4.5Hz (as delimited by the red rectangle in Fig. 1.A). This par-
171 ticular frequency band contains a series of modes of resonance of the InSight lander which
172 are continuously excited by the wind. The complexity of the modal distribution stems
173 from the fact that the lander is assembled from different mechanical parts. The various
174 components resonate in different frequency bands, that depend in particular on their elas-
175 tic properties (Murdoch, Mimoun, et al., 2017). Hence, the periodic modulation of the
176 resonance spectrum is a direct consequence of the thermo-elastic response of the lander
177 induced by daily temperature variations. Finally, we note that the vast majority of lan-
178 der modes are found in the 1-50Hz frequency range and that most of them produce strongly
179 polarized signals that are detected by SEIS-VBB. As a consequence, the lander modes
180 rarely contaminate simultaneously all components of the signal.

181 The spectrogram of Figure 1.A also shows a sharp peak of energy at exactly 1Hz
182 frequency. This feature is more clearly visible on the mean power spectrum shown in Fig-
183 ure 1.B. In addition to the main peak at 1Hz, we observe various harmonics at 2Hz, 3Hz,
184 etc. These harmonics are not all visible on the spectrogram due to the low image res-
185 olution. The signal at the origin of the peaks at 1Hz, 2Hz, ... seen on the spectrogram
186 is called “tick noise” and corresponds to a periodic cross-talk induced by the tempera-
187 ture acquisition at 1sps. Because the temperature sensors and the seismometer axes share
188 the same clock, the cross-talk signal (tick noise) is perfectly synchronized with the ac-
189 quisition of the SEIS records.

190 Figure 1 (black rectangles) also reveals a permanent excitation of a continuum of
191 frequencies between 2Hz and 3Hz, that are not modulated in time in sharp contrast with
192 the Lander modes. This feature is called the “2.4Hz resonance” and is interpreted by Giardini

193 et al. (2020) as a local ground resonance. Nevertheless, the exact way this resonance is
 194 generated and excited remains unknown.

195 There also exist two families of transient perturbations, presented in Figure 2, that
 196 deserve attention. One of these transients dominates the low frequency band and is re-
 197 ferred to as “glitch” (panels 2.A and 2.B). The other dominates the high frequency band
 198 and is referred to as “donk” (panels 2.C and 2.D). The most likely origin of these signals
 199 is the activation of presumably pre-existing cracks in the various mechanical parts of the
 200 InSight station including the lander, the Sensor Assembly (SA) of SEIS and the tether
 201 between SEIS and the lander (Ceylan et al., 2021). Indeed, the temperature variations
 202 between day and night at the InSight landing site can reach 100 K. All the mechanical
 203 parts are thus subject to high thermal stresses and the elastic energy accumulated is partly
 204 released in the form of low- and high- frequency acoustic emission. For a detailed anal-
 205 ysis of glitch signals we refer the reader to Scholz et al. (2020). Because glitches, tick noise
 206 and donks can adversely affect the results of seismic interferometry, section 3.1 describes
 207 several data procedures to mitigate their effect.

208 2.3 Seismic Events

209 Since the beginning of the operation phase SEIS has recorded more than a hun-
 210 dred seismic events (Giardini et al., 2020). The event nomenclature used in this study
 211 refers to the catalogue provided by the MarsQuake Service (MQS) (InSight Marsquake
 212 Service, 2020) described in Giardini et al. (2020). The events are classified into five types
 213 and have an assigned quality score from A (best) to D (worst). The description of the
 214 five event types is presented in Table 3. Up-to-date information on SEIS events and the
 215 Mars quake catalog are provided by Clinton et al. (2021).

216 In this study, we focus our analysis on the High Frequency events (HF), Very High
 217 Frequency events (VF) and 2.4Hz events. As described by Lognonné et al. (2020) and
 218 Giardini et al. (2020), the high-frequency seismic events (HF, VF and 2.4Hz events) wave-
 219 forms have a diffusive character. The abundance and long duration of high-frequency
 220 seismic events offer a unique opportunity to apply seismic interferometry to the retrieval
 221 of the local seismic response below InSight. All in all, we have used forty-one HF, four-
 222 teen VF and sixty-nine 2.4Hz events. Only seismic events with quality better than or
 223 equal to C were selected. The complete list of events used is given in Appendix A. For
 224 all these events we were able to exploit the entire waveform as previous polarization and
 225 multiple-scattering analyses strongly suggest that the diffusive regime sets in almost im-
 226 mediately after signal onset (Lognonné et al., 2020).

Table 3. Characteristics of the different types of events as defined by the MQS (InSight Marsquake Service, 2020)

Event type	Description
Low Frequency (LF)	Energy exclusively below the 2.4Hz resonance
Broadband (BB)	Excite the 2.4Hz resonance but with the major part of their energy at lower frequencies
2.4Hz event	Excite only the 2.4Hz resonance
High Frequency (HF)	Excite the 2.4Hz resonance but also the higher frequencies
Very High Frequency (VF)	Same as HF events but with larger energy on the horizontal components than on the vertical component

227 3 PROCESSING AND RESULTS

228 3.1 Pre-Processing

229 3.1.1 Tick Noise Removal

230 The tick noise is an electrical disturbance (cross-talk) resulting from the acquisition
 231 of the temperature inside SEIS. The frequency content of this deterministic noise
 232 depends mostly on the sampling rate of the temperature sensor. It is important to note
 233 that the tick noise waveform differs on the three components U, V and W of the VBB.
 234 As the acquisitions of the temperature and seismic channels are synchronized, the tick
 235 noise repeats periodically every N samples, where N is the sampling rate of the SEIS
 236 channel. This implies in particular that it is not sensitive to the temporal drift of the
 237 SEIS clock. As observed in Figure 1, the tick noise peaks in the frequency domain at 1Hz
 238 but also exhibits a non-negligible amplitude at each harmonics (2Hz, 3Hz, ...). In order
 239 to remove this noise from the raw data at 20sps, we stack non-overlapping contiguous
 240 20-samples windows. Under the assumption that the background noise is random, the
 241 stack should converge towards a good estimate of the tick noise waveform. To obtain the
 242 estimates presented in Fig. 3.A, we stacked two months 20sps VBB records acquired be-
 243 tween 18:00 and 22:00 Local Mean Solar Time (LMST). We only employ evening data
 244 because they sample the quietest period of the day on Mars. Finally, to remove the tick
 245 noise from the data we first determine its lag-time with respect to the raw time-series
 246 using a simple cross-correlation algorithm. We then appropriately shift the tick noise to
 247 align it with the raw time-series and remove the former from the latter in contiguous win-
 248 dows of 20 samples by subtraction. Figure 3.B shows the spectrograms before and af-
 249 ter the tick noise removal around a frequency of 1Hz for each component. Figure 3.C and
 250 3.D show the time-series and the spectral contents of VBB-V during the evening of Sol
 251 183 before and after the tick noise removal. We see that our procedure successfully re-
 252 moves the tick noise at the target frequency, while preserving the rest of the spectral con-
 253 tent.

254 3.1.2 Glitch suppression

255 As described in Lognonné et al. (2020), the term “glitch” refers to a particular type
 256 of signal in the seismic channels of SEIS whose waveform is similar to the response of
 257 the instrument to a step in acceleration. Glitches are broadband signals but most of their
 258 energy is localized in the low frequency domain ($< 1\text{Hz}$). Rarely, glitches can be pre-
 259 ceded by a high-frequency precursor. Glitch amplitude extends over six orders of mag-
 260 nitude. They may happen anytime during a Sol but those with highest amplitudes ap-
 261 pear to occur when the temperature exceeds certain specific values (Scholz et al., 2020).
 262 Polarity analysis suggests that glitches have preferential polarization in the directions
 263 of the feet of the WTS, the feet of SEIS Leveling System (LVL) and the LSA/tether (Lognonné
 264 et al., 2020; Scholz et al., 2020). The fact that a large number of glitches are thermally
 265 activated can be an issue for passive seismic applications. Notwithstanding the fact that
 266 some glitches have very high amplitude, if their temporal distribution shows some reg-
 267 ularity and reproduces at fixed temperature conditions during each Sol, these transients
 268 may eventually deteriorate the ACFs and mask interesting signals. To mitigate the risk
 269 of contamination by glitches, we apply a glitch-correction algorithm (Scholz et al., 2020)
 270 to the raw data, that detects and removes the low-frequency waveform of the most en-
 271 ergetic glitches. Due to the variability in their waveforms, some glitches may leave a small
 272 imprint in our data, even after correction. For this reason, their impact on our results
 273 will be further discussed in section 3.4.2.

274 In the next sections, we present two methods to retrieve empirically the seismic re-
 275 sponse below InSight from the pre-processed continuous data. The first method is based
 276 on the well established identity between the temporal correlation function of a diffuse
 277 wavefield and the Green’s function of an elastic medium (Lobkis & Weaver, 2001; Campillo

278 & Paul, 2003). The second method proceeds in the frequency domain and exploits the
 279 Wiener-Khinchine relation between the power spectral density of random signals and
 280 their autocorrelation function (Yaglom, 2004).

281 **3.2 Computation of Autocorrelation Functions (ACFs) and Signal-to-** 282 **Noise Ratio (SNR) analysis**

283 To compute the velocity ACF of Martian ambient vibrations, we follow the work-
 284 flow described by Bensen et al. (2007) with minor modifications. After tick noise and
 285 glitch removal, the instrument response is removed and the traces are rotated onto the
 286 local geographical coordinate system Z, N, E, with Z the upward vertical, N the hori-
 287 zontal North component and E the horizontal East component. The signal is subsequently
 288 cut into segments of one Sol duration which are processed independently. Due to the highly
 289 non-stationary character of both the ambient Martian vibrations and the perturbations
 290 caused by the environment, we further process independently each hour (in Local Mean
 291 Solar Time) of the continuous record. This hourly processing allows us to check the sta-
 292 bility of the ACFs and to remove segments that are potentially contaminated by spu-
 293 rious phases related to environmental noise, whose excitation depends strongly on the
 294 daily variation of wind and temperature (Scholz et al., 2020).

295 A band-pass filter is applied to each 1-hour trace. We subsequently subdivide each
 296 trace into windows of 60 seconds duration with 70% overlap. To mitigate the impact of
 297 energetic transients, a 1-bit normalization is applied to enforce stationarity of the sig-
 298 nal amplitude, thereby improving the signal-to-noise ratio (SNR) (Bensen et al., 2007;
 299 Ito & Shiomi, 2012). Following De Plaen et al. (2016), we do not apply any spectral whiten-
 300 ing. Depending on the bandwidth and the component involved, we also apply several notch
 301 filters to remove the lander modes resonances. The low-frequency band 0.4-1 Hz does
 302 not appear to contain lander modes. The 1-2Hz and 1-3Hz bands contain a lander mode
 303 around 1.6Hz but this one is mainly polarized on the horizontal components. As a con-
 304 sequence, a notch filter centered at 1.6 Hz, which corresponds to the frequency of the
 305 lander mode averaged over one Sol, is applied to the East and North components. The
 306 3-6Hz band contains two lander modes at 3.3Hz and 4Hz visible on the three components.
 307 Two notch filters are consequently applied to the *Z*, *N* and *E* traces during the pre-processing.
 308 We used a second-order infinite impulse response notch filter with a quality factor $Q =$
 309 30. The width of the rejected band at -3dB is approximately one thirtieth of the center
 310 frequency. Finally, we compute the full normalized autocorrelations (ZZ, NN and EE)
 311 for each of these 60 second-long traces, and we stack them to obtain the ACF for the given
 312 LMST and the given Sol. For the computation of ACFs from seismic events waveforms,
 313 the processing is almost identical. Different seismic events are simply considered as dif-
 314 ferent Sols and the first subdivision into LMST is not applied. Note nevertheless that
 315 a large number of seismic events are recorded during the evening.

316 In order to check the stability of the various phases observed in the ACFs, we use
 317 the definition of the Signal-to-Noise Ratio (SNR) given by Clarke et al. (2011) based on
 318 a method of Larose et al. (2007). This SNR is a function of N , the number of realiza-
 319 tions, and t , the correlation time-lag. In our case N represent either the number of Sols
 320 or the number of seismic events. The SNR is given by:

$$SNR(N, t) = \frac{s(N, t)}{\sigma(N, t)} \quad (1)$$

321 With $s(N, t) = \|\langle ACF(t) \rangle + i\mathbf{H}(\langle ACF(t) \rangle)\|$ and $\sigma(N, t) = \sqrt{\frac{\langle ACF(t)^2 \rangle - \langle ACF(t) \rangle^2}{N-1}}$.
 322 Here $\langle ACF(t) \rangle = \frac{1}{N} \sum_{i=1}^N ACF_i(t)$ with i the index labelling the Sol (or the event).
 323 We denote $s(N, t)$ the envelope of the stacked autocorrelation function $\langle ACF(t) \rangle$, \mathbf{H} the
 324 Hilbert transform and $\sigma(N, t)$ the amplitude of the residual fluctuations normalized by
 325 the number of realizations minus one to avoid biasing. We smooth the time-dependent
 326 SNR using a moving time window with the following frequency-dependent duration: 2.5s

327 in the 0.4-1Hz band, 0.5s in the 1-2Hz and 1-3Hz bands and 0.25s in the 3-6Hz and 4.5-
328 7Hz bands.

329 We show in Figure 4.A the SNR estimated from 149 ambient vibration ACFs de-
330 rived from data recorded from Sol 222 to Sol 399. We remark that the phases that are
331 visible on individual correlograms as well as on the stacked waveform between 5s and
332 8s, 10s and 13s and around 21s also correspond to peaks of the SNR. In Figure 4.B, we
333 show the SNR for each hour of the day expressed in LMST. We see that the most en-
334 ergetic arrivals (5-8s, 10-13s and 21s) are visible and stable during nighttime (i.e. from
335 17:00 LMST to 06:00 LMST) and are particularly clear during the evening (from 17:00
336 LMST to 23:00 LMST). This period of the day corresponds to the lowest atmospheric
337 activity on Mars. By contrast, when atmospheric noise is particularly strong during day-
338 time (from 06:00 LMST to 17:00 LMST), we cannot discern any clear seismic phase in
339 the ACF. This observation suggests that the signals recorded by SEIS during daytime
340 are not seismic waves but rather ground deformation induced by atmospheric forcing.

341 **3.3 Reflectivity via Power Spectral Density (PSD) estimate**

342 By the Wiener-Khintchine theorem, it is known that the PSD of a stationary ran-
343 dom signal contains the same information as its ACF, the two being related by a Fourier
344 transform. This property suggests an alternative method to process our data set. First,
345 we compute the average power spectral density of each 1-hour long data segment using
346 the Welch method (Welch, 1967) with sub-windows of 60 seconds duration and 70% over-
347 lap. Note that no 1-bit normalization is applied to the original dataset, in sharp contrast
348 with the method described in the previous section. The application of Welch’s approach
349 to non-normalized data has been recommended in the framework of ambient seismic vi-
350 bration processing by Seats et al. (2012). All the PSD estimated between 18:00 and 23:00
351 LMST on the Z-component are shown in the 0.5-4Hz frequency band in Figure 5.A. At
352 the top of Figure 5.A we show the PSD averaged over all Sols. In Figure 5.A, we observe
353 the broad 2.4Hz resonance first reported by Giardini et al. (2020). Superposed on the
354 broad resonance, we observe characteristic oscillations of the PSD on smaller frequency
355 scales. In order to improve the SNR ratio around the 2.4Hz resonance, we have normal-
356 ized the PSDs by their maximum in the 1-3Hz frequency band prior to the stack. This
357 procedure downweights data from Sols with anomalously high energies (as around Sol
358 320 in Figure 5.A) and therefore improves the ensemble averaging. Furthermore, although
359 it may not be apparent on the individual PSDs, there may remain a small imprint of the
360 tick-noise, even after application of the denoising algorithm. To mitigate this issue, we
361 simply replace the value of the PSD at 1Hz (and higher harmonics) by the mean value
362 of the PSD at the two nearest samples. The averaged, normalized PSD is shown in Fig-
363 ure 5.B.

364 Using both numerical simulations and real data examples, Oren and Nowack (2017)
365 have suggested that the rapid oscillations of the PSD may contain information on the
366 reflection of propagating waves from deep interfaces. Therefore, to extract the reflectiv-
367 ity structure under InSight, it is natural to deconvolve the PSD from the smooth 2.4Hz
368 resonance. In the example shown in Figure 5.C, this operation is performed by divid-
369 ing the original PSD by its smoothed version using a 0.5Hz window. In order to remove
370 contamination from unwanted spectral oscillations caused by Lander modes, we also nor-
371 malize the PSD to one outside the frequency band of interest (Figure 5.D). The final step
372 of the process consists in taking the inverse Fourier transform of the deconvolved PSD
373 to reveal the arrival times of the possible seismic phases at the origin of the spectral os-
374 cillations. In the following we refer to this method as the “Welch Method”.

375 The deconvolution stage is often used in seismic interferometry to mitigate the ef-
376 fect of the source time function of ambient vibrations, which creates strong side lobes
377 near 0 lag-time (Ruigrok et al., 2010; Casas et al., 2020). In this operation, the band-

378 width of the smoothing window used to estimate the PSD of the source function is a key
 379 parameter. In particular, we remark that both the amplitude and the arrival time of the
 380 wave packets in the first 4s depend on the smoothing parameter. As a consequence, we
 381 will refrain from interpreting any arrival reconstructed by the Welch method at lag time
 382 smaller than 4s.

383 3.4 Results

384 3.4.1 ACFs and SNR analysis

385 The autocorrelation functions (ACFs) of the ambient vibrations have been com-
 386 puted in four different frequency bands: 0.4-1Hz, 1-2Hz, 1-3Hz and 3-6Hz. The SNR and
 387 power spectra of the resulting ACFs are shown in Figure 6 for the *ZZ* component. The
 388 high values of SNR (in red) near 0 lag-time are caused by the noise source time func-
 389 tion since no source deconvolution has been applied during the processing. We see in Fig-
 390 ure 6 that outside of the time window near 0 lag-time, the SNR is close to zero every-
 391 where except in the 1-3Hz bandwidth between 17:00 LMST and 23:00 LMST (Figure 6.E).
 392 We recall that the evening is known to be the period of the Sol where the atmospheric
 393 disturbances are the lowest. Hence, it is only during this time of the Martian day that
 394 seismic ambient vibrations may be expected to predominate. The second peculiarity of
 395 the 1-3Hz frequency band is the presence of the 2.4Hz resonance. We see on the power
 396 spectra of Figure 6.F that this resonance dominates the frequency content of the ACF.
 397 Our interpretation is that the 2.4Hz resonance amplifies the ambient vibration at the In-
 398 Sight’s landing site, thereby allowing a better reconstruction of the zero-offset reflection
 399 response. In the following, we therefore focus our analysis on the results obtained in the
 400 1-3Hz frequency band.

401 Our main results are shown in Figure 7 where we represent all the ACF waveforms
 402 computed from ambient vibrations from Sol 222 to Sol 399 for the Z, E and N compo-
 403 nents (upper panels), as well as the Z, E and N ACFs waveforms obtained from 124 seis-
 404 mic events (HF, VF and 2.4Hz events, lower panels). In addition, Figures 8, 9 and 10
 405 show the average waveforms for the three approaches outlined above: seismic events, Welch
 406 method, and ambient vibration for the *ZZ*, *EE* and *NN* components respectively. The
 407 ACFs referring to “Seismic Events” have been obtained by stacking linearly the individ-
 408 ual ACFs of all HF events, VF events and 2.4Hz events (124 diffuse seismic events in to-
 409 tal) shown in Figure 7.D.E.F. The ACFs referring to “ambient vibrations” have been ob-
 410 tained by stacking linearly the hourly ACFs during the evening period (17:00 to 23:00
 411 LMST) of each Sol and by subsequently averaging the results from Sol 222 to Sol 399
 412 shown in Figure 7.A.B.C. Note that because source deconvolution has been applied in
 413 the Welch method, the waveform amplitudes shown in panel B are not directly compa-
 414 rable with the one displayed in panels A and C. In Figure 8, 9 and 10 we highlight in
 415 gray the wave packets that are simultaneously visible on the three different types of ACFs.
 416 When the envelope of the wave packet presents a clear maximum, common to the three
 417 methods, we mark its arrival time with a vertical dark grey line.

418 The excellent agreement between the three correlograms is worth noting. The close
 419 similarity between the waveforms derived from ACFs of seismic events and ambient vi-
 420 brations is particularly compelling. Furthermore, the agreement between these two ACFs
 421 and the results from the Welch method, which proceeds in the frequency domain, con-
 422 firms that the arrival time of the different wavepackets is indeed encoded in the period-
 423 ical oscillations of the PSD around the 2.4Hz resonance. Again, this should come as no
 424 surprise by the Wiener-Khintchine theorem. Examining Figures 7.A.B.C, we also notice
 425 that the individual ambient vibration ACFs computed over a single Sol already contain
 426 all the arrivals that show up in the complete stack. By contrast, the individual ACFs com-
 427 puted from seismic events waveforms (Figure 7.D.E.F) exhibit much more variability. Quite
 428 remarkably, the average ACF nevertheless converges toward the same waveform as ob-

429 tained from the ambient seismic vibration. Interestingly, Hillers and Campillo (2016) ob-
 430 served the same variability of cross-correlation waveforms derived from earthquake coda
 431 waves on Earth. This comforts us in our interpretation of the arrivals visible in the ACFs
 432 as true propagating seismic signals.

433 *3.4.2 Potential contamination by Glitches and Donks*

434 We have seen in section 3.1.2 that only the low frequency part of a given glitch is
 435 removed by the detection-correction algorithm. This implies that the temporal distri-
 436 bution of glitches can still have an impact on the correlation analysis. In the same way,
 437 the distribution of donks is susceptible to contaminate the ACFs. These possible issues
 438 are now critically examined. In Figure 11.A, we show the statistics of the lapse-time be-
 439 tween pairs of glitches detected in the 20 sps VBB data. A clear pattern can be distin-
 440 guished on the plots, where each glitch is represented as a point in the (LMST, Sol num-
 441 ber) plane. In particular, a high density of glitches can be observed along certain curves
 442 suggesting that glitches are driven by environmental forcing. Indeed, Scholz et al. (2020)
 443 have shown that the curves correspond to particular values of the temperature, which
 444 varies seasonally. The regularity and repeatability observed in the glitch distribution leads
 445 us to take into consideration the time delay between two consecutive glitches. This pa-
 446 rameter is key to unravel a potential contamination of ACFs. In Figure 11.A, we show
 447 the histogram of the time delays between two consecutive glitches on the V component
 448 at different LMST. We focus our analysis on the evening part of each Sol because it is
 449 the period during which we obtain the best results. We see on the histogram that the
 450 smallest delay is approximately 30 seconds and that the mean delay between two con-
 451 secutive glitches is around 200 seconds. These values are too large to explain the arrivals
 452 visible on the ACFs. Moreover we see that the distribution of the delays depends on the
 453 LMST. This observation is not compatible with the stability of the arrivals over the night-
 454 time windows.

455 We show in Figure 11.D the temporal distribution of the donks detected between
 456 17:00 and 23:00 LMST from Sol 180 to Sol 261. This period is delimited by the red rect-
 457 angle in Figure 11.B. As the 100 sps SP data are not always available, we perform the
 458 detection of donks on a composite SP channel called ESTASP (Energy Short Term Av-
 459 erage - SP) which is available in the continuous data stream. The output of this chan-
 460 nel is defined as the root mean square of the raw vertical SP components (SP1), filtered
 461 in the 12-14Hz bandwidth and averaged over 1 second (Lognonné et al., 2019). The peaks
 462 visible on the ESTASP channel time series shown in Figure 11.E are markers of donks.
 463 Application of a simple STA/LTA (1s/25s) criterion thus permits the automatic detec-
 464 tion of the vast majority of donks from ESTASP records. In Figure 11.D we may observe
 465 three time windows with a particularly high density of donks at the beginning of the evening.
 466 Each time window opens at a particular Sol and extends gradually Sol after Sol. We hy-
 467 pothesize that the appearance of a high number of donks is related to the seasonal re-
 468 activation of lander cracks. We see on the histogram of Figure 11.C that the typical de-
 469 lay between two donks is much smaller than the delay between glitches. A broad max-
 470 imum in the distribution of delays is visible around 10 seconds between 17:00 and 18:00
 471 LMST. Such a peak could cast doubts on the physical origin of the arrival seen around
 472 10.5s in the ZZ ACFs. Nevertheless, there are a number of arguments that favor the in-
 473 terpretation of this arrival in terms of wave propagation. (1) The phases seen in the ACF's
 474 are stable during the whole evening, while donks activity strongly decreases after 18:00
 475 LMST. (2) Donks leak very little energy into the 2-3Hz bandwidth. (3) All the arrivals
 476 seen on ambient vibration ACFs are also present in the events ACFS. The latter are tens
 477 to thousands of times more energetic than the ambient vibration, making donk contam-
 478 ination rather unlikely.

489 4 Interpretation of ACFs

480 Having detected clear arrivals in the ACFs, that are furthermore consistent between
 481 two different datasets, we now explore the possibility that these phases correspond to
 482 the reflection of body waves on deep interfaces under InSight. Other interpretations based
 483 on scattered surface waves are of course possible but are left for future works.

484 4.1 Possible reflectivity structure below InSight

485 We begin our analysis with the vertical ACFs which show high S/N ratio (> 4)
 486 up to lapse time of 30s. Following the basic principles of seismic interferometry, we inter-
 487 pret the identified phases in terms of P-wave reflectivity. The most energetic arrival
 488 (besides the side lobe at time $t = 0$) seen on both ambient vibration and event ACFs
 489 arrives at a two-way traveltime of 5.6s. This arrival is most directly interpreted as a re-
 490 flection from an upper-crustal interface that was also detected by Receiver Function anal-
 491 ysis. As reported by Lognonné et al. (2020), the plausible depth of this interface is 9.6km
 492 (± 1.8 km), corresponding to an arrival time in the range 3.5s-8.2s. A series of later ar-
 493 rivals is detected at lapse-time 10.6s, 12.6s, 21.s, whose amplitudes decay gradually. As
 494 an illustration, the amplitude ratio between the 5.6s and 21s phases is typically in the
 495 range 1.5-2. This makes it rather unlikely that any of the late arrivals corresponds to
 496 a multiple reflection. Assuming the same range of P-wavespeeds in the lower crust as Lognonné
 497 et al. (2020) (reported in Table 4), our observations suggest the presence of several deep
 498 interfaces at approximate depths of 21.6km \pm 4.8km, 26.4km \pm 6km and 46.5 \pm 11.1km,
 499 corresponding respectively to arrivals at 10.6s, 12.6s and 21.0s. The uncertainty on the
 500 depth of the interfaces is directly inherited from our assumption on the plausible range
 501 of P-wave velocities in the crust. This analysis of the ZZ ACFs is summarized in Table
 502 4.

503 We now examine the horizontal ACFs and interpret them in terms of shear wave
 504 reflectivity. In doing so, we try to identify arrivals that possibly correspond to reflections
 505 from the interfaces deduced from the vertical ACF interpretation. This task is compli-
 506 cated by the fact that the arrival times of phases seen on the EE and NN ACFs do not
 507 necessarily match. Comparing the Figures 9 and 10 we observe that the NN component
 508 presents more similarity up to 40s lag-time between the three methods than the EE com-
 509 ponent. Since the agreement between ambient vibration and event ACFs is by far bet-
 510 ter on the NN component than on the EE component, we focus our interpretation on
 511 the former. We observe a broad high-amplitude arrival between 4s and 8s lapse-time. This
 512 arrival corresponds to lapse-time that are too short to be unambiguously interpreted on
 513 the ZZ ACFs. The dispersed nature of the signal may be the signature of scattering from
 514 the surface regolith which hampers the identification of an interface. A series of later and
 515 lower amplitude arrivals can be discerned simultaneously on the event and ambient vi-
 516 bration NN ACFs at lapse-times of 11.9s, 14.4s, 16.5s and 22.4s. The simplest interpre-
 517 tation of these arrivals, compatible with the P-wave reflectivity is the following one. The
 518 11.9s phase could correspond to the reflection of S waves from the upper crustal inter-
 519 face detected on the ZZ ACF. This allows us to determine the P-to-S wavespeed ratio
 520 $V_p/V_s = 2.1$ which in turn puts the first interface at a depth of 11.6km \pm 0.9km. The
 521 reduction in uncertainty with respect to the ZZ analysis comes from a far better con-
 522 straint of the S-wave velocities by Lognonné et al. (2020) (reported in Table 5) than the
 523 P-wave velocities. The next phase that we identify arrives at 22.4s and corresponds to
 524 the 10.6s reflection seen on the ZZ ACF. Taking into account the range of shear wave
 525 velocities deduced from RF by Lognonné et al. (2020) and shown in Table 5, this implies
 526 that the second interface could be located at 25.2km \pm 2.5km depth. We summarize this
 527 analysis in Table 5. This interpretation is not entirely satisfactory, as we observe two ar-
 528 rivals at respectively 14.4s and 16.5s that are difficult to reconcile with the P-reflectivity
 529 profile. The two uninterpreted arrivals on the NN ACF correspond to phases arriving
 530 between 5.6s and 10.5s lapse-time for P-waves. In this time window, the ZZ ACF shows

531 a broad wave packet where individual arrivals are difficult to discern. Interestingly, the
 532 14.4s arrival is visible on both the EE and NN ACF, which indeed suggests the presence
 533 of an interface between 11.6km and 25.2km depth.

Table 4. Extension of the crustal model by Lognonné et al. (2020) derived from the main arrivals observed in the ZZ ACF.

	PP reflection in the Z-ACF (s)	Expected PP arrival (s)	V_p range (km/s)	thickness (km)	Depth (km)
Layer 1	5.6	[3.5; 8.1]	[2.8; 4.4]	9.6 ± 1.8	9.6 ± 1.8
Layer 2	10.6		[3.6; 6.0]	12.0 ± 3.0	21.6 ± 4.8
Layer 3	12.6		[3.6; 6.0]	4.8 ± 1.2	26.4 ± 6.0
Layer 4	21.0		[3.6; 6.0]	20.1 ± 5.1	46.5 ± 11.1

Table 5. Extension of the crustal model by Lognonné et al. (2020) based on a combined interpretation of ZZ and NN ACFs.

	PP reflection in the Z-ACF (s)	SS reflection in the N-ACF (s)	V_p/V_s ratio	V_s range (km/s)	Depth (km)
Layer 1	5.6	11.9	2.1	[1.8; 2.1]	11.6 ± 0.9
Layer 2	10.6	22.4	2.1	[2.3; 2.9]	25.2 ± 2.5

534 4.2 Discussion

535 We now critically examine our interpretation as well as those proposed in the re-
 536 cent literature. The work by Deng and Levander (2020) is particularly relevant to ours.
 537 These authors used vertical ACFs at long and short period to propose a stratified view
 538 of Mars interior. We will focus the discussion on the short period band that is common
 539 to both studies. Deng and Levander (2020) reported the observations of two arrivals at
 540 11.5s and 21.s. The most notable difference with our findings is that instead of a single
 541 arrival at 11.5s, we observe two arrivals at 10.6s and 12.6s. We therefore see the interest
 542 in considering both ambient vibrations and coda waves in the processing.

543 The plausibility that the reconstructed phases correspond to deep reflections de-
 544 pends crucially on the crustal attenuation below InSight. As reported in Lognonné et
 545 al. (2020), the scattering attenuation as quantified by the seismic diffusivity $D = 90\text{km}^2/\text{s}$
 546 is rather moderate. This diffusivity corresponds to a scattering attenuation length of about
 547 90kms (Lognonné et al., 2020) so that ballistic waves propagating two-way through the
 548 crust would see their amplitude reduced by a factor of 3 due to scattering attenuation.
 549 The absorption quality factor Q has also been estimated to be in the range 1250-1325
 550 for S waves at 2.5 Hz and is probably much higher for P waves. Thus absorption likely
 551 affects negligibly the ballistic wave amplitudes. All these estimates are of course subject
 552 to large uncertainties but they do not rule out our interpretation of ACFs as body waves
 553 reflections.

554 Although scattering is moderate in the Martian crust, we have observational ev-
 555 idence that the wavefield of high-frequency Martian events is diffuse (Lognonné et al.,
 556 2020). Since the minimal hypocentral distance of the events used in our study is larger
 557 than 500km (Giardini et al., 2020), the diffuse character is acquired by long range prop-
 558 agation through an inhomogeneous crust rather than by strong local scattering (Lognonné
 559 et al., 2020). Coda records are more likely to possess the diffusive character required for
 560 the application of seismic interferometry. Therefore, by contrast with Deng and Levan-
 561 der (2020) we would rather interpret the phase detected at 21s as a PmP rather than
 562 as an SmS. We also note that the horizontal ACFs, which are supposed to be more faith-
 563 ful to the S reflectivity profile, lack a clear reflection associated to the 21s phase seen on
 564 the ZZ ACF. Therefore, we believe that the depth of the Moho under InSight is still to
 565 be confirmed by additional studies. To carry out this task, a joint interpretation of the
 566 vertical and horizontal ACFs would be necessary. This will require more advanced mod-
 567 eling approaches such as full-waveform inversion. Even more importantly, additional con-
 568 straints could come from the analysis of converted phases as in RF analysis, which in
 569 addition provide constraints on the absolute velocities in the crust.

570 5 CONCLUSION

571 The ground velocity records of the SEIS instrument have been analyzed with seis-
 572 mic interferometry methods. The stability analysis of the autocorrelation functions of
 573 SEIS components demonstrates that the ambient seismic vibration is most reliably ob-
 574 served in a specific frequency band (2.4Hz resonance) and only when the environmen-
 575 tal noise is lowest (17:00 to 23:00 LMST from Sol 222 to Sol 399). Based on the Power
 576 Spectral Density (PSD) of ambient vibrations, we show that the 2.4Hz resonance has an
 577 oscillating structure which is perfectly stable with time and which is directly related to
 578 the Empirical Green’s functions reconstructed in the 1-3Hz band by autocorrelation anal-
 579 ysis. The good agreement between the autocorrelation functions computed on ambient
 580 seismic vibration in the 1-3Hz range and the autocorrelation functions computed on the
 581 Marsquake waveforms is consistent with the interpretation of the 2.4Hz resonance as a
 582 local ground amplification due to the shallow structure beneath the InSight’s landing site.
 583 The autocorrelation functions present seismic energy arrivals in the 4 to 30 seconds lag-
 584 time range that are validated by Signal to Noise Ratio (SNR) analysis and inter-comparisons
 585 between results obtained from ambient vibration and seismic event records. We report
 586 the possible detection of vertically propagating P-waves reflected on internal disconti-
 587 nuities with two-way travel times of 5.6s, 10.6s, 12.6s and 21s. A clear identification of
 588 the corresponding S-waves reflections is more speculative due to the poor agreement be-
 589 tween the EE and NN components. Nevertheless, based on the more reliable component
 590 (NN) we suggest that the 11.9s and 22.4s arrivals could be the S-waves reflections cor-
 591 responding to the P-waves reflections at 5.6s and 10.6s. Two internal structure models
 592 deduced from these travel times are presented, but they must be further constrained by
 593 other seismic analysis such as receiver functions, in order to obtain a reliable internal struc-
 594 ture model.

595 **Appendix A Seismic events****Table A1.** List of seismic events used in this study referring to the catalog V3 by the MQS (InSight Marsquake Service, 2020)

HF events		VF events		2.4Hz events		2.4Hz events	
Name	Quality	Name	Quality	Name	Quality	Name	Quality
S0423c	B	S0424c	B	S0405d	C	S0346d	C
S0405f	B	S0421a	B	S0405b	C	S0344a	C
S0392a	B	S0387a	B	S0401b	C	S0342a	B
S0385a	C	S0376a	C	S0398b	C	S0340b	C
S0384d	C	S0358c	C	S0397d	C	S0339c	C
S0384c	C	S0343a	C	S0397b	C	S0338b	B
S0384b	B	S0334b	C	S0397a	C	S0338a	C
S0375a	C	S0334a	B	S0394a	B	S0327a	B
S0371b	B	S0306c	C	S0390c	C	S0325c	B
S0363d	C	S0264e	B	S0386b	C	S0323c	B
S0361c	B	S0241a	C	S0385b	C	S0321a	B
S0352a	B	S0226a	C	S0384a	C	S0314a	B
S0351b	C	S0202b	C	S0383a	C	S0311b	B
S0349a	B	S0128a	B	S0378b	B	S0265e	B
S0347a	C			S0378a	C	S0264b	B
S0343b	B			S0373b	C	S0263c	B
S0340a	B			S0372a	B	S0257b	B
S0331a	B			S0370a	C	S0255b	B
S0327c	B			S0369b	C	S0248b	B
S0325b	B			S0368a	C	S0248a	B
S0323a	B			S0367d	C	S0247b	B
S0319b	B			S0367c	B	S0247a	B
S0319a	B			S0366e	C	S0229a	B
S0315b	B			S0366d	C	S0227d	B
S0314b	B			S0366c	B	S0222a	B
S0311a	C			S0365a	C	S0219c	B
S0308a	B			S0363c	C	S0216b	B
S0306a	C			S0363b	C	S0194c	B
S0304b	B			S0363a	C		
S0303a	C			S0361b	C		
S0292a	C			S0359a	C		
S0291c	B			S0358b	C		
S0262b	C			S0355a	C		
S0260a	B			S0353d	C		
S0246a	B			S0353c	C		
S0239a	B			S0353b	C		
S0231b	B			S0349b	C		
S0228c	B			S0348d	C		
S0213a	C			S0348c	C		
S0202c	C			S0348b	C		
S0185b	B			S0348a	C		

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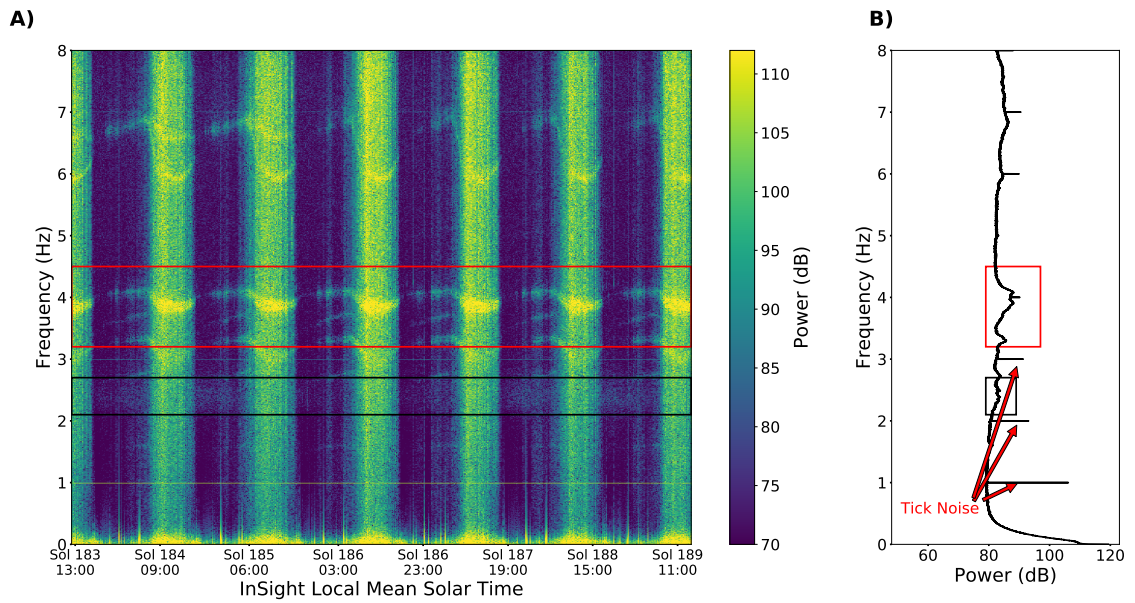


Figure 1. A) Spectrogram of a 6 Sols-long record of raw 20sps VBB data (V component in count). The spectrogram is computed using a moving time window of 15 minutes without overlap. The vertical bands of high amplitude correspond to daytime windows, i.e. between 5:00 and 16:00 LMST (Local Mean Solar Time). B) Mean power spectrum of the same data (in dB). The red rectangles delimit specific frequency ranges where lander modes are clustered. The black rectangles indicate the broad resonance around 2.4Hz.

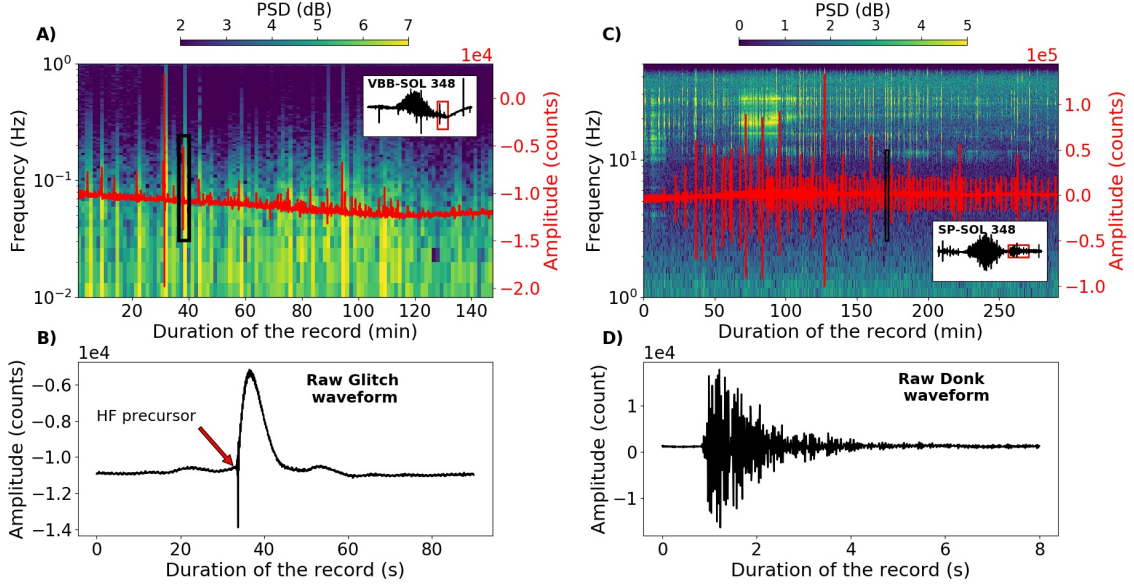


Figure 2. A) Spectrogram of the raw VBB-V component at 20sps at the beginning of the evening of Sol 348. The spectrogram is computed using a moving time window of 100 seconds with 20% overlap. Each high energy peak in the low frequency band ($< 0.1\text{Hz}$) is the signature of a glitch. Glitches are also clearly visible in the time-series (red line) superposed on the spectrogram. The black rectangle delimits the time window of the glitch presented in B). In inset, the whole VBB-V record is shown for Sol 348. The red rectangle delimits the time window used for the spectrogram computation. B) Typical raw glitch waveform. C) Spectrogram of the raw SP2 (horizontal) component at 100sps during the evening of Sol 348. The spectrogram is computed using a moving time window of 5 seconds with 20% overlap. Each high-energy peak in the high frequency band is the signature of a donk. Donks are also clearly visible in the time-series (red line) superposed onto the spectrogram. The black rectangle delimits the time window of the donk presented in sub-Figure D). The inset in sub-Figure C shows the complete SP2 record for Sol 348. The red rectangle delimits the time window used for the spectrogram computation. D) Typical raw donk waveform.

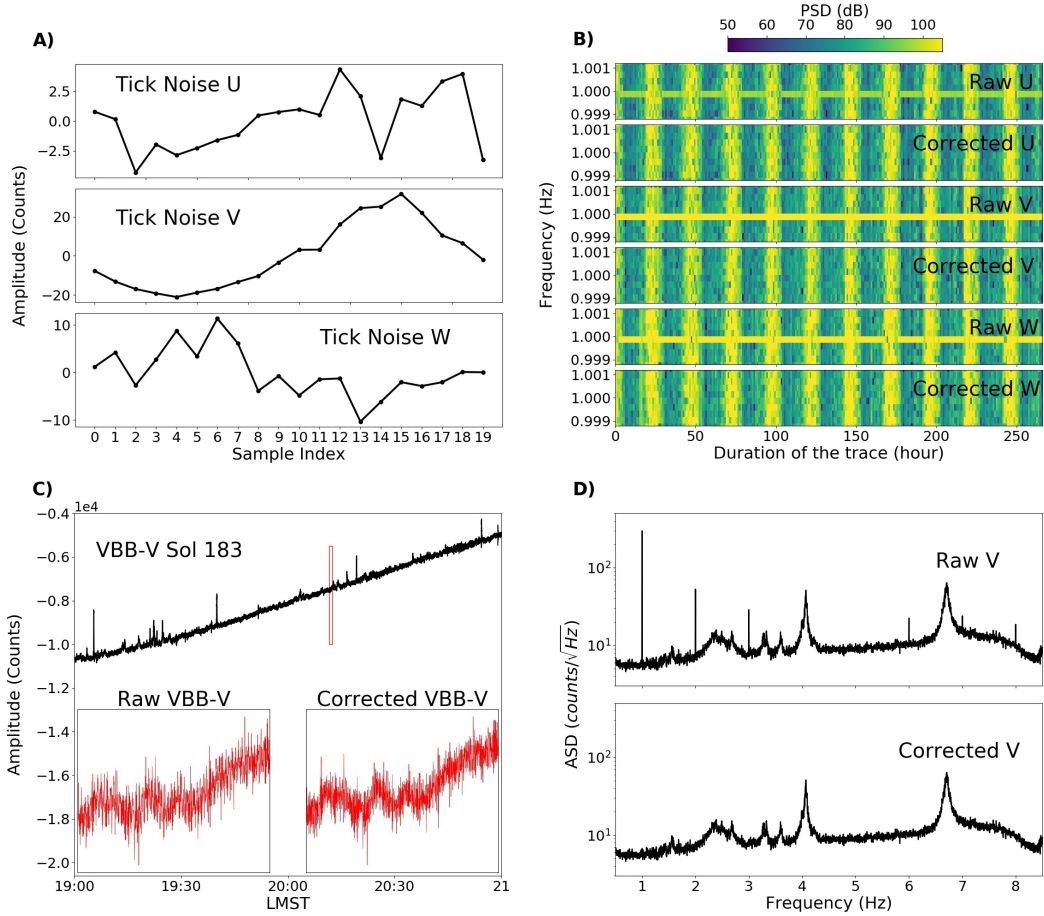


Figure 3. A) Estimated waveforms of the tick noise on the U, V and W channels of SEIS-VBB at 20sps. B) Spectrograms of the U, V and W components of SEIS-VBB before (raw) and after (corrected) tick-noise removal. The spectrograms have a temporal resolution of 1 hour and are represented in the 0.999Hz-1.001Hz frequency band. C) Raw VBB-V record between 19:00 and 21:00 LMST (black line) on Sol 183. Zooms into the time-window delimited by the red rectangle are provided in insets to highlight the effect of the correction. D) Amplitude Spectral Density (ASD) of the Raw VBB-V record shown in C) before and after tick-noise removal.

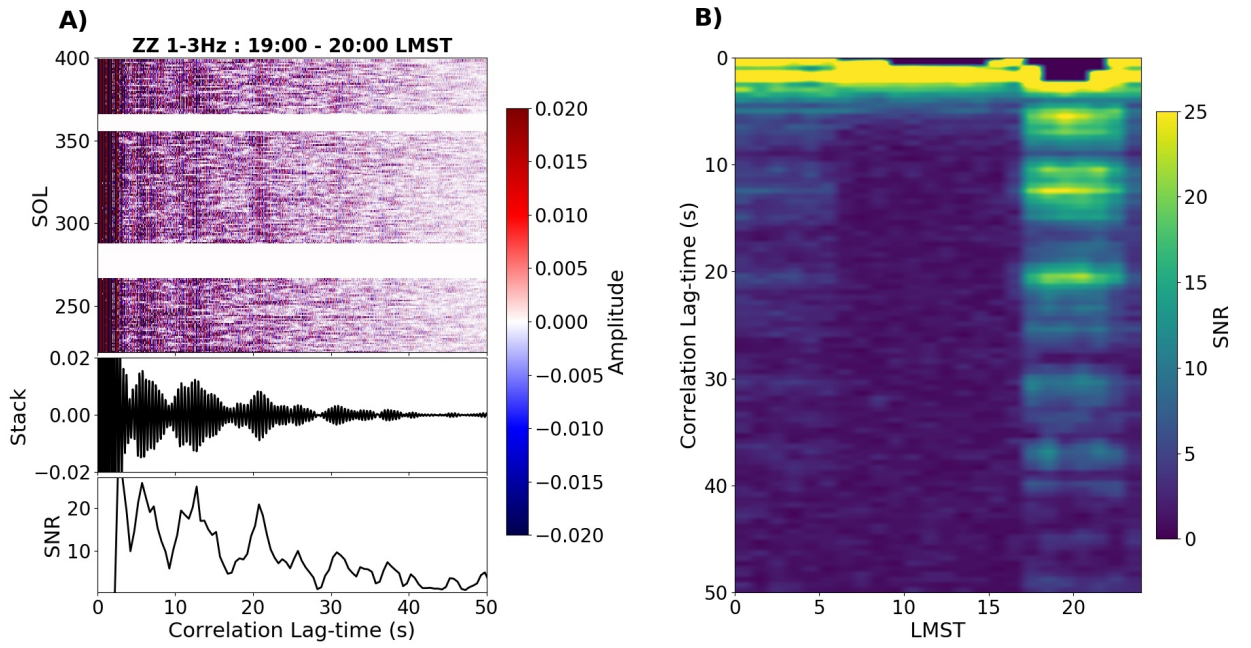


Figure 4. A) From top to bottom : ZZ-Correlograms computed from Sol 222 to Sol 399 between 19:00 and 20:00 LMST in the 1-3Hz frequency band; Resulting stacked ACF; SNR as a function of the correlation lag-time, following the method of Clarke et al. (2011). B) SNR (see colorbar) as a function of LMST (Local Mean Solar Time) and correlation lag-time for the ZZ component filtered between 1Hz and 3Hz.

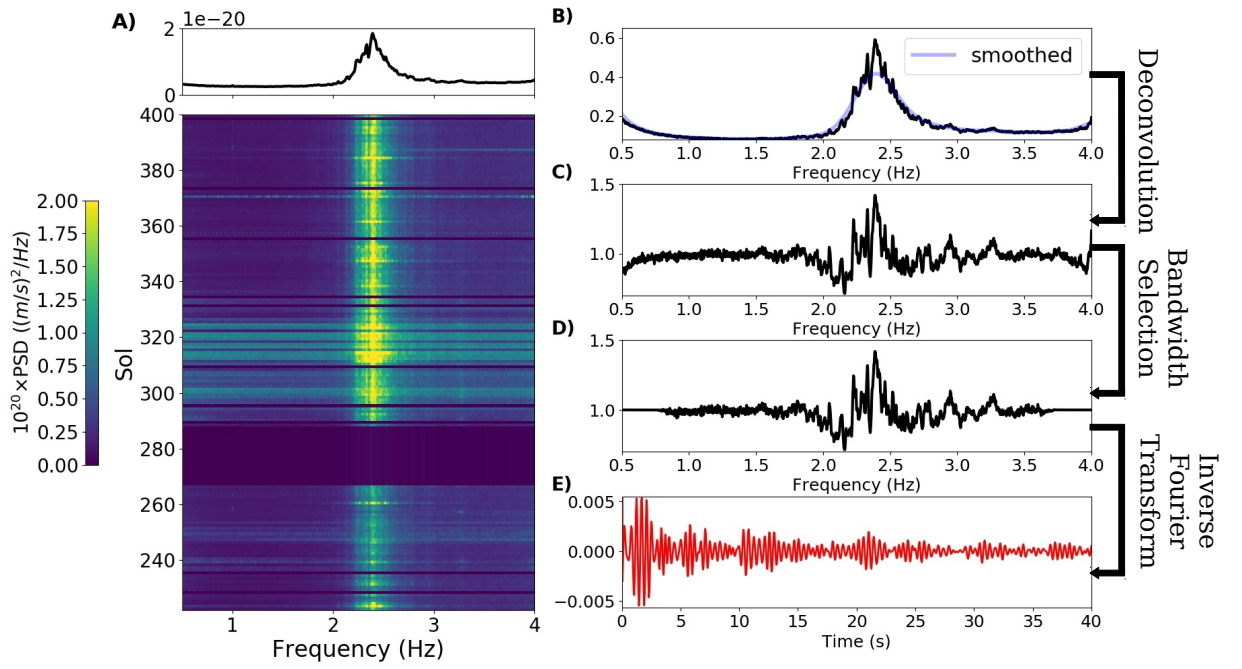


Figure 5. A) Spectrogram showing the power spectral density (PSD) in the 0.5-4Hz frequency band during the evening period (18:00 - 23:00 LMST) from Sol 222 to Sol 399. The spectrogram is computed using a moving time window of 1 minute with 70% overlap. The averaged PSD is shown at the top of the spectrograms. B) Averaged and normalized PSD estimated between 18:00 and 23:00 LMST and its smoothed version. C) Deconvolved PSD. D) Deconvolved PSD after frequency band selection. E) Inverse Fourier Transform of the PSD shown in D).

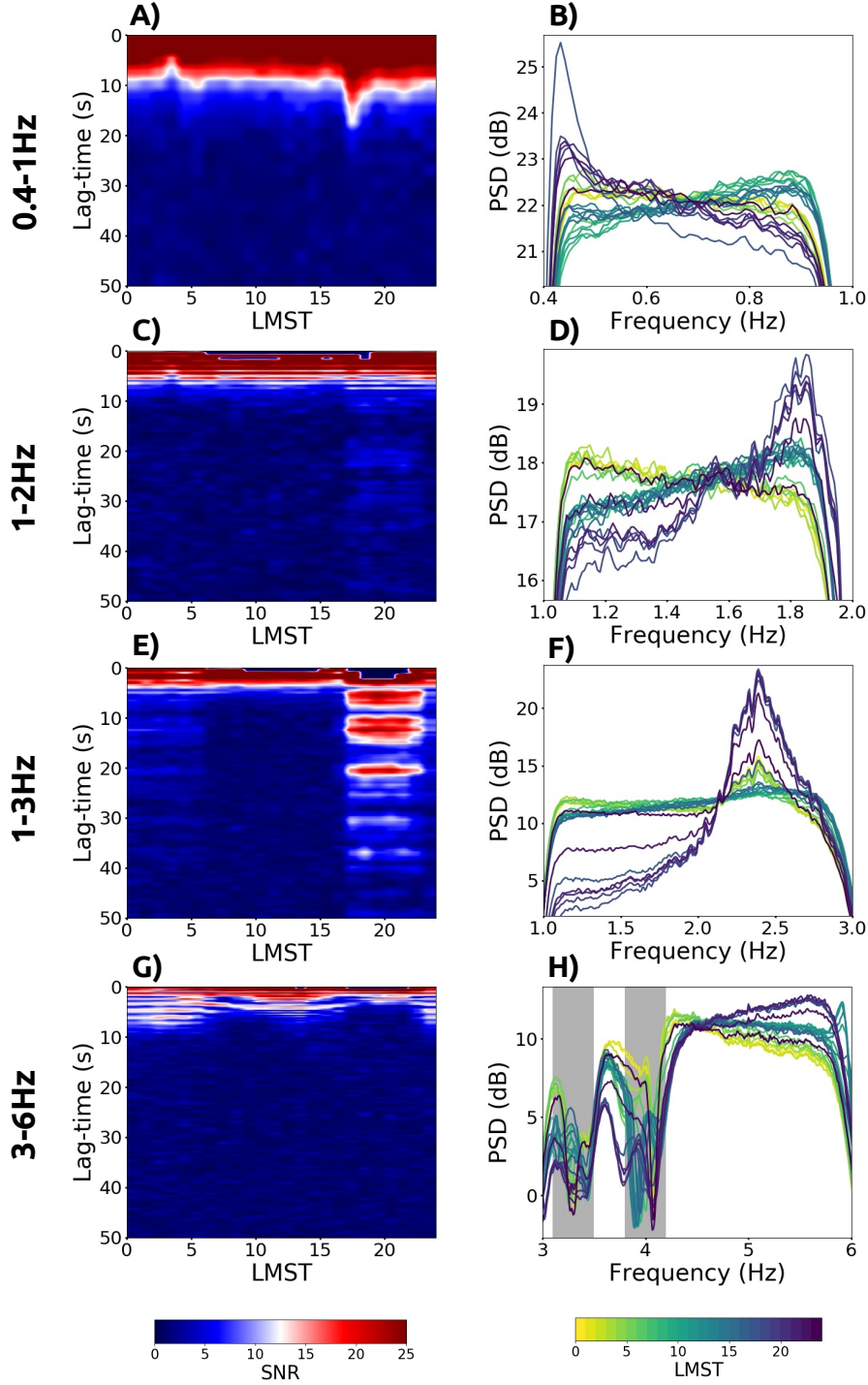


Figure 6. Left: Signal-to-Noise Ratio (SNR, see color scale) of the hourly ZZ autocorrelation functions as a function of Local Mean Solar Time (LMST) and lag-time in the following frequency bands: 0.4-1Hz (A), 1-2Hz (C), 1-3Hz (E) and 3-6Hz (G). On the right, Power Spectral Density (PSD, see color scale) of the hourly ZZ autocorrelation functions as a function of LMST in the following frequency bands: 0.4-1Hz (B), 1-2Hz (D), 1-3Hz (F) and 3-6Hz (H). The frequency band of the notch filters applied to remove the lander modes from the data are delimited by gray rectangles around 3.3Hz and 4Hz in H).

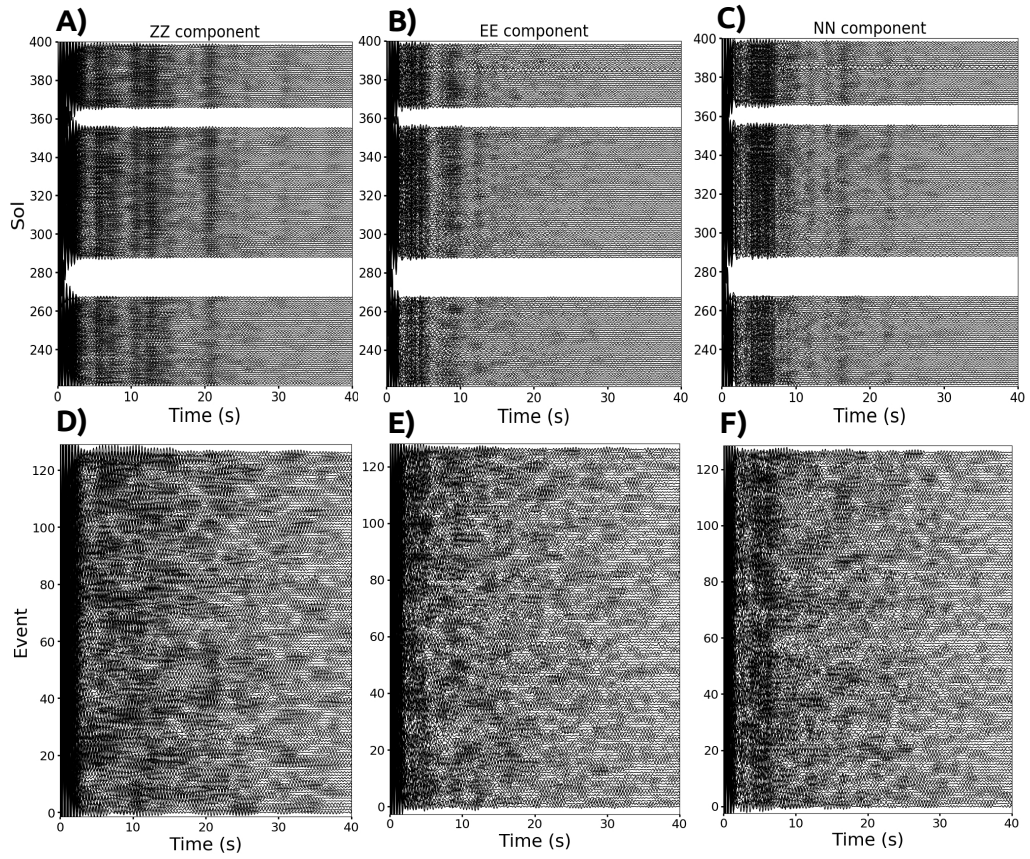


Figure 7. A) ZZ, B) EE and C) NN autocorrelation functions of ambient vibrations computed between 17:00 and 23:00 LMST from Sol 222 to Sol 399 in the 1-3Hz frequency band. D) ZZ, E) EE and F) NN autocorrelation functions of HF, VF and 2.4Hz events in the 1-3Hz frequency band, ordered by event number.

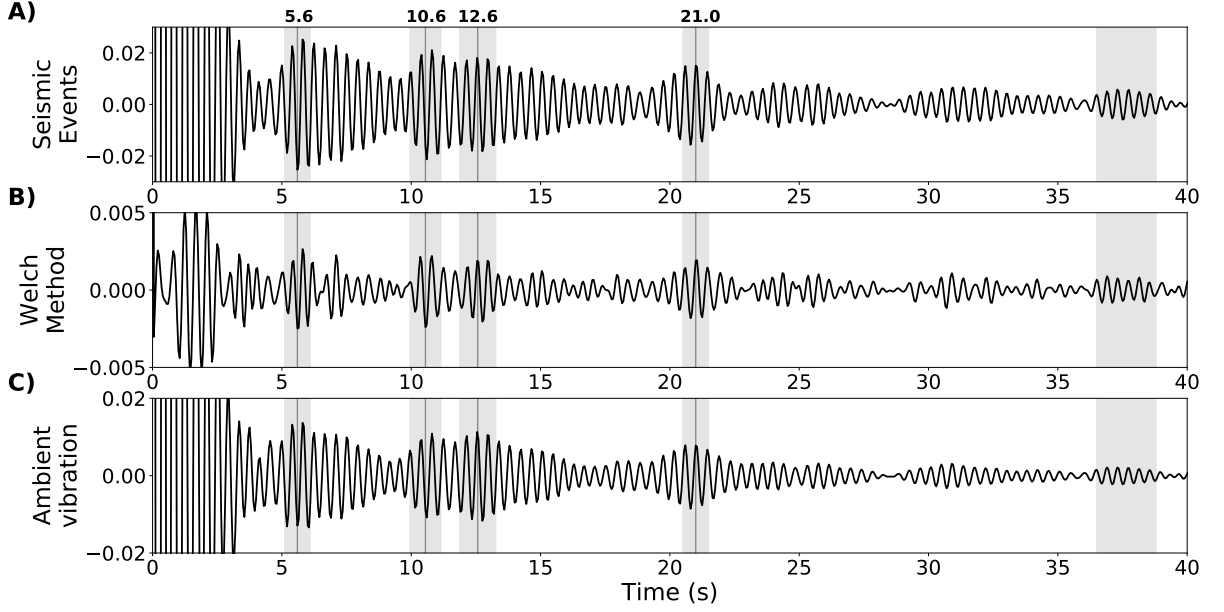


Figure 8. ZZ ACFs in the 1-3Hz frequency band derived from A) seismic events waveforms (linear stack of all HF, VF and 2.4Hz events); B) Welch’s Method applied to ambient vibrations (see section 3.3) and C) time domain processing of ambient vibrations (linear stack from Sol 222 to Sol 399) between 17:00 and 23:00 LMST (see section 3.2). Note that in the Welch method, an additional source deconvolution is applied. Arrivals that are simultaneously visible on the three waveforms are highlighted in grey. The arrival time of the maximum of each wave packet (marked by a vertical line) is indicated at the top of the Figure.

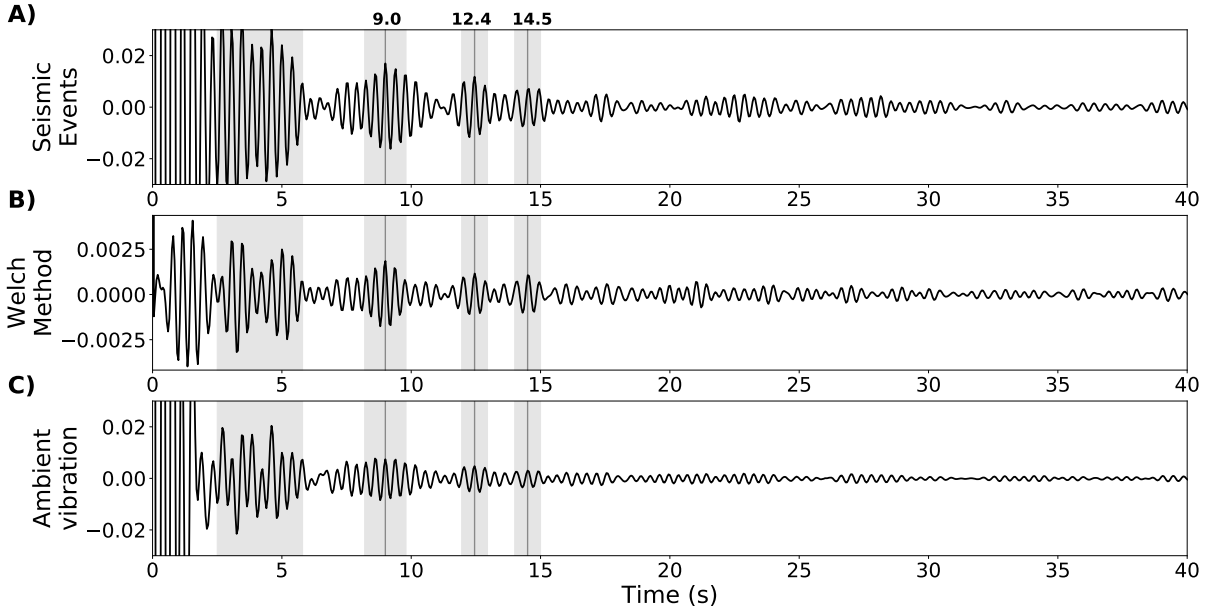


Figure 9. Same as Figure 8 for EE ACFs in the 1-3Hz frequency band. Note that in the Welch method, an additional source deconvolution is applied.

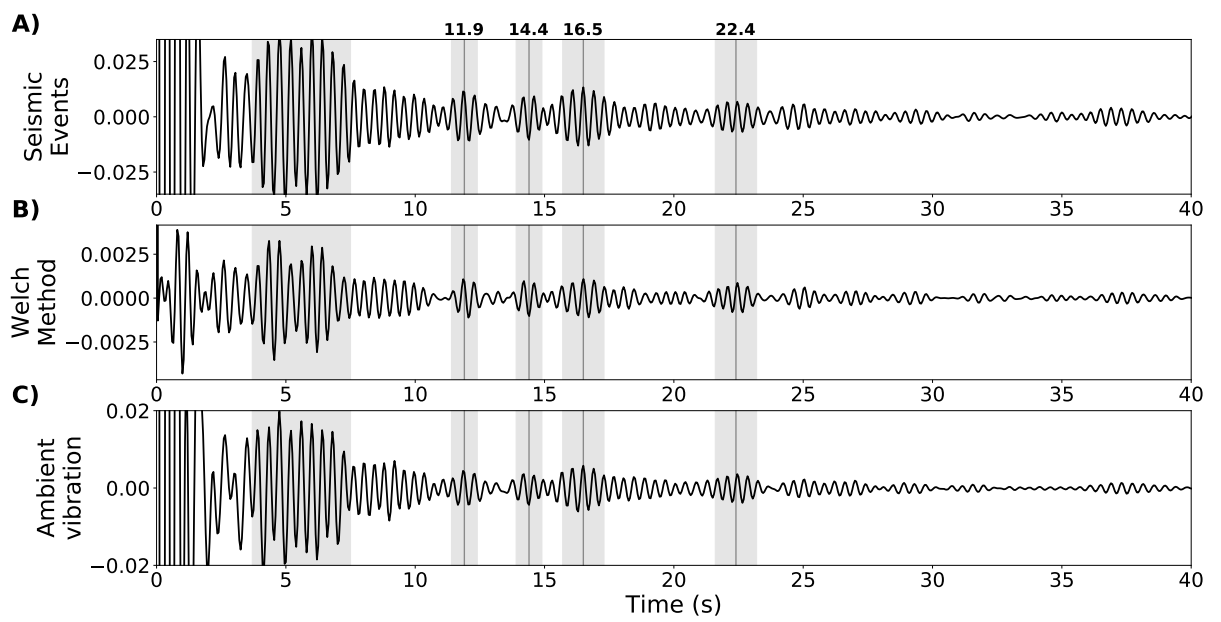


Figure 10. Same as Figure 8 for NN ACFs in the 1-3Hz frequency band. Note that in the Welch method, an additional source deconvolution is applied.

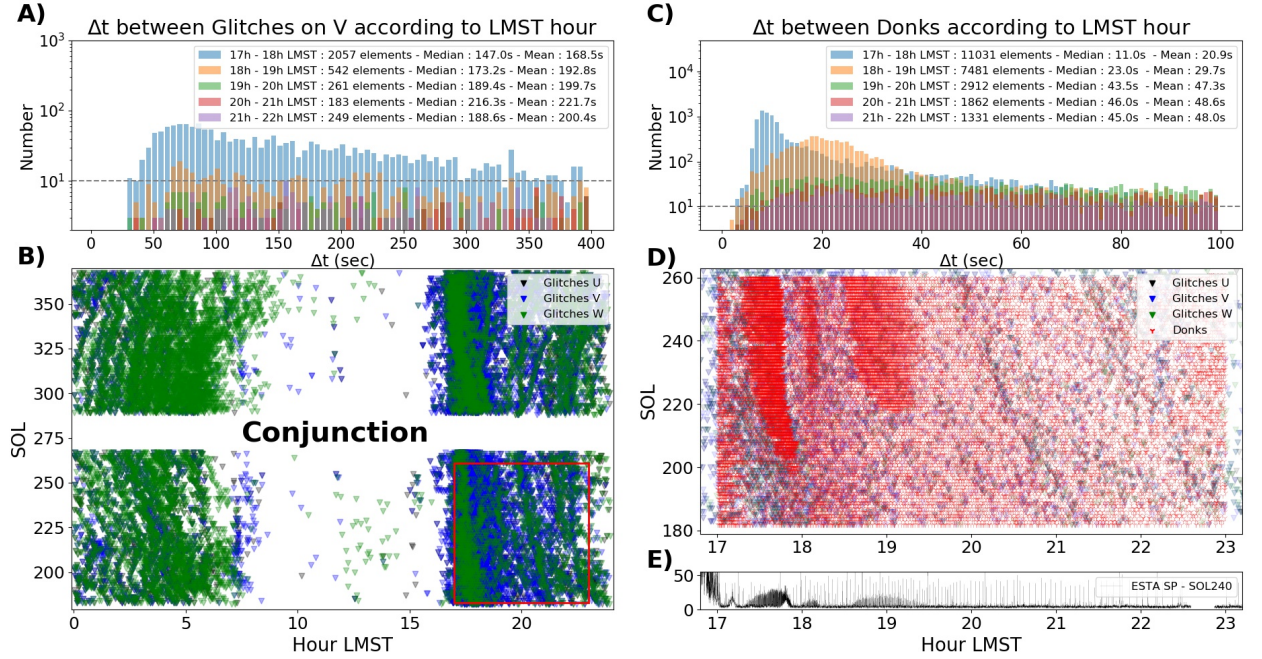


Figure 11. Temporal distribution of glitches and donks. A) Histogram of the distribution of delays between two consecutive glitches of the V component in different LMST windows. B) Time of occurrence of glitches detected on the U (black triangles), V (blue triangles) and W (green triangles) components of the VBB sensor from Sol 180 to Sol 361. Note that the high noise level during daytime (7:00 LMST to 17:00 LMST) hampers detection of glitches by our algorithm. C) Histogram of the distribution of delays between two consecutive donks in different LMST windows. D) Zoom in the red inset shown in B). The time of occurrence of the donks detected from Sol 180 to Sol 260 is shown with red markers. E) Typical time-series of the ESTASP channel (see text for the definition).