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The site tilt and lander transfer function from the short period seismometer of InSight on Mars

Alexander E. Stott^{1,2,*}, Constantinos Charalambous¹, Tristram J. Warren³, William T. Pike¹, Robert Myhill⁴, Naomi Murdoch², John B. McClean^{1,5}, Ashitey Trebi-Ollennu⁶, Grace Lim⁶, Raphael F. Garcia², David Mimoun², Sharon Kedar⁶, Kenneth J. Hurst⁶, Marco Bierwirth⁷, Philippe Lognonné^{8,9}, Nicholas A. Teanby⁴, Anna Horleston⁴ and William B. Banerdt⁶

* Corresponding author: Alexander E. Stott, alexander.stott@isae-supaero.fr

¹ Department of Electrical and Electronic Engineering, Imperial College London, London, UK

² Institut Supérieur de l'Aéronautique et de l'Espace SUPAERO, Toulouse, France

³ University of Oxford, Department of Physics, Parks Road, Oxford OX1 3PU, UK

⁴ School of Earth Sciences, University of Bristol, Bristol, UK

⁵ MIT Haystack Observatory, 99 Millstone Rd, Westford, MA, 01886, United States

⁶ Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

⁷ Max Planck Institute for Solar System Research, Justus-von-Liebig-Weg 3, 37077 Göttingen, Germany

⁸ Université de Paris, Institut de physique du globe de Paris, CNRS, Paris, France

⁹ Institut Universitaire de France, 1 rue Descartes, Paris, France

Declaration of Competing Interests

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Abstract

The NASA InSight mission has deployed the seismic experiment, SEIS, on the surface of Mars and has recorded a variety of signals including marsquakes and dust devils. This work presents results on the tilt and local noise sources, which provide context to aid interpretation of the observed signals and allow an examination of the near surface properties. Our analysis uses data recorded by the short period (SP) sensors on the deck, throughout deployment and in the final configuration. We use thermal decorrelation to provide an estimate of the Sol to Sol tilt. This tilt is examined across deployment and over a Martian year. After each modification to the site, the tilt is seen to stabilise over 3–20 Sols depending on the action and the total change in tilt is <0.035 degrees. Long term tilt over a Martian year is limited to <0.007 degrees. We also investigate the attenuation of lander-induced vibrations between the lander and SEIS. Robotic arm motions provide a known lander source in the 5–9 Hz bandwidth, yielding an amplitude attenuation of lander signals between 100 and 1000 times. The attenuation of wind sensitivity, from the deck to ground, presents a similar value in the 1.5–9 Hz range, thus favouring a noise dominated by lander vibrations induced by the wind. Wind sensitivities outside this bandwidth exhibit different sensitivity changes, indicating a change in the coupling. The results are interpreted through a finite element analysis of the regolith with a depth-dependent Young's modulus. We argue that discrepancies between this model and the observations are due to local compaction beneath the lander legs and/or anelasticity. An estimate for the effective Young's modulus is obtained as 62–81 MPa, corroborating previous estimates for the top layer duricrust.

Introduction

The NASA InSight lander (Banerdt et al., 2020) has been operating for over a complete Martian year (approximately two Earth years). The seismic experiment, SEIS, includes two seismometers known as the short period (SP) microseismometer and the very broadband (VBB). As detailed in Lognonné et al. (2019), the VBB sensor has a self-noise floor of $\sim 3 \times 10^{-10} \text{ m/s}^2/\text{Hz}^{1/2}$ over the bandwidth 3×10^{-2} – 7×10^{-1} Hz, whereas the SP sensor has a self-noise floor of $\sim 3 \times 10^{-9} \text{ m/s}^2/\text{Hz}^{1/2}$ over the bandwidth 0.1–7 Hz. Both the SP and VBB have been jointly recording throughout much of the mission to date (Ceylan et al., 2021; Clinton et al., 2021). The VBB sensor assembly, however, required levelling to within 0.1 degrees before operation and so

48 was initially inactive (Bierwirth et al., 2019). On the other hand, the SP is a MEMS (microelec-
49 tromechanical system) sensor and is able to operate at a tilt of up to 15 degrees without recentering
50 (Lognonné et al., 2019; Pike et al., 2016). As a result, the SP sensor began collecting data during
51 the deployment phase between Sols 4 and 66, where a Sol is a Martian solar day with Sol 1 be-
52 ginning the local mean solar time midnight after landing. This was before the VBB could operate.
53 This includes 48 hours of data on the deck over seven Sols (between Sol 4 and 21) (Panning et al.,
54 2020) and uncovered surface data from Sol 24 until SEIS reached its final setup on Sol 66 when
55 the WTS (wind and thermal shield) was deployed (Lognonné et al., 2020). The SP sensor was
56 even operated during cruise where it recorded its self-noise (McClean et al., 2019). This unique
57 dataset was useful to make decisions during the deployment of SEIS and in Panning et al. (2020)
58 has been used to assess the potential of future on-deck planetary deployments which could be a
59 cost effective approach for some planetary seismic studies.

60 Prior to achieving its final installation, where the VBB sensor would continuously record in its
61 high performance scientific mode in tandem with the SP, several further deployment activities were
62 required to minimise the seismic noise from the lander and atmosphere of Mars and are detailed in
63 Lognonné et al. (2019). These were:

- 64 • the tether storage box (TSB) release on Sol 37, to unveil the full tether length from its pro-
65 tective box after SEIS was deployed on the ground.
- 66 • three stages of levelling (LVL) on Sol 30, 39 and 44, where the legs of SEIS were ex-
67 panded/contracted to move SEIS close to the ground and level.
- 68 • load shunt assembly (LSA) release on Sol 40. The LSA is the connection of the tether to
69 SEIS and is designed to mechanically uncouple them, similarly to coiling cable around a
70 seismometer.
- 71 • pinning mass adjustments on Sols 56, 59 and 61, where the tether was moved to open the
72 LSA further.
- 73 • wind and thermal shield (WTS) deployment on Sol 66.

74 Several of these stages required the irreversible breaking of frangibolts that held the seismometer
75 assembly in its stowed configuration. The levelling sequences consisted of extending/contracting

76 the three legs of the LVL system on which SEIS sits (Bierwirth et al., 2019; Lognonné et al., 2019).
77 After each step, it was crucial to confirm that the current situation was stable and verify the site
78 noise, tasks which the SP sensor could perform.

79 In this paper, we analyse the long period response of the seismometer to obtain a measurement
80 of tilt and verify the stability of the site. To do this, we examine the SP mass position channel over
81 the deployment and the science monitoring phases of the mission. The mass position channel is
82 proportional to acceleration and is sometimes known as acceleration or tilt output of a seismometer.
83 To compute the tilt, we first quantify the thermal response of the SP sensors (Stott et al., 2018a).
84 This dominates the long period response of the sensor, particularly on a diurnal scale, and so
85 must be removed before the tilt can be obtained. Two algorithms are proposed which remove the
86 diurnal temperature response to give a relative, delta tilt between Martian Sols providing that the
87 SP sensor remains within the same feedback null point. These null points are due to the operation
88 of the sensor which is based on the force feedback principal of Wielandt et al. (1982). The sensor
89 coils drive the proof mass to try to remain stationary at these null points. The SP implements a
90 grid of several feedback null points in order to operate over a wide range of tilts (Lognonné et al.,
91 2019; Pike et al., 2016). However, the SP temporarily loses feedback when transitioning between
92 null points and the value of the mass position output may not physically correspond to that of the
93 preceding null point. As such, the proposed methods only give the relative tilt between Sols while
94 the sensor remains within a single null point. We do not examine tilts when the sensor transitions
95 between them. These null points have a periodicity of $48 \mu\text{m}$, which means the feedback null
96 transitions to another for a tilt of 1.58 degrees.

97 In this study, we analyse the extracted relative tilt on the deck, between each levelling operation
98 on the ground and, after the final levelling operation, over the science monitoring phase of the
99 mission. This provides an insight into the point stability (Kümpel et al., 2001) on Mars over nearly
100 2 Earth years.

101 The deployment data also provides important context for understanding local noise sources. The
102 sensor is installed on the ground, shielded from direct wind forcing and the harsh Martian temper-
103 ature variation by the WTS. However, wind can still force vibrations of the lander (with attached
104 solar panels) and the WTS, which are coupled to SEIS through the martian regolith (Mimoun et al.,
105 2017; Murdoch et al., 2018, 2017). Testing of the lander-ground interaction was not performed on

106 Earth prior to launch. While such testing would have provided useful information, it is not pos-
107 sible to replicate a suitable analogue of Martian conditions on Earth for a thorough examination
108 (Panning et al., 2020). The data recorded on deck, however, provide an ability to quantify the
109 atmospheric forcing on the lander and coupling through the Martian regolith.

110 InSight has a robotic arm known as the IDS (instrument deployment system) used for deploy-
111 ing and interacting with SEIS and other instruments (Trobi-Ollennu et al., 2018). Motions of the
112 robotic arm produce vibrations which are experienced by the seismometer (Ceylan et al., 2021;
113 Stott et al., 2020). Consider that the robotic arm motions observed by the seismometer on the
114 deck can be compared to those observed on the ground to calculate the absolute part of the transfer
115 function, a transfer coefficient, in the 5–9 Hz bandwidth. This follows a preliminary investiga-
116 tion into the robotic arm motions in (Stott et al., 2020). The observed transfer coefficient for this
117 lander-induced signal is then compared with the wind-induced acceleration over a range of fre-
118 quencies. In doing so, we highlight the lander as a source of vibrations. Moreover, we observe the
119 seismometer’s sensitivity to wind without added cultural noise that would be seen on Earth.

120 To understand the factors at play for these attenuation estimates, we present a finite element
121 model (FEM) which simulates the elastic deformation of the Martian regolith resulting from vi-
122 brations of the lander feet building upon the pre-launch studies of Teanby et al. (2017) and Myhill
123 et al. (2018). This simulation models the regolith as an elastic half-space with a depth-dependent
124 Young’s modulus. In addition, we estimate the effective Young’s modulus through a consideration
125 of the equation of motion for the lander with the wind forcing and the SP acceleration on the lander.

126 **SEIS site stability from tilt**

127 **SP long period response and temperature sensitivity**

128 The long period response of horizontal seismometers can be inferred to be due to tilting (De An-
129 gelis et al., 2012; Rodgers, 1968) and so we must retrieve the low frequency acceleration from the
130 SP. As detailed in Stott et al. (2018a), the SP has two outputs from the force feedback system: the
131 velocity and mass position channel. These two channels are the outputs of the two coils used to
132 drive the sensor feedback. The velocity channel is the main scientific output digitised at 24 bits
133 for fine control whereas the mass position is used for coarser control of large displacements and is

134 digitised at 12 bits. The velocity channel is proportional to the velocity above the sensor transfer
 135 function corner frequency $\sim 1/35$ Hz and the mass position output is proportional to acceleration
 136 at frequencies below this corner frequency. To this end, the SP sensor mass position output can
 137 be used to retrieve the acceleration at long periods through multiplying the signal by a gain. Fur-
 138 ther technical specification and details on the SP transfer function can be found in [Lognonné et al.](#)
 139 (2019) and [Stott et al. \(2018a\)](#).

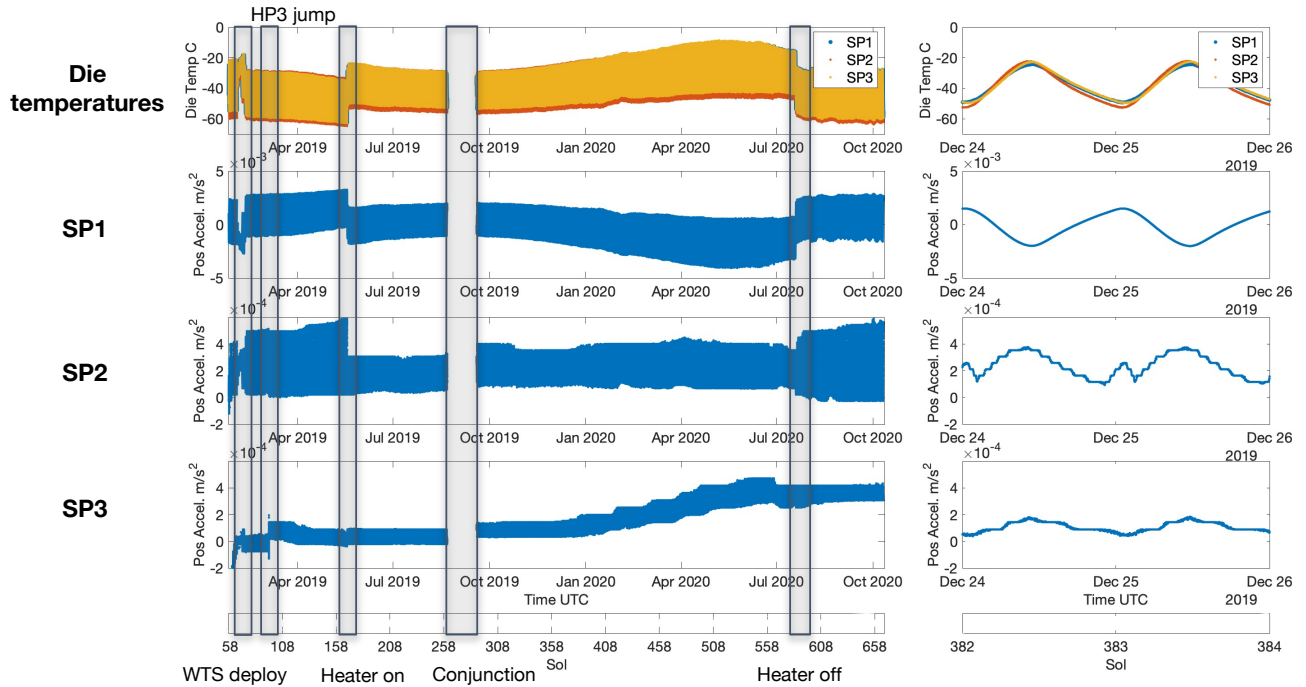


Figure 1. The sensors die temperature (top row) and mass position of the SP1 (vertical, second row), SP2 (horizontal, third row) and SP3 (horizontal, fourth row) sensors from Sol 58 to Sol 668. Several key events in Table 1 are indicated. Note that the vertical variation in the mass position is the diurnal variation, highlighted in the second column which shows a zoom over 2 Sols. For SP1 and SP2 this is the most significant motion over the Martian year but for SP3 the annual variation is of an equivalent magnitude.

140 Figure 1 shows the acceleration from SP mass position channels for each sensor from Sol 58 to
 141 Sol 667 along with their die temperatures. Note that there is a large data gap during solar conjunc-
 142 tion, when Mars passed around the opposite side of the Sun, prohibiting direct communication.
 143 Just prior to this, the SEIS system fell into safe mode and so could not record during this period.
 144 This could not be restored until communication with the spacecraft was re-established. The key

Event	Sol
Landing	Sol 0
First SP data	Sol 4
SEIS deployed on the ground	Sol 22
Levelling motions	Sol 30, 39 and 44
Tether storage box (TSB) release	Sol 37
Load shunt assembly (LSA) release	Sol 40
Pinning mass adjustments	Sol 56, 59 and 61
WTS deployment	Sol 66
Mass position jump associated with HP3 hammering	Sol 95
Heater switch on/off	Sol 168 and 584
Conjunction data gap	Sol 261 to 288

Table 1: Summary of important events in the displayed data.

145 features observed in this time series are:

- 146 1. the WTS deployment on Sol 66.
- 147 2. a jump in the mass position on Sol 95 associated with the second sequence of HP3 hammer-
148 ing, most notable in SP3.
- 149 3. the heater switch on (used to keep the sensors within the operating conditions) on Sol 168.
- 150 4. a large gap from Sol 261 to 288 during conjunction.
- 151 5. the heater switch off on Sol 584.

152 A full list of significant events over the mission is given in Table 1. Aside from the mass position
153 jump on Sol 95, each of these features was induced by a change in the thermal environment. As
154 a result, before we consider a tilt derived from the SP sensors the temperature sensitivity must be
155 addressed.

156 The middle row of Figure 2 shows the SP acceleration versus temperature for each sensor over
157 the mission, including data on the deck and on the ground. Prior to launch, [Stott et al. \(2018a\)](#)
158 derived a model to predict the SP acceleration from temperature effects as

$$a_{SP} = \alpha_{Die} T_{Die} + \alpha_{\Delta} (T_{Die} - T_{Enc}) \quad (1)$$

159 where a_{SP} is the acceleration (in m/s^2) of the SP, T_{Die} is the SP sensor die temperature (in C) and
 160 T_{Enc} is the temperature (in C) of the SP enclosure. This model takes into account two physical
 161 pathways, the change in Young's modulus with temperature of the sensor's cantilever (the sensor
 162 spring) and a thermoelastic component due to a temperature difference between the sensor and its
 163 enclosure. [Stott et al. \(2018a\)](#) found these two pathways to be sufficient to model the SP's accel-
 164 eration output in pre-mission testing and depend on the instantaneous sensor (die) and enclosure
 165 temperature. The α_{Die} coefficient accounts for the change in the cantilever's Young's modulus
 166 with temperature while the α_{Δ} coefficient accounts for a thermoelastic effect from the temperature
 167 difference to SP enclosure ([Liu et al., 2019](#); [Stott et al., 2018a](#)). The thermal model (1) can be
 168 written as a regression format as

$$\mathbf{y} = \mathbf{X}\mathbf{b}$$

where N data samples $1, 2, \dots, N$ are collated into the vectors/matrices as

$$\mathbf{y} = [a_{1,2,\dots,N}], \quad \mathbf{X} = \begin{bmatrix} T_{Die,1,2,\dots,N}, & (T_{Die,1,2,\dots,N} - T_{Enc,1,2,\dots,N}), & 1_{1,2,\dots,N} \end{bmatrix}, \quad (2)$$

$$\mathbf{b} = \begin{bmatrix} \alpha_{Die}, & \alpha_{\Delta}, & \alpha_{DC} \end{bmatrix}^T,$$

169 The parameters α_{Die} and α_{Δ} are calculated through the least squares solution $\mathbf{b} = (\mathbf{X}^T \mathbf{X})^{-1} \mathbf{X}^T \mathbf{y}'$
 170 where \mathbf{y}' refers to a vector of measured SP acceleration values rather than an estimate of them.

171 The model parameters were fitted to mission data, shown in Figure 2. The on-deck response
 172 of the horizontal sensors changes from deck to ground while the vertical SP1 sensor has similar
 173 sensitivity for both datasets. The horizontal response on the deck, however, could not be well fitted
 174 by the thermal model (1). This indicates an additional thermoelastic contribution from the lander.
 175 We now consider the temperature sensitivities seen on the ground. The observed responses are
 176 not exactly the same as those from the pre-launch testing. These exhibited a strong thermoelastic,
 177 α_{Δ} , contribution for both the vertical and horizontal sensors. On Mars, however, the acceleration
 178 of the vertical SP1 sensor can be explained by a linear sensitivity to the die temperature fitted
 179 as $\alpha_{Die} = -1.4 \times 10^{-4} \text{ m/s}^2/\text{K}$ using (2). The horizontal SP2 sensor shows a piecewise linear
 180 sensitivity, which is also demonstrated in the time series in Figure 1. As this is a horizontal sensor
 181 it is sensitive to thermoelastic tilting. This bilinear sensitivity could then be due to a change in
 182 contact points of the sensor mounting, whereby a gap may open and close at a certain threshold.
 183 This would alter the thermoelastic forces on the sensor and therefore, the sensitivity to temperature.

184 Below -49C the thermal model was fitted to SP2 as $\alpha_{Die} = -4.2 \times 10^{-5} \text{ m/s}^2/\text{K}$ and above -49C
185 by $\alpha_{Die} = 8.9 \times 10^{-6} \text{ m/s}^2/\text{K}$ and $\alpha_{\Delta} = -6.7 \times 10^{-5} \text{ m/s}^2/\text{K}$. The other horizontal SP3 was
186 fitted by just the linear component as $\alpha_{Die} = 8.1 \times 10^{-6} \text{ m/s}^2/\text{K}$.

187 Figure 2 shows the rtPSD (square root of the power spectral density) of each sensor’s mass
188 position channel after the solar conjunction data gap, the largest continuous trace. This is shown
189 alongside the fitted thermal model (the estimate $\mathbf{y} = \mathbf{X}\mathbf{b}$ from (2)) and a decorrelated response,
190 whereby the estimate $\mathbf{y} = \mathbf{X}\mathbf{b}$ was subtracted from the mass position data.

191 For the vertical SP1, the decorrelation reduces both the diurnal peak, its harmonics and the
192 long period response. At frequencies above $5 \times 10^{-5} \text{ Hz}$ (higher than the diurnal variation) the
193 decorrelated signal has a generally higher power than the acceleration. This is because the tem-
194 perature sensor has too high a noise above these frequencies to decorrelate successfully. Although
195 the diurnal harmonics are still reduced, the noise floor is increased above what would be the sen-
196 sor noise floor. This effect is only observed for the vertical SP1 data. The decorrelation for the
197 horizontal sensors similarly suppresses diurnal peaks. The long period decorrelation has removed
198 less power in comparison to the vertical. This is because they generally have a lower sensitivity
199 to temperature, for example, SP3 shows a long term trend which is not well correlated with the
200 die temperature. For some higher frequency harmonics, the decorrelation has not removed all the
201 variation. This could be due to the low resolution of the data, as these channels are recorded as
202 housekeeping data and so are digitised over 12 bits which limits the resolution (Lognonné et al.,
203 2019). While this is important to consider these aspects with respect to the SP noise floor and tem-
204 perature induced noise the decorrelation is sufficient for the scope of this paper. This is because
205 our approaches focus on separating the thermal response from the DC component over the diurnal
206 scale. From Figure 2, the average attenuation in amplitude at the diurnal peak is by a factor of 62,
207 8 and 3 for SP1, SP2 and SP3 respectively.

208 **Obtaining the relative tilt from the SP horizontal sensors**

209 After accounting for diurnal variation due to temperature in the SP acceleration, the long period
210 acceleration of the horizontal sensors can be attributed to changes in tilt. We propose two methods
211 to estimate this acceleration:

- 212 1. obtain the mass position values for SP2 and SP3 at a reference temperature each Sol.

213 2. calculate the thermal model response for SP2 and SP3 for each Sol and compare the DC bias
 214 component.

215 These approaches are summarised as algorithms in Tables 2 and 3 respectively and remove the
 216 temperature sensitivity for each Sol. Note that the output tilt values $\theta_{SP2,n}$ and $\theta_{SP3,n}$ therefore
 217 require a calibration in order to equate to an absolute tilt of the SEIS assembly. The subtraction
 218 of the acceleration of the first Sol in the sequence as $a_{SP2,n} = a_{SP2,n} - a_{SP2,1}$ and $a_{SP3,n} =$
 219 $a_{SP3,n} - a_{SP3,1}$ means that the output tilt is a relative, delta tilt.

Algorithm 1: Constant temperature based tilt algorithm

- 1: **Input:** $T_{ref}, T_{DIE,SP2}, T_{DIE,SP3}, a_{SP2}, a_{SP3}, g = 3.711m/s^2$
 - 2: **for** Each Sol in sequence $n = 1, 2, \dots, N$ **do**
 - 3: Find the value $a_{SP2,n} = a_{SP2}(T_{DIE,SP2} = T_{ref})$ when $T_{DIE,SP2}$ is falling
 - 4: Find the value $a_{SP3,n} = a_{SP3}(T_{DIE,SP2} = T_{ref})$ when $T_{DIE,SP2}$ is falling
 - 5: Subtract the value of the first Sol in the sequence $a_{SP2,n} = a_{SP2,n} - a_{SP2,1}$ and $a_{SP3,n} =$
 $a_{SP3,n} - a_{SP3,1}$
 - 6: $\theta_{SP2,n} = \arcsin a_{(SP2,n)/g}$
 - 7: $\theta_{SP3,n} = \arcsin a_{(SP3,n)/g}$
 - 8: Store $\theta_{SP2,n}$ and $\theta_{SP3,n}$
 - 9: **end for**
-

Table 2: A tilt retrieval algorithm based on taking the acceleration values when the sensor is at a reference temperature.

220 **The relative tilt over the deployment phase**

221 The two tilt algorithms in Tables 2 and 3 were applied to the deployment data, beginning on the
 222 deck and then on the ground until SEIS was covered by the WTS. We separated the estimates of
 223 relative tilt over the deployment into five sections:

- 224 1. On the deck - Sol 10 to 21 (the first recording on Sol 4 was for only 10 minutes),
- 225 2. First placed on the ground - Sol 23 to 30,

Algorithm 2: Thermal decorrelation based tilt algorithm

- 1: **Input:** $T_{DIE,SP2}, T_{DIE,SP3}, a_{SP2}, a_{SP3}, g = 3.711m/s^2$
 - 2: **for** Each Sol in sequence $n = 1, 2, \dots, N$ **do**
 - 3: Calculate least squares regression to fit thermal model for $a_{SP2}(T_{DIE,SP2} > -49C)$
 - 4: Calculate least squares regression to fit thermal model for a_{SP3}
 - 5: Take the DC bias of each regression as $a_{SP2,n} = a_{DC,SP2}$ and $a_{SP3,n} = a_{DC,SP2}$
 - 6: Subtract the value of the first Sol in the sequence $a_{SP2,n} = a_{SP2,n} - a_{SP2,1}$ and $a_{SP3,n} = a_{SP3,n} - a_{SP3,1}$
 - 7: $\theta_{SP2,n} = \arcsin(a_{SP2,n}/g)$
 - 8: $\theta_{SP3,n} = \arcsin(a_{SP3,n}/g)$
 - 9: Store $\theta_{SP2,n}$ and $\theta_{SP3,n}$
 - 10: **end for**
-

Table 3: A tilt retrieval algorithm based on taking the bias obtained from the thermal model decorrelation.

226 3. After the first levelling motion - Sol 31 to 39,

227 4. After the second levelling “MEMS offset tuning” motion - Sol 40 to 44,

228 5. After the third levelling low motion - Sol 45 onward.

229 Each section is separated by an action causing a change in the feedback null point, either the
230 sensor being moved or a levelling motions. In a levelling activity, the legs of the LVL (that SEIS is
231 mounted on) are actuated in order to get the SEIS assembly close to the ground and level (Bierwirth
232 et al., 2019). During these motions, the horizontal SP sensors moved through feedback null points
233 (which occur at tilt intervals of 1.58 degrees) and the mass position channel output was at its
234 maximum slew rate (Lognonné et al., 2019). Over a null point transition, the mass position outputs
235 are not physically comparable and so the proposed tilt algorithms cannot be used to estimate the
236 tilt through, or compare before and after, these levelling motions. The tilt estimate for each Sol
237 is, therefore, the relative tilt referred to the first Sol of its section. Before the WTS was deployed
238 the SP was switched off overnight on each Sol as the sensor was outside the thermal limits for

239 operation, meaning that the sensor was not continuously in feedback. During this phase we assume
240 that the SPs remained within the same feedback null point when turned back on.

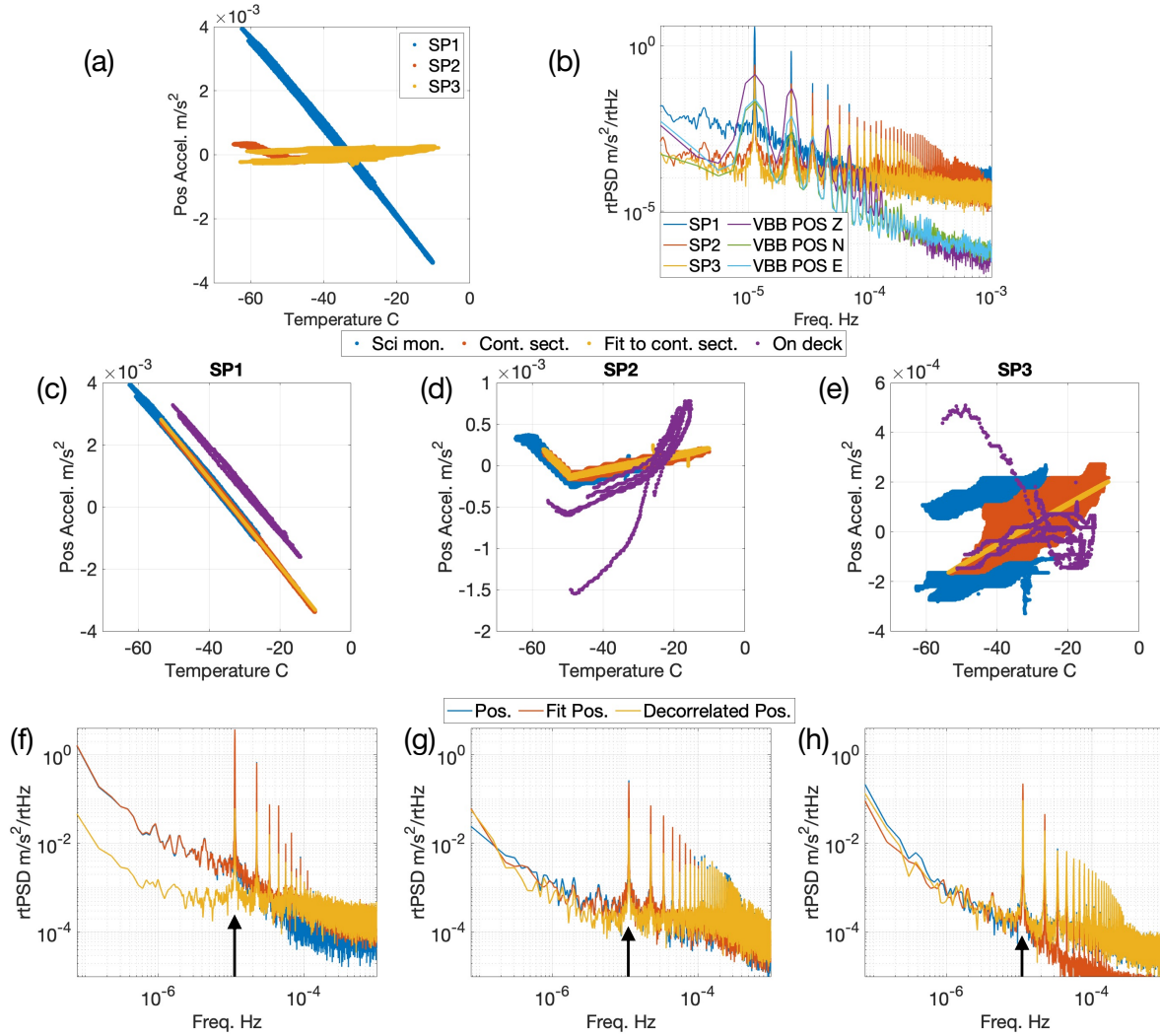


Figure 2. (a): The temperature versus acceleration (from mass position output) for SP1, SP2 and SP3 all together to show the relative differences. (b): The SP and VBB mass position rtPSDs showing the relative level of noise. (c), (d) and (e): the temperature versus acceleration (from mass position output) separately for SP1, SP2 and SP3. The blue data are for after the WTS from Sol 73 to 667, the red data correspond to the period after the solar conjunction to the heater turn off on Sol 584 which is the longest continuous section under the same thermal environment, the yellow are the output of the fitted thermal model to this longest continuous section and the purple are the SP response from on the deck. In each case the data are set to have zero mean. (f), (g) and (h): the rtPSD of SP1, SP2 and SP3 respectively for the longest continuous section (blue), the fitted thermal model output (red) and the decorrelated (the thermal model is subtracted from the original data) data (yellow). The arrow indicates a period of a Martian Sol.

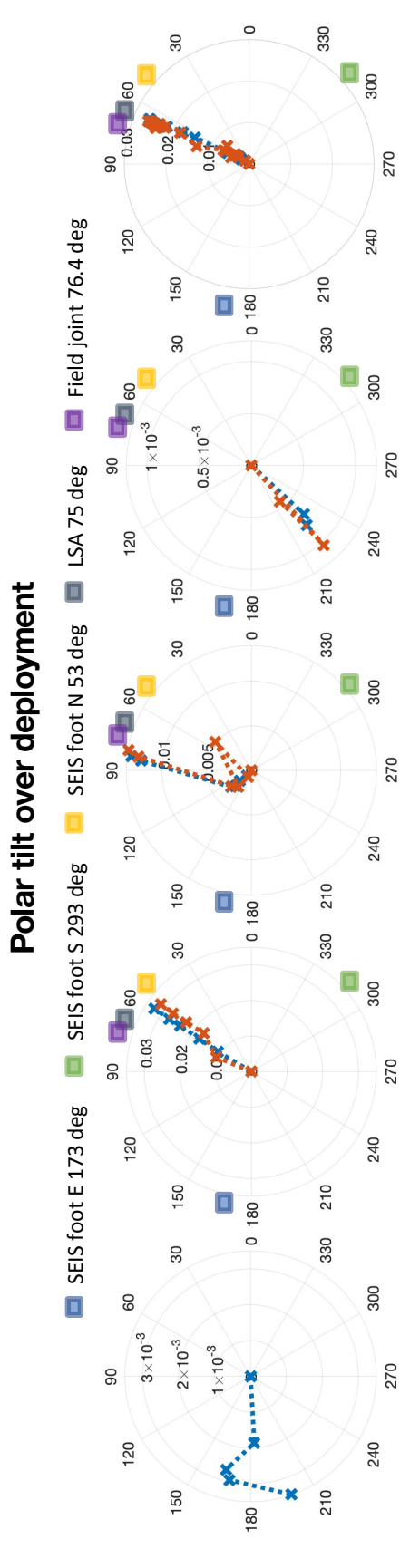
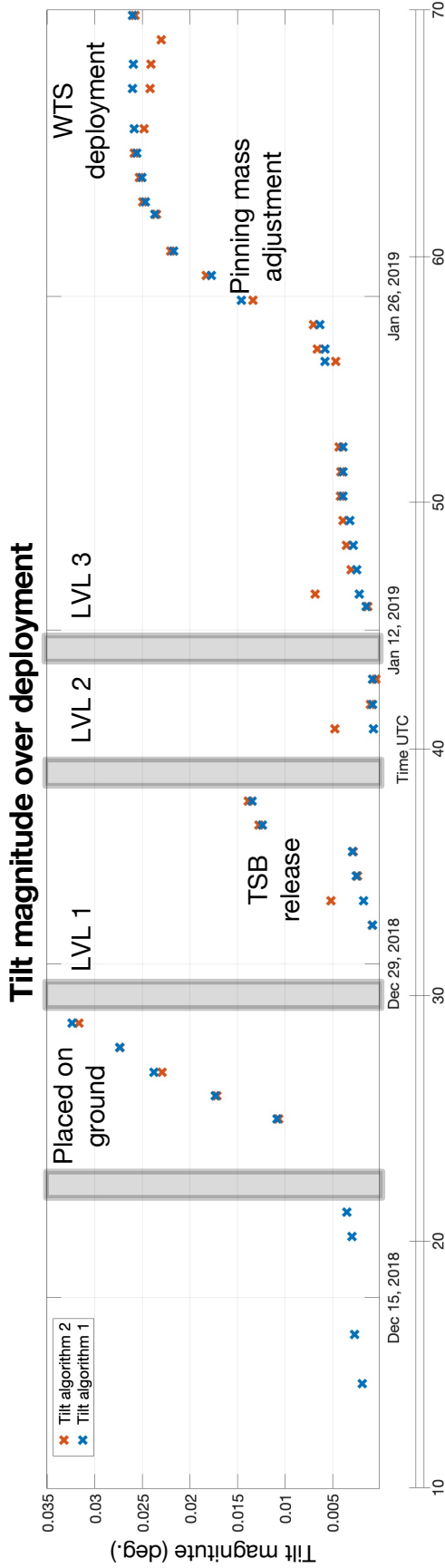


Figure 3. The evolution of tilt over the deployment phase of the mission until Sol 70. The top row shows the aggregate delta tilt for each data section beginning on the deck, separated by deployment/levelling activities (indicated by the grey boxes) which prevent the SP staying in feedback so tilt cannot be calculated between the before and after. The bottom row gives the polar plot of these tilts with the direction of key features indicated.

241 Figure 3 shows the tilt, in magnitude and direction, relative to the first Sol of each of the five
242 sections calculated with both algorithms in Tables 2 and 3, and rotated into geographic coordinates
243 where east is at 0 degrees azimuth and north at 90 degrees azimuth. The location of each item
244 around SEIS is detailed in [Ceylan et al. \(2021\)](#) and [Lognonné et al. \(2019\)](#). A constant reference
245 SP2 temperature of $T_{ref} = -25$ C was used for the reference temperature based algorithm in Table
246 2. It can be seen that the two tilt retrieval algorithms in Tables 2 and 3 are in general agreement.
247 The tilt derived from the thermal decorrelation based algorithm in Table 3 sometimes produces
248 erroneous values owing to a poor fit of the thermal model on that Sol, e.g. in the third section on
249 the ground an erroneous value was observed when the LSA was opened or in the final section after
250 the WTS was deployed. Only tilt estimates from the reference temperature algorithm in Table 2
251 are presented for the on deck section. This is because the relationship between the horizontal SPs
252 (SP2 and SP3) and their die temperature for the on deck section of data (shown in Figure 2) is
253 not modelled by (1) and so the thermal decorrelation based algorithm in Table 3 cannot be used
254 to retrieve a tilt estimate. This different relationship for the horizontal SPs on the deck and on the
255 ground could be due to extra thermoelastic contributions from the assembly being bolted to the
256 deck.

257 During the 11 Sols since the first long term SP acquisition on the deck on Sol 10, the cumulative
258 tilt did not exceed 0.005 degrees, generally tilting toward the west but with a varying azimuth.
259 This shows that the lander was reasonably stable at this point. The largest rate of tilting was
260 observed during the first 7 Sols on the ground, totalling 0.033 degrees at the end of that period.
261 This happened at a slowly decreasing rate with an azimuth of ~ 55 degrees, which is approximately
262 in the direction of the SEIS north foot. The period after the first levelling sequence shows a much
263 lower rate of tilt which again decreases over time with an azimuth of 140 degrees. On Sol 38 the
264 TSB release was performed, marked by a large tilt with an azimuth of 80 degrees which is close
265 to that of the tether field joint. The TSB release action was to unfurl the entire length of the tether
266 to allow it to lie along the ground, uncoupling it from the lander. The third period on the ground
267 is only a few Sols and shows very little tilt with an azimuth of 220 degrees. The final stage after
268 the last levelling motion shows a period of settling where the assembly tilted up to 0.005 degrees
269 and then a larger set of tilts associated with the pinning mass adjustments. The pinning mass is a
270 mass with a hook attached so that the robotic arm can move it to widen the gap of the LSA and

271 in turn help uncouple the tether from the SEIS assembly. After these motions, the tilt stabilised at
272 0.026 degrees for the WTS deployment. This tilt had an azimuth of 65 degrees which is between
273 the LSA/field joint and the SEIS north foot.

274 **The relative tilt over the science monitoring phase**

275 The final stage of deployment was the emplacement of the WTS. Once the thermal environment had
276 stabilised, the SP and VBB were placed in continuous operation for the science monitoring phase.
277 The tilt algorithms in Tables 2 and 3 were applied to this continuous phase, with the reference
278 Sol corresponding to the end of the final levelling sequence on Sol 44. Figure 4 shows the results
279 in terms of the aggregate tilt and azimuth which demonstrate that the cumulative tilt of the SEIS
280 assembly is <0.007 degrees since Sol 70 and is therefore extremely stable. A jump in the tilt is
281 observed early in the mission on Sol 95 (March 2019) associated with the HP3 hammering and
282 is seen in the mass position data in Figure 1, most notably on SP3. There is a broad agreement
283 between the two algorithms with a generally constant difference of around 0.003 degrees. The
284 constant SP2 temperature, T_{ref} , used for the algorithm in Table 2 was changed to -35 C compared
285 to the -25 C used to analyse deployment. The change in reference temperature is because data
286 was not recorded at the same reference temperature (on the rising edge) on all Sols as the sensor
287 was turned off overnight. This does not affect the comparison of the results between sections as
288 the temperature is a reference point to compare Sol to Sol acceleration values.

289 A very gradual apparent tilting can be observed during the scientific monitoring phase (Figure
290 4) whose rate increases slightly after Jan 2020. Additionally, there appears to be a three-month
291 (Earth) quasiperiodic tilt signal with a peak to peak amplitude of 0.002 degrees. This is most
292 notable in the thermal decorrelation based algorithm in Table 3 between Sol 94 and 244. Figure 5
293 shows the tilt since Sol 44 in Cartesian coordinates. This shows that after the initial settling period
294 in a direction between the LSA and north SEIS foot the long term tilt is not in a single direction.

295 **Discussion of the tilt results**

296 The derived tilt signals are estimates based on removing the diurnal temperature variation in the
297 data and comparing the residual mean on a Sol to Sol basis. This means they do not account for
298 unmodelled longer period temperature sensitivities. To this end, the estimates may encapsulate

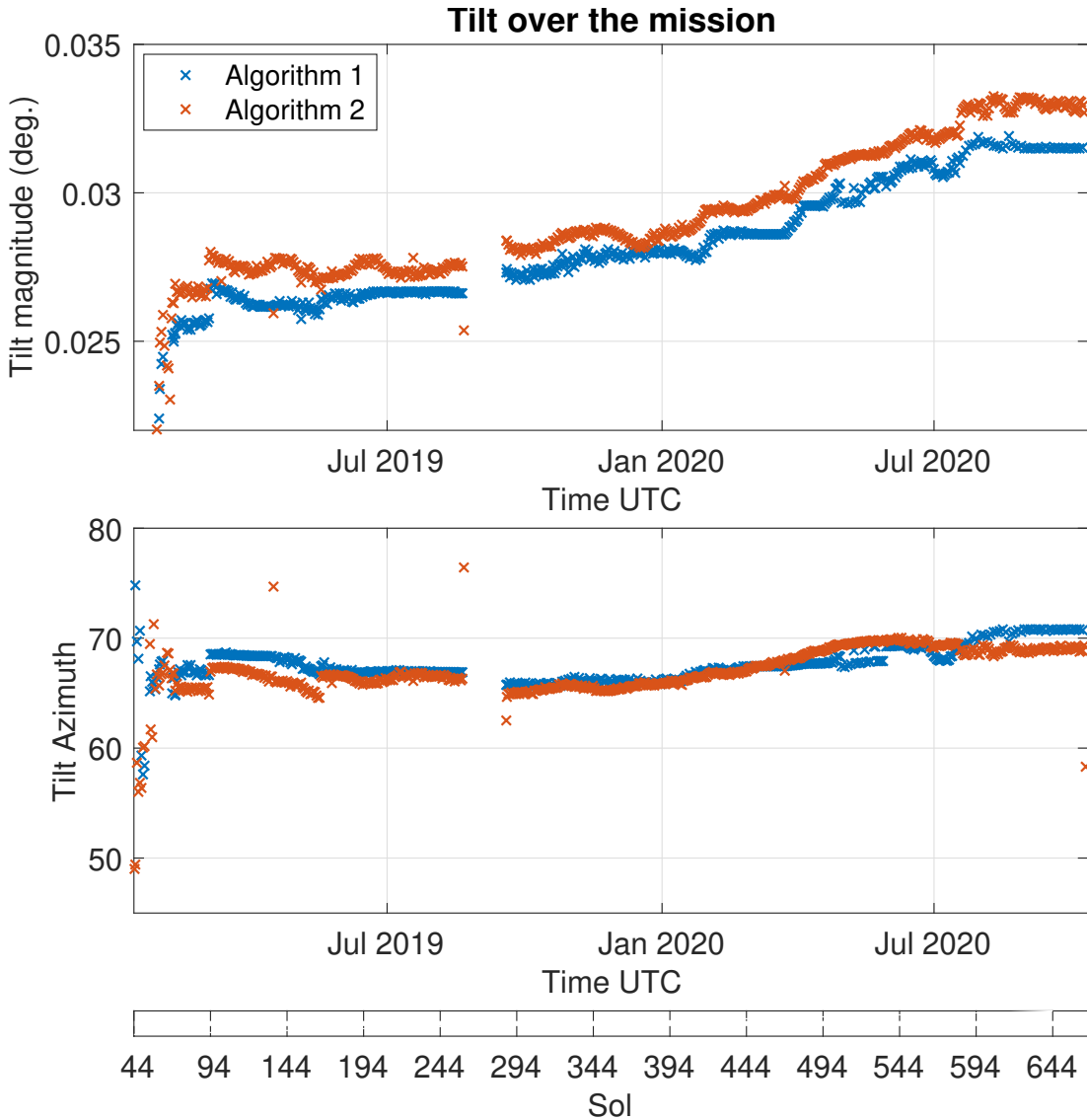


Figure 4. The evolution of tilt over the scientific monitoring phase of the mission from Sol 44 to 668. The tilt is the aggregate delta tilt referred to Sol 44, from where the SP has remained in the same feedback null. The blue data points correspond to the reference temperature based algorithm in Table 2 and the red data points to the thermal decorrelation based algorithm in Table 3.

299 both motion of the regolith and thermoelastic tilting of the SEIS assembly. On top of thermoelastic
 300 contributions from the SEIS assembly, the tilt estimates may also contain sensor drift. However,
 301 the aggregate tilt recorded since the beginning of the scientific monitoring phase is <0.007 degrees
 302 which corresponds to $4.5 \times 10^{-4} \text{ m/s}^2$. While we do not have a value for the sensor drift, it is
 303 above the sensor self-noise for this time period which is $\sim 5 \times 10^{-5} \text{ m/s}^2/\text{Hz}^{1/2}$ at $1 \times 10^{-8} \text{ Hz}$

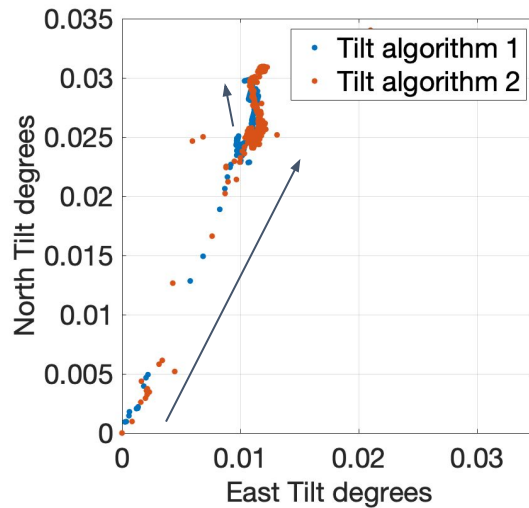


Figure 5. Tilt over the mission from Sol 44 to 668 in Cartesian coordinates, reported as the aggregate delta tilt. The blue data points correspond to the reference temperature based algorithm in Table 2 and the red data points to the thermal decorrelation based algorithm in Table 3. The direction of the tilting is indicated by the arrows. The largest arrow accounts for the tilt due to the pinning mass adjustments and initial settling. The tilt direction does fluctuate but generally progresses in the direction of the smaller arrow.

304 (Stott, 2018b).

305 There are several key features in the tilt estimates which do indicate a reasonable retrieval by
 306 the proposed algorithms. In the deployment phase, key activities resulted in an estimated tilt in the
 307 expected direction. For example, the response to the pinning mass adjustments shown in Figure
 308 4. The long term overall settling (in Figure 4 and 5) after the final deployment step is towards
 309 the direction of the tether which could have been undergoing relaxation. The heater switch on/off
 310 significantly modified the thermal environment which could have induced a thermoelastic response
 311 in the SEIS assembly. The retrieved tilt signals show a small overall response to this large transient
 312 modification.

313 This work uses the SP sensor to examine the tilt as it was available to analyse the deployment
314 phase of the mission, before the VBB could be used. Although the VBB has better low frequency
315 performance than the SP sensor, the SP is suitable to look at the general tilt over the whole mission.
316 The VBB requires occasional recentering and has active thermal compensation which is tuned ev-
317 ery few months and so the long period data are interrupted and thermal response altered (Lognonné
318 et al., 2019). This makes it difficult to establish a consistent tilt estimate over longer periods with
319 the VBB. These tilt estimates derived from the SP can therefore be useful to aid future efforts to
320 extract lower noise long period signals from the VBB. The VBB thermal noise and decorrelation
321 are shown in supplement 1 of Lognonné et al. (2020). Figure 2 shows the rtPSDs of the accelera-
322 tion derived from the VBB mass position output compared to the SP which indicates the level of
323 thermal noise in each over such periods. The VBB has a lower sensitivity to temperature but it is
324 still significant so that the thermal contribution must also be removed before a tilt can be extracted.

325 These algorithms are useful to examine the tilt in high noise environments, where the tempera-
326 ture is the dominant factor. Other factors such as pressure forcing (Ringler, 2020; Rodgers, 1968;
327 Sorrells, 1971) could be considered to improve the model for other applications. If another such
328 factor induced as significant a variation over a diurnal scale, the thermal model coefficients may
329 be erroneous, affecting the decorrelation. The reference temperature based algorithm in Table 2,
330 however, is not model based and so would not suffer from such an issue. As the tilt estimates from
331 each algorithm agree, this indicates that the temperature is the dominant diurnal contribution, as
332 expected in Mimoun et al. (2017).

333 The algorithms are also intended to be robust to issues with the data, for example, data gaps.
334 During deployment the sensor was turned off over night and there are several smaller gaps through-
335 out the mission. There are also several transient signals. As a result, an alternative, low-pass filter
336 based approach to remove the diurnal variation would not be straightforward to implement for
337 much of the data.

338 The main qualities of the tilt signal are the overall long period and the peak to peak variation. The
339 long term aggregated tilt observed in the InSight data is <0.007 degrees and the largest peak to peak
340 variation is the quasiperiodic three month variation which is limited to ~ 0.002 degrees. We can
341 make a brief comparison to Earth studies to illustrate the various features of ground tilt estimates.
342 Kämpel et al. (2001) found seasonal tilts in the north Rhine region have a peak to peak amplitude of

343 0.0046 degrees and the super-annual tilt of 0.0023 degrees per year. [Petrosino et al. \(2020\)](#) report
344 a comparable super-annual tilt at the Campi Flegrei caldera. These studies highlight that seasonal
345 effects on Earth are driven by tidal stresses and temperature. These factors are influenced strongly
346 by the water cycle which generates changes in the ground medium and particularly impacts near
347 surface deployments ([Wolin et al., 2015](#)) which would be absent at InSight ([Golombek et al.,](#)
348 [2017](#)). As we only have one Martian year of data, the seasonal effects cannot be fully separated
349 from super-annual tilt. Further data collection over several Martian years would help identify any
350 seasonal change or periodicity.

351 **The effect of lander-induced vibrations**

352 **Robotic arm motions as a source of lander motion**

353 *The signature of robotic arm motions in the seismic data*

354 In order to deploy the SEIS assembly on the surface of Mars, the InSight lander is equipped with
355 a robotic arm known as the Instrument Deployment Arm (IDA) ([Trebi-Ollennu et al., 2018](#)). This
356 robotic arm also has a camera which is used for deployment and scientific imaging ([Maki et al.,](#)
357 [2018](#)). During an arm motion, vibrations are also sensed in the SEIS data. The signature of such
358 motions ([Ceylan et al., 2021](#); [Stott et al., 2020](#)) in the spectrogram consist of:

- 359 1. broadband excitation above 4 Hz
- 360 2. excitation of narrowband modes
- 361 3. excitation of several chirp signatures

362 A set of spectrograms of seismic records of lander motions are shown in Figure 6 which exhibit
363 these characteristics. On the deck, the amplitude is larger but detail is often obscured by higher
364 environmental noise. The two most significant chirping signatures, a tone changing in frequency
365 over time, have frequencies of 4–9 Hz and 10–20 Hz. The arm motions are typically between a
366 few seconds to a few minutes long. The chirping depends on the arm motor positions. Timings
367 of arm activity are used by the marsquake service to confirm they do not overlap with a detected
368 marsquake ([Ceylan et al., 2021](#); [Clinton et al., 2021](#)).

369 *Using robotic arm motions to estimate the attenuation of lander motions*

370 These robotic arm motions provide a known source of vibrations and were observed by the SP
371 sensors both on and off the deck. We compare the recorded signatures on and off the deck and
372 estimate the ratio of the robot arm excited amplitudes. This is the absolute part of the transfer
373 function for a lander-induced vibration through the lander legs and regolith to SEIS, and thus
374 provide a calibration for lander-induced noise sources. The absolute part of this transfer function
375 is termed the transfer coefficient. This builds upon an experiment performed in Iceland by [Teanby
376 et al. \(2017\)](#), where a wind driven mass on a spring system was used to simulate forcing from the
377 WTS by wind. This work and a follow up study from [Myhill et al. \(2018\)](#) showed that in situ
378 estimations of this transfer coefficient are required to update noise injection models and therefore
379 to understand the site noise.

380 In order to achieve this, we must identify two similar arm motions performed on and off the
381 deck. A candidate motion is the “Tau sequence” which directs the camera towards the sky to
382 measure the optical depth of the atmosphere ([Banfield et al., 2020](#); [Maki et al., 2018](#)). Similar
383 motions were performed on Sol 14 on the deck and on Sol 71 on the ground covered by the WTS
384 in the final observational configuration ([Stott et al., 2020](#)). These are shown in Figure 7 along with
385 the arm joint positions. The arm elbow position correlates to the lower frequency chirp 4–9 Hz
386 across both of these motions, indicating it is the driver of this motion. This is confirmed as the arm
387 position can be used to predict the frequency of the chirp through multiplying the square of the
388 position by a constant factor of 0.6 and adding a bias of 3.8 Hz across motions, as shown in Figure
389 7 where the scaled elbow position is superimposed on the spectrogram chirp. This chirp is a good
390 candidate signal for which to measure the attenuation as it has a relatively high SNR both on and
391 off the deck and can be separated from lander mode excitation from other sources. Furthermore,
392 the chirp signature only occurs while the robot arm is moving (as seen by the match to the elbow
393 motor position) and is not excited by the ambient wind.

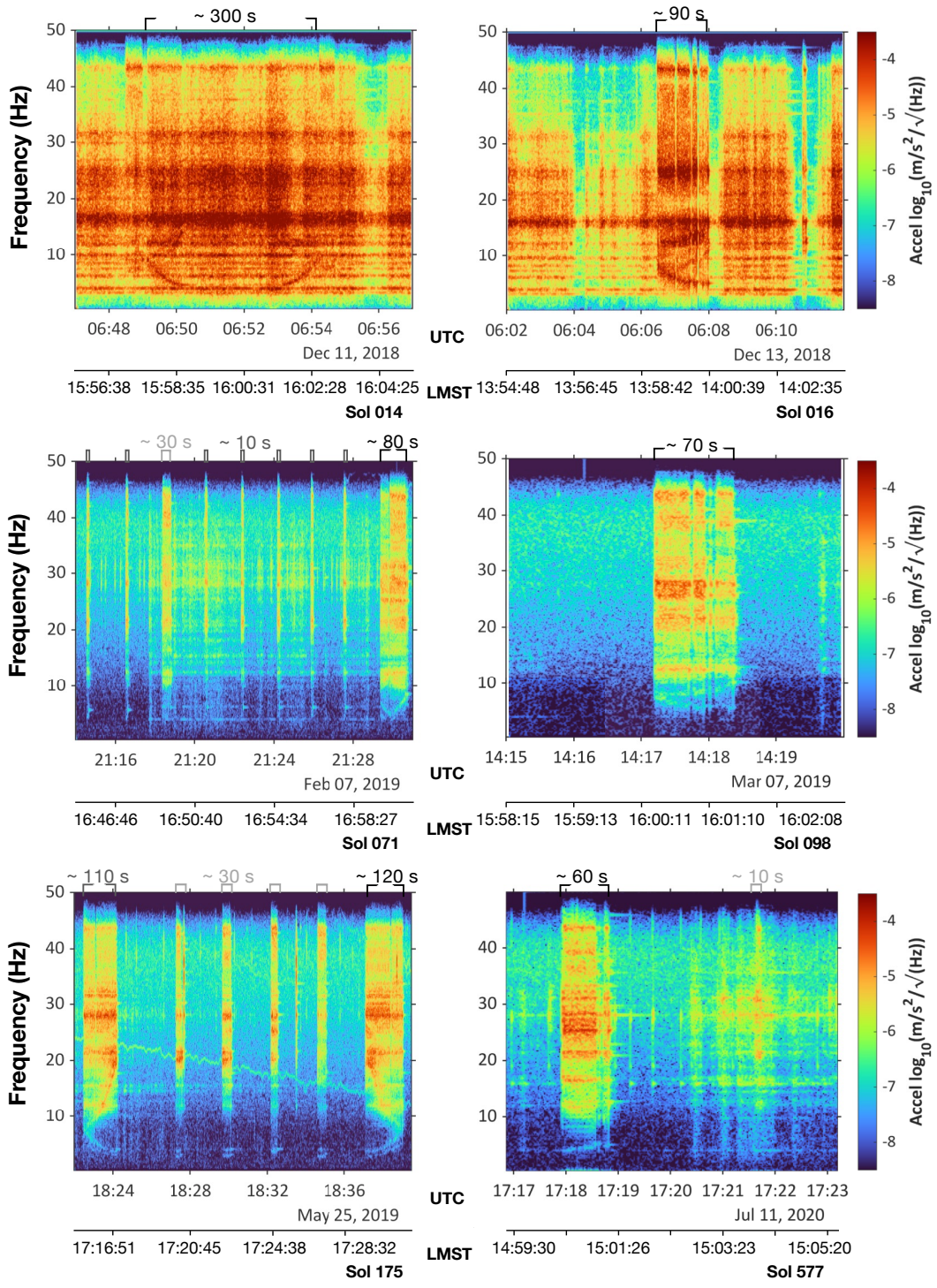


Figure 6. Spectrograms of 100 sps SP vertical (Z) data illustrating robot arm example signatures over the mission. For Sols 14 & 16 SEIS was uncovered on deck, while for Sols 71, 98, 175 & 577 SEIS was covered by the WTS on the ground. The duration of the robotic arm motions are indicated at the top.

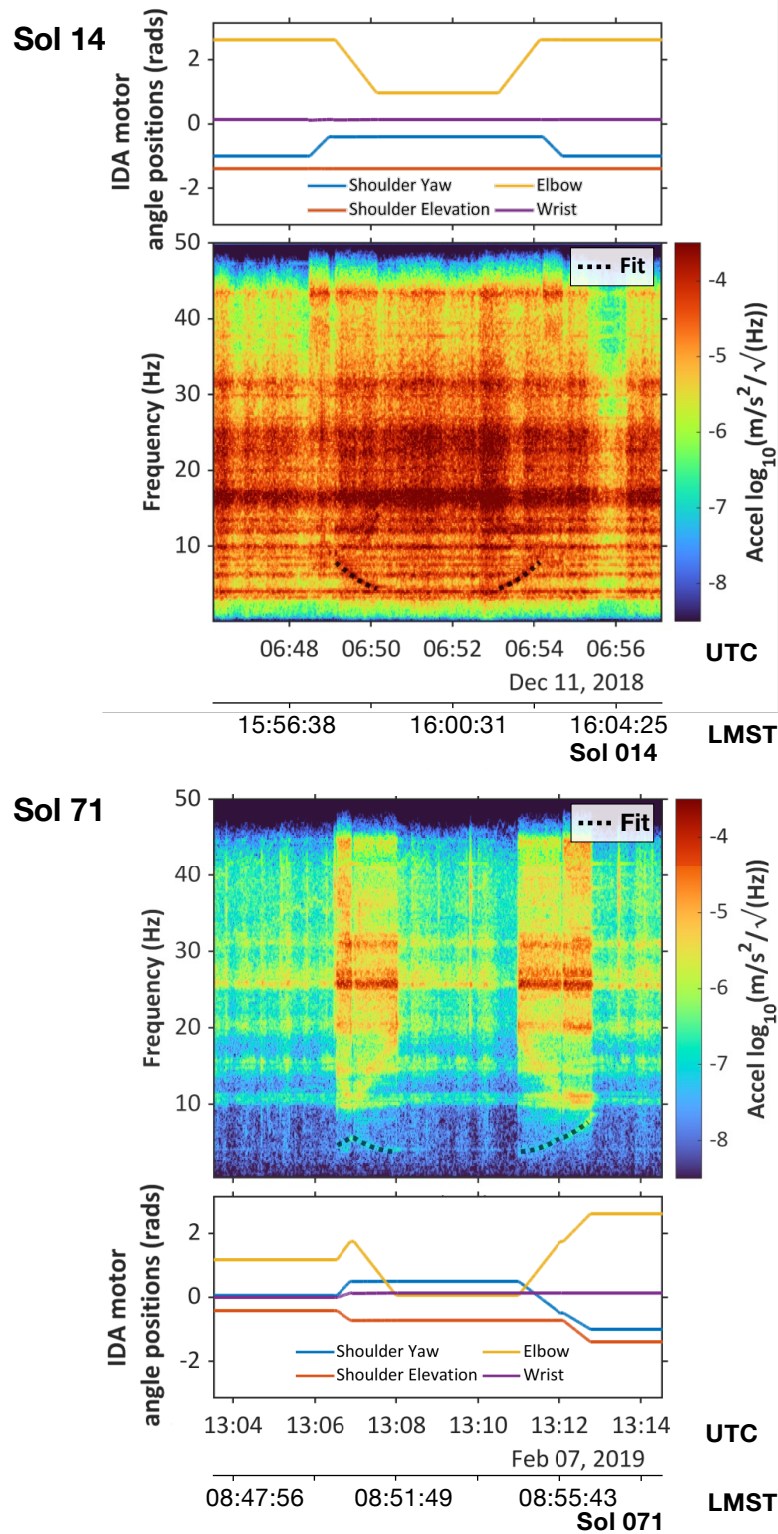


Figure 7. The spectrogram of the SP vertical (Z) acceleration and corresponding robot arm motor positions for the Tau estimation poses on Sol 14, SEIS on the deck, and Sol 71, SEIS on the ground, respectively. The overlaid fit, black dotted line, is the square of the elbow motor position scaled by 0.6 with a 3.8 Hz bias added.

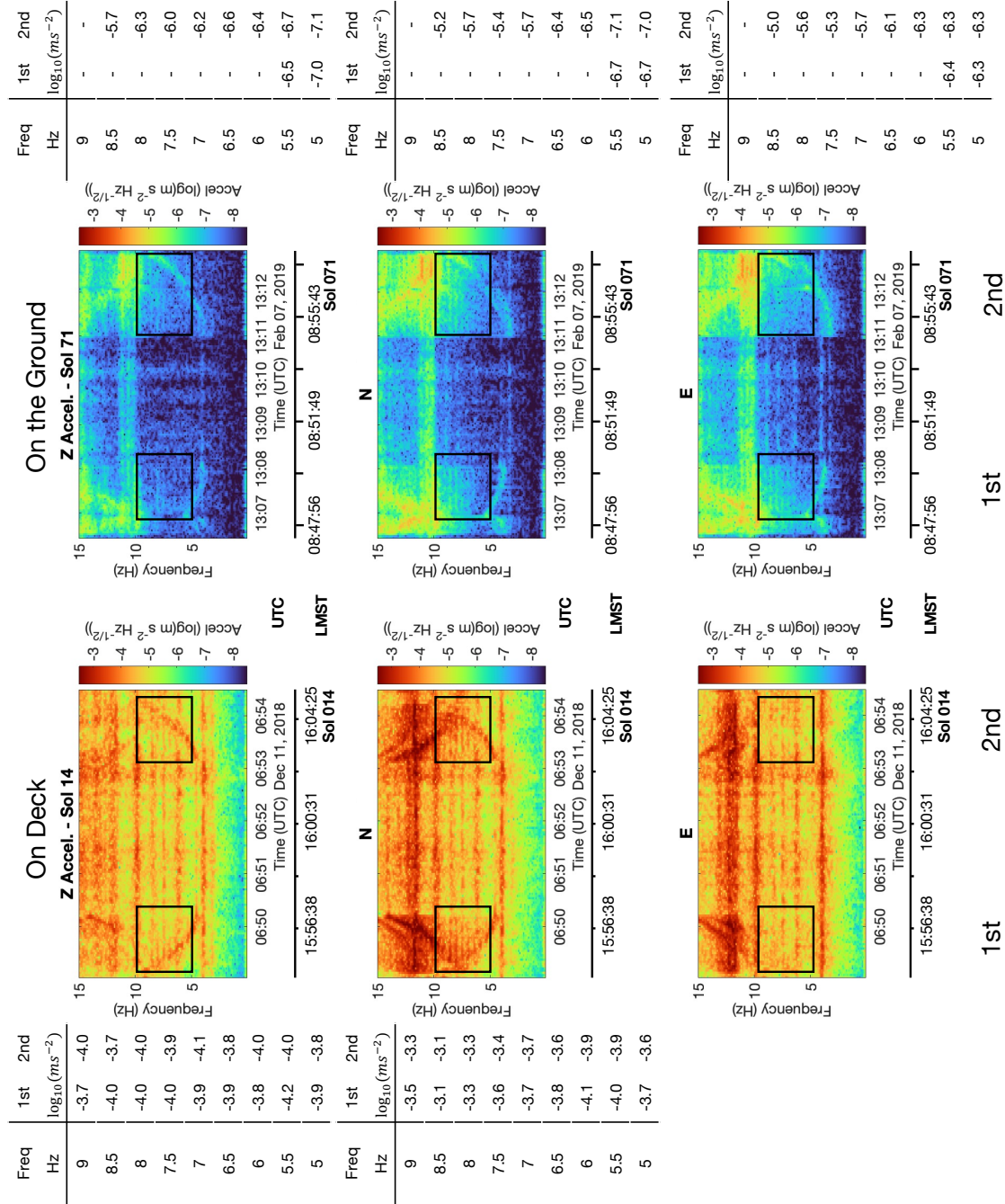


Figure 8. Determination of a transfer coefficient from robotic arm motions. The left of the middle two columns show the spectrogram of the two tau-pose robotic arm motions on and off the deck (Sol 14 and Sol 71) for the Z (vertical), N (north horizontal) and E (east horizontal) directions. Each has overlaid boxes highlighting the two chirp signatures per arm motion and the frequency range analysed. The outer columns are tables of the acceleration excited during each chirp motion for each frequency.

394 Figure 8 shows the spectrogram signatures for vertical (Z), north (N) and east (E) of the robotic
395 arm for the similar, tau activity, arm motions on Sols 14 on the deck and 71 on the ground. The
396 amplitude of the 4–9 Hz chirp signature is recorded in the tables either side of each component’s
397 spectrogram. This is done for both the first and second chirp in the motion. The excitations are
398 taken from above 5 Hz as there is a known wind excited ambient mode at 4 Hz.

399 The mean value (taken from Figure 8) of excitation on the deck for the vertical and north com-
400 ponents are $-3.9 \log_{10}(\text{m/s}^2)$ and $-3.6 \log_{10}(\text{m/s}^2)$ respectively while for on the ground they are
401 $-6.5 \log_{10}(\text{m/s}^2)$ and $-6.3 \log_{10}(\text{m/s}^2)$. The uncertainty in each of these estimates of the mean is
402 given by the confidence intervals, CI , as

$$CI = \frac{1.96\sigma}{(N)^{1/2}} \quad (3)$$

403 where 1.96 is a factor from the Student’s t-distribution representing 95% confidence, σ is the
404 standard deviation of the acceleration values and N is the number of values. A derivation of this
405 confidence interval can be found in [DeGroot et al. \(2012\)](#).

406 The transfer coefficients are then given as -52 ± 6 dB for the vertical and -54 ± 10 dB for the
407 north components, where the confidence interval is the sum of both the on and off deck confidence
408 intervals for the mean acceleration value. An estimate for the east component is not given as the
409 on deck signature of the robot arm motion does not have good enough SNR as only a portion can
410 be seen above the noise in Figure 8.

411 **Wind as a source of lander-induced noise**

412 The wind is a major source of noise on Mars ([Giardini et al., 2020](#); [Lognonné et al., 2020](#); [Murdoch
413 et al., 2017](#)). The sensitivity of the acceleration to wind has been examined through the notion of
414 comodulation ([Charalambous et al., 2020](#)). This approach dictates that the acceleration signal
415 power is correlated to the wind speed. To this end, the sensitivity of the SEIS-recorded signal to
416 wind is determined by comparison of the root mean square (RMS) envelope of the acceleration
417 signal to the wind speed. Calculating the RMS envelope for a specific bandwidth of acceleration
418 allows the sensitivity to be examined over frequency.

419 Figure 9 shows the acceleration sensitivity obtained on the deck on Sol 21, on the ground prior to
420 the WTS deployment on Sol 46 and in its final deployment covered by the WTS on Sol 268 for the

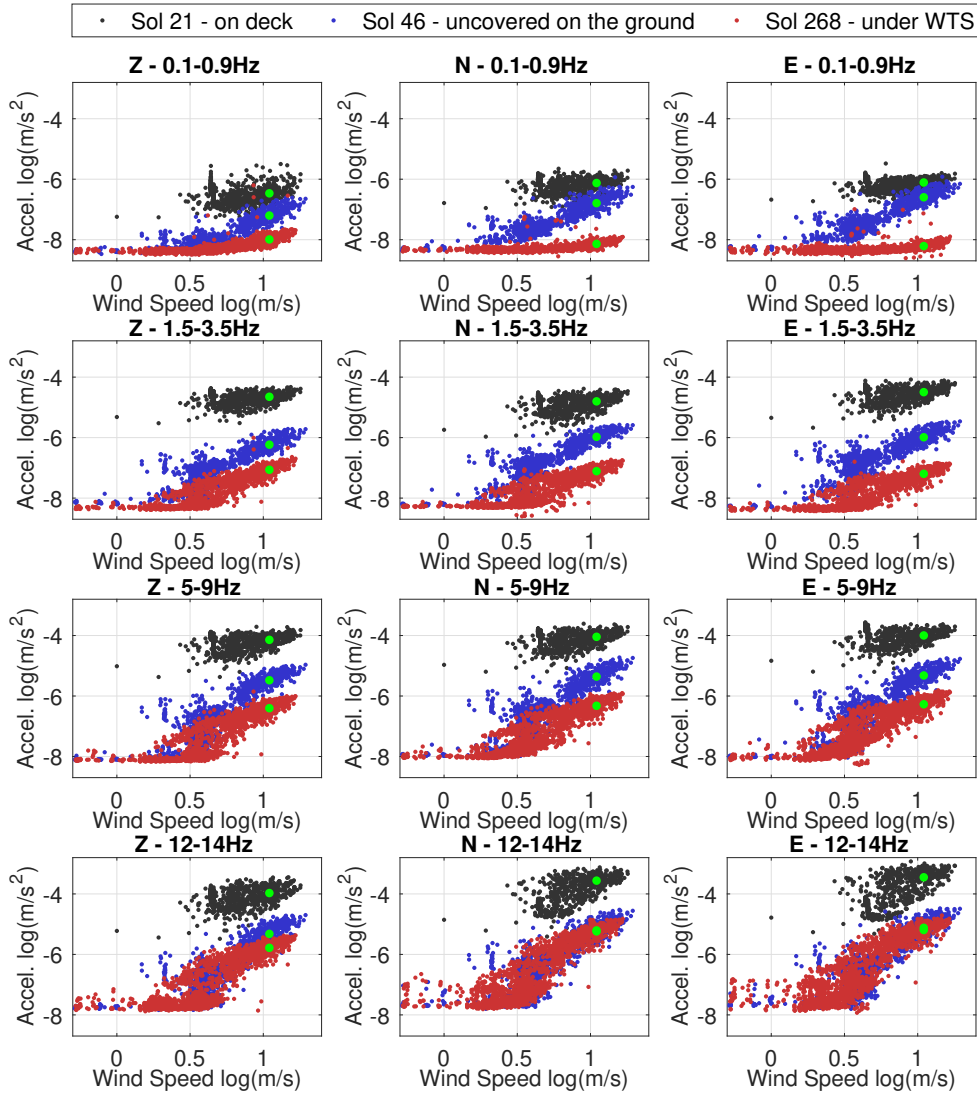


Figure 9. The wind speed versus RMS of the SP acceleration for Sol 21 on the deck (black), Sol 46 uncovered on the ground (blue) and Sol 268 under the WTS on the ground (red). This is shown for the Z (vertical), N (north horizontal) and E (east horizontal) components in the left to right columns. Each row demonstrates this sensitivity relationship for the acceleration in the bandwidths 0.1 – 0.9 Hz, 1.5 – 3.5 Hz, 5 – 9 Hz and 12 – 14 Hz from top to bottom. The green dots are the average acceleration at a wind speed of 11 m/s.

421 range of bandwidths: 0.1–0.9 Hz, 1.5–3.5 Hz, 5–9 Hz and 12–14 Hz. The 5–9 Hz bandwidth allows
422 a direct comparison to the robot arm analysis. The 0.1–0.9 Hz bandwidth covers the majority of low

423 frequency marsquakes whereas the 1.5–3.5 Hz contains the 2.4 Hz resonance which is excited by
 424 higher frequency marsquakes (Clinton et al., 2021; Giardini et al., 2020). The 12–14 Hz bandwidth
 425 then gives a picture of higher frequencies. These bands also avoid the lander modes at 4 Hz and
 426 10 Hz and tick noise at 1 Hz (Ceylan et al., 2021).

427 The green dots on each curve in Figure 9 denote the mean RMS acceleration for a wind speed
 428 of 11 m/s, using the interval 10.5–11.5 m/s. This is done because the sensitivity to wind also
 429 depends on the current conditions, such as wind density and Reynolds number (Charalambous
 430 et al., 2020). Such wind speeds require similar strong turbulent conditions and so the acceleration
 431 values are comparable. These comparison of these values yields the signal amplitude attenuation
 432 between each deployment stage and are given in Table 4. These values then summarise the affect
 433 of placing SEIS on the ground and the emplacement of the WTS. Placing SEIS on the ground
 434 yields an attenuation of between -36 ± 2 dB and -24 ± 2 dB for frequencies above 1 Hz and between
 435 -14 ± 2 dB and 10 ± 2 dB below. For frequencies below 10 Hz, the WTS provides an attenuation of
 436 between -18 ± 2 dB and -16 ± 2 dB for the vertical component and -32 ± 2 dB and -20 ± 2 dB for the
 437 horizontal component. Above 10 Hz only the vertical component observes attenuation of -10 ± 2
 438 dB with none on the horizontals. This suggests that the direct influence of the wind on SEIS was
 439 much less important at these higher frequencies as there is little change before and after the direct
 440 forcing pathway on SEIS is removed by the WTS.

Bandwidth	Deck to ground, Sol 21 to 46 (dB)			WTS, Sol 46 to 268 (dB)		
	Z	N	E	Z	N	E
0.1–0.9 Hz	-14 ± 2	-14 ± 2	-10 ± 2	-16 ± 2	-26 ± 2	-32 ± 2
1.5–3.5 Hz	-32 ± 2	-24 ± 2	-30 ± 2	-16 ± 2	-22 ± 2	-24 ± 2
5–9 Hz	-26 ± 2	-26 ± 2	-26 ± 2	-18 ± 2	-20 ± 2	-20 ± 2
12–14 Hz	-26 ± 2	-32 ± 2	-34 ± 2	-10 ± 2	0 ± 2	-2 ± 2

Table 4: Summary of wind induced signal amplitude attenuation.

441 The full attenuation values between Sol 21 on the deck on Sol 268 are given in Table 5. This
 442 is the combination of the attenuation values provided by placing SEIS on the ground and then
 443 the WTS on top, that is, the total level of amplitude attenuation provided by the full deployment.

444 These total attenuation coefficients each have similar values for vertical and horizontal directions
 445 for the 1.5–3.5 Hz and 5–9 Hz bandwidths, aside from the east component in the 1.5–3.5 Hz band.
 446 At higher frequencies, in the 12–14 Hz range, the total attenuation is lower than the 1.5–9 Hz
 447 band indicating there is less apparent attenuation. For lower frequencies, in the 0.1–0.9 Hz band,
 448 the attenuation coefficients are also slightly lower than the 1.5–9 Hz range. In the 0.1–0.9 Hz band
 449 there is also a notable difference between the vertical and horizontal estimates, unlike all the values
 450 above 1 Hz, which are broadly equivalent in all axes aside from the east component in the 1.5–
 451 3.5 Hz bandwidth. If it is assumed that the wind generated seismic noise observed while covered
 452 on the ground is due to wind-induced lander vibrations, then these total attenuation coefficients
 453 represent transfer coefficient estimates. The validity of this assumption is discussed in the sequel.

454 Notice that on the deck the east component has a marginally higher sensitivity to wind than
 455 the north component in the 1.5–3.5 Hz bandwidth. The average RMS acceleration at 11 m/s wind
 456 speed is $3.2 \times 10^{-5} \text{ m/s}^2$ for the east component but $1.6 \times 10^{-5} \text{ m/s}^2$ for the north. This bears out
 457 in the east component total attenuation coefficient of $-54 \pm 2 \text{ dB}$ which is lower than the north com-
 458 ponent’s $-46 \pm 2 \text{ dB}$ at 1.5–3.5 Hz. This feature may be caused by the lander geometry. Consider
 459 that the lander is aligned with the solar panels along the east/west axis but is due north of SEIS
 460 when it is on the ground. However, the distance between the lander and SEIS is not large compared
 461 to the distance between lander footpads. It should also be noted that there is a heterogeneity in at
 462 the InSight landing site (Garcia et al., 2020; Murdoch et al., 2020), whereby SEIS’s location within
 463 the Homestead Hollow crater results in an increased compliance in the west direction.

Bandwidth	Robotic arm motions (dB)			Wind sensitivity changes (dB)		
	Z	N	E	Z	N	E
0.1–0.9 Hz				-30 ± 2	-40 ± 2	-42 ± 2
1.5–3.5 Hz				-48 ± 2	-46 ± 2	-54 ± 2
5–9 Hz	-52 ± 6	-54 ± 10		-46 ± 2	-46 ± 2	-46 ± 2
12–14 Hz				-36 ± 2	-34 ± 2	-34 ± 2

Table 5: Summary of transfer coefficient (signal amplitude attenuation from the lander deck to the ground) estimates.

464 **Discussion and comparison of the observed transfer coefficients**

465 The transfer/attenuation coefficients estimated from the robotic arm motions and the wind sensi-
466 tivities are summarised in Table 5. These values are, in fact, summary statistics of the amplitude
467 attenuation component of the transfer function between the lander deck and SEIS on the ground.
468 To that end, it averages more complex aspects of the noise injection. For example, resonances, the
469 response of the lander and the unloading of the deck (placement of instruments on the floor) may
470 affect the comparison. Nevertheless, these values can be used to study the ambient noise injections
471 at InSight. Here we will compare the values, assess their suitability as transfer coefficients and
472 show what conclusions can be drawn about local noise sources of the InSight seismic station.

473 First consider the transfer coefficients estimated from the robotic arm motions. While the robot
474 arm provides a useful known source of vibrations, it is not as suitable a source as the purpose built
475 mechanical system used in the terrestrial studies of [Teanby et al. \(2017\)](#) and [Myhill et al. \(2018\)](#).
476 For example, the SNR for the robotic arm signature in the east component is too low to accurately
477 obtain a transfer coefficient estimate. It is also assumed that the robotic arm motions produce the
478 same vibration by the lander each time. This is reasonable as the compared arm motions are very
479 similar. Furthermore, it has been demonstrated that the compared chirp signals are only generated
480 by the arm elbow position motor and not from ambient excitation, hence, the driving force is from
481 the same mechanism. The confidence intervals do span a relatively wide range (± 6 dB and \pm
482 10dB) and so represent these limitations. This means that these transfer coefficients should be
483 taken as a broad indication of the attenuation of lander generated signals.

484 Consider that the attenuation coefficients from the comparison of wind sensitivities on the deck
485 and covered on the ground are indeed transfer coefficient estimates. In this case, the confidence
486 intervals (all within ± 2 dB) suggest a relatively high level of statistical reliability compared to
487 those from the robotic arm motion. This is because there are a larger amount of data points to
488 compare. For these estimates to be interpreted as transfer coefficients, though, it must be assumed
489 that the signal observed on the ground is due to wind-induced lander vibrations. Alternative path-
490 ways for wind-induced signals include wind-forcing on the WTS, HP3, nearby rocks or the ground
491 itself. Should any of these dominate, then the combined attenuation value from the deck to the
492 ground would not be appropriate to interpret as a transfer coefficient. Note that for these other
493 forcing pathways, the wind speed obtained from TWINS is not the wind speed creating the force

494 as this, wind shear, scales with height (Murdoch et al., 2017). However, pre-mission modelling by
495 Murdoch et al. (2017) and Mimoun et al. (2017) does indicate that wind-induced lander vibrations
496 would be the dominant factor in these bandwidths. Furthermore, the attenuation given by the WTS
497 deployment shown in Table 4 shows that it reduced the wind sensitivity for frequencies below
498 9 Hz, removing the impact of direct forcing. The comparison of signals was also performed at a
499 high wind speed of 11 m/s to ensure the atmospheric conditions (and so forcing) are comparable
500 between the data sets.

501 Consider also that in the 5–9 Hz band the attenuation coefficient estimated from the wind sensi-
502 tivity is -46 ± 2 dB for all components. This is within the range of the estimates from the robotic
503 arm motions. Furthermore, the vertical and north component attenuation coefficient estimates in
504 the 1.5–3.5 Hz bandwidth are similar (-48 ± 2 dB and -46 ± 2 dB) to those in the 5–9 Hz bandwidth.
505 The east component has a lower value (-54 ± 2 dB) than the 5–9 Hz bandwidth which is explained
506 by the east versus north wind sensitivity on the deck. All these values generally match the transfer
507 coefficients estimated from the robotic arm motions. This further indicates that the combined at-
508 tenuation coefficients could be interpreted as transfer coefficients as they generally match a value
509 for a known signal from the lander. This, in turn, suggests that wind-induced lander vibrations are
510 the dominant source of ambient seismic noise at the site in the 1.5–9 Hz bandwidth. Outside of
511 the 1.5–9 Hz bandwidth the transfer coefficient estimates have different values. It is still possible,
512 however, that the lander is responsible for wind driven background noise as the attenuation may
513 change as a function of frequency.

514 **A comparison between the observations and simple elastic models**

515 The estimated transfer coefficients summarise the attenuation of the signal amplitude between the
516 lander deck and SEIS's location on the ground. In this section we compare the InSight data to
517 simple models of the regolith in order to highlight the various factors at play.

518 A key part of this attenuation is a geometric factor from the regolith, which is governed by its
519 elastic properties. To a first approximation the regolith can be modelled as a homogeneous elastic
520 half space. In this case the regolith is parameterised through an effective Young's modulus, Pois-
521 son's ratio and density throughout the medium, whereby its response to forcing/wave propagation

522 is provided by the elastic equations (Morgan et al., 2018). A value for such a model acts to average
523 the parameters across the volume that the estimation method is sensitive to. At InSight such esti-
524 mates have been obtained using pressure forcing (sensitive to tens of metres) through compliance
525 by Garcia et al. (2020) and dust devils by Murdoch et al. (2020), which yielded a Young’s modulus
526 of 239 ± 140 MPa. The LVL resonances, on the other hand, gave a Young’s modulus of 47 ± 10
527 MPa (Lognonné et al., 2020). This approach is sensitive to the top few centimetres and the mea-
528 surement corresponds to the duricrust. The ground is equivalently parameterised by p- and s- wave
529 velocities. For example, Lognonné et al. (2020) use the Young’s modulus estimate from the LVL
530 resonances and assume a regolith density, ρ_r , of 1400 kg/m^3 to obtain an apparent p-wave velocity
531 of 137 ± 15 m/s. The apparent p-wave velocity at a 1 metre scale was also directly measured from
532 HP3 hammer strokes to be 118 ± 34 m/s. The difference/similarities in these results, which are
533 sensitive to different scales, indicates that these properties do vary with depth. The local subsur-
534 face at InSight has been constrained using an inversion based on both pressure forcing and the HP3
535 hammering data which established parameter profiles down to 20 m (Kenda et al., 2020; Lognonné
536 et al., 2020). This analysis considered a range of models including multiple layers, examining the
537 effects of the regolith and bedrock.

538 **An estimate of the effective Young’s modulus from wind forcing on the lander**

539 Consider the homogeneous elastic half space model for the regolith. We now estimate an effective
540 Young’s modulus for such a model by considering the ground response from wind forcing on the
541 lander. From Teanby et al. (2017) the equation of motion for the lander and regolith response is
542 given as

$$F = m\ddot{x} + \frac{6r_f E}{1 - \nu^2} x \quad (4)$$

543 where F is the vertical force applied to the lander, $m\ddot{x}$ is the inertial response of the lander (m
544 is the mass of the lander and \ddot{x} is the vertical acceleration of the lander) and $\frac{6r_f E}{1 - \nu^2} x$ is the is the
545 approximate force from displacing the three lander feet by x , where r_f is the lander footpad radius,
546 ν the Poisson’s ratio and E the Young’s modulus. A value of the force F applied to the lander
547 can be obtained from the wind sensitivity. For a given wind speed a lift F_L and drag force F_D is
548 applied to the lander as

$$F_L = \frac{1}{2} \rho_w C_L A_L u^2$$

$$F_D = \frac{1}{2}\rho_w C_D A_D u^2$$

549 where ρ_w is the wind density, C_L , C_D are the lift and drag coefficients, A_L , A_D is the surface
550 area the wind is applied to and u is the wind speed. If we assume that the vertical acceleration, \ddot{x} ,
551 observed on the deck in Figure 9 is due to the lift force, F_L , and that the lander acts as a rigid body
552 (so that the acceleration on the deck is that at the feet) then we can obtain an estimate of E from
553 equation (4) where $F = F_L$. We take the confidence interval range around the average vertical
554 acceleration in the 0.1–0.9 Hz band at a wind speed of 11 m/s as in this band the lander is most
555 likely to act as a rigid body. Using the required parameters, ρ_w , C_L , A_L , r_f and ν in Table 6 from
556 [Murdoch et al. \(2017\)](#) we obtain the value $E = 62\text{--}81$ MPa. This estimate will have additional
557 uncertainty based on the whether the prior assumptions/parameter values are appropriate. This
558 value, however, is of a similar order to that obtained for a duricrust on the surface layer [Lognonné](#)
559 [et al. \(2020\)](#) of 47 ± 10 MPa and is lower than the estimates in [Murdoch et al. \(2020\)](#) of $239 \pm$
560 140 MPa. Our approach is sensitive to a shallower depth than that in [Murdoch et al. \(2020\)](#) as we
561 examine local displacements. [Kenda et al. \(2020\)](#) find a similar Young’s modulus at the surface,
562 increasing with depth in a two-layer model.

Parameter	Value
g	3.72 m/s ²
r_f	0.145 m
C_L	0.1
A_L	7.53 m ²
ρ_w	1.55×10^{-2} kg/m ³
ρ_r in FEA	1300 kg/m ³
m	365 kg
ν	0.25
\ddot{x} for 0.1–0.9 Hz	3.0×10^{-7} m/s ² – 3.9×10^{-7} m/s ²

Table 6: A table of parameter values used for Young’s modulus estimation.

563 **A comparison between the observations and simple elastic models**

564 In this section, we compare the estimated transfer coefficients to a transfer coefficient derived from
565 a simple elastic model of the regolith. The aim is to investigate the components which affect
566 these transfer coefficients and provide context in terms of the regolith elastic behaviour. The pre-
567 landing study of [Teanyby et al. \(2017\)](#) examined analogue experiments in Iceland prior to launch
568 to estimate the attenuation between the WTS and SEIS on the LVL. The WTS was replaced with
569 a wind driven mass on a spring system (to provide a known source with good SNR) on a tripod
570 surrounding an LVL model tripod both with disc feet to emulate the coupling. A follow-up study
571 by [Myhill et al. \(2018\)](#) extended the analysis to a frequency band of 2–40 Hz, and conducted
572 further experiments to study the attenuation at source-receiver distances up to 4 m. An analytical
573 formula for the ratio of the vertical displacement at the LVL feet to the displacement of the WTS
574 model feet, i.e. the vertical transfer coefficient, was derived for the case where the ground is
575 a homogeneous elastic half space. [Stott et al. \(2020\)](#) implemented this formula for the case of
576 the lander footpads to each SEIS foot yielding transfer coefficients of the order -19.2 dB. This
577 value gives a much lower attenuation than any of our estimates in Table 5. A similar discrepancy
578 between the experimental values and the analytical formula was also observed in the analogue
579 experiments. [Myhill et al. \(2018\)](#) showed that the signal amplitude in the Icelandic analogue
580 experiments decayed with distance r roughly as $A \sim r^{-n}$, with $n \sim 1.5\text{--}2.0$, rather than $n \sim 1$,
581 as predicted for a homogeneous isotropic half-space. There are several possible causes of this
582 more rapid attenuation. Regolith or lander anelasticity, depth-dependent elastic properties, or local
583 increase in regolith Young's modulus beneath the lander/SEIS feet could all decrease effective
584 transfer coefficients. [Myhill et al. \(2018\)](#) investigated one of these possibilities by implementing a
585 finite element model (FEM) where the regolith is modelled as an elastic half space with a Poisson's
586 ratio of 0.25 and a depth dependent Young's modulus. These models consider the static solution,
587 neglecting inertial forces, and so are frequency independent. This is discussed in [Myhill et al.](#)
588 [\(2018\)](#) who showed that it is appropriate for near-field displacements at these frequencies, whereas
589 above 10 Hz inertial forces would need to be considered. Here we implement the same FEM
590 adapted for the lander feet to SEIS interaction. To simulate the vertical and horizontal coupling
591 between the lander footpads and the ground surface, we controlled the displacement of the surface
592 along one Cartesian axis (i.e. motion along the E-, N- or Z-axis) underneath each footpad. On

593 other axes, and away from the footpads, the surface of the domain was allowed to deform freely.
594 The Young's modulus profile is given by

$$E = E_0(b + z/r_f)^k \quad (5)$$

595 where the depth z is normalised by the lander footpad radius r_f , k determines the rate at which
596 the Young's modulus increases with depth, E_0 is a reference Young's modulus and $b = \frac{\sigma_0}{\rho_r g r_f}$ is a
597 dimensionless parameter dependent on the confining stress σ_0 , the density ρ_r , the gravity g and the
598 lander foot radius r_f . This formulation incorporates the depth variation of the Young's modulus
599 observed in unconsolidated clays and sands due to the depth dependent increase in confinement
600 pressure (Santamarina et al., 2001) and non-zero surface confining stress (Delage et al., 2017). The
601 model is designed for small displacements of otherwise unstressed regolith, and so does not include
602 the stresses on the regolith deriving from the weights of the lander or SEIS. The displacement ratio
603 map around the lander for $k = 0.9$ and $b = 10$ or 1 is shown in Figure 10 for motions in each of
604 the three axes.

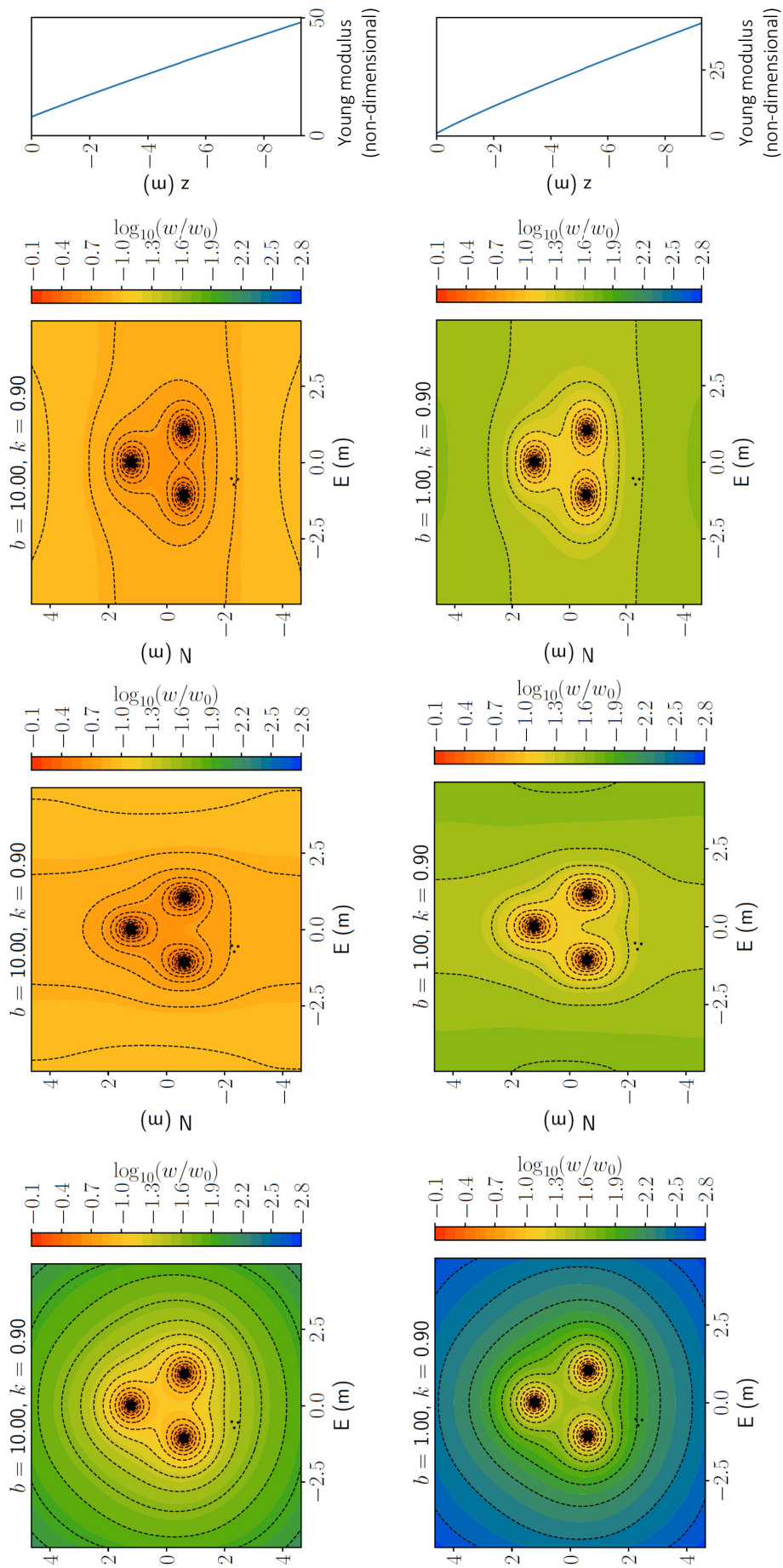


Figure 10. The relative displacement, w , observed around InSight for a given displacement of the lander feet, w_0 , predicted by the elastic model (5). From left to right: vertical displacement, north-south displacement, and east-west displacement. The large black circles correspond to the positions of the lander feet. The small black circles correspond to the positions of the SEIS feet.

605 Figure 11 shows the relative vertical, north-south and east/west displacement ratios (transfer
 606 coefficients) predicted by the FEM at each SEIS foot for vertical, north/south and east/west motions
 607 respectively over a range of k and b . The transfer coefficient of ~ -49 dB estimated for the 1.5–9 Hz
 608 bandwidth requires a high value of $k = \sim 0.9$ and a low value of $b = \sim 0.01$ to explain the observed
 609 attenuation as from the propagation in the regolith. The value of k in the model (5) is linked to
 610 the amplitude decay with distance $A \sim r^{-n}$ by $n = 1 + k$. The value of $k = 0.9$ gives a decay
 611 proportional to $n = -1.9$, which is close to that measured at Fellabær by [Myhill et al. \(2018\)](#).
 612 The value of b is related to the effective confining stress over the surface between the lander and
 613 SEIS and is homogeneous in this model. The confining stress is given as $\sigma_0 = F/A$ where F is a
 614 force on the surface over an area, A . Consider that the lander will have a significant effect nearby.
 615 If it is assumed that the weight of the lander dominates then the force is due to the weight of the
 616 lander, $F = mg$ spread over the three lander footpads as $A = 3\pi r_f^2$. Using the values in Table
 617 6 gives $\sigma_0 = 6840$ Pa which leads to an expected value of $b = 9.77$ using the regolith density
 618 of $\rho_r = 1300$ kg/m³ from [Delage et al. \(2017\)](#). This value is much greater than the $b = \sim 0.01$
 619 required to describe the 1.5–9 Hz bandwidth. This can be interpreted as the effect of the lander on
 620 the confining stress being localised to the area underneath the lander feet, or to a strong variation in
 621 density. Another potentially significant factor is that the lander may not act as a rigid body in this
 622 frequency range. As a result, the acceleration obtained on the deck does not correspond to that at
 623 the feet, that is, the lander legs attenuate some of the deformation experienced by the lander deck.
 624 Consider now the transfer coefficient estimates in the 0.1–0.9 Hz bandwidth estimated from
 625 the wind sensitivity changes in Figure 9. The vertical transfer coefficient is -30 ± 2 dB shows
 626 less attenuation than the horizontals which are -40 ± 2 dB and -42 ± 2 dB. In this frequency band
 627 the lander may act more as a rigid body, as indicated by the reduced attenuation. The vertical
 628 component could be matched by a set of parameters $k = 0.7$ – 0.9 and $b = 1$ – 5 , through consideration
 629 of Figure 11. However, both vertical and horizontal transfer coefficients cannot be produced using
 630 the model (5) by any value of k and b as the horizontal attenuation is less than or similar to the
 631 vertical.

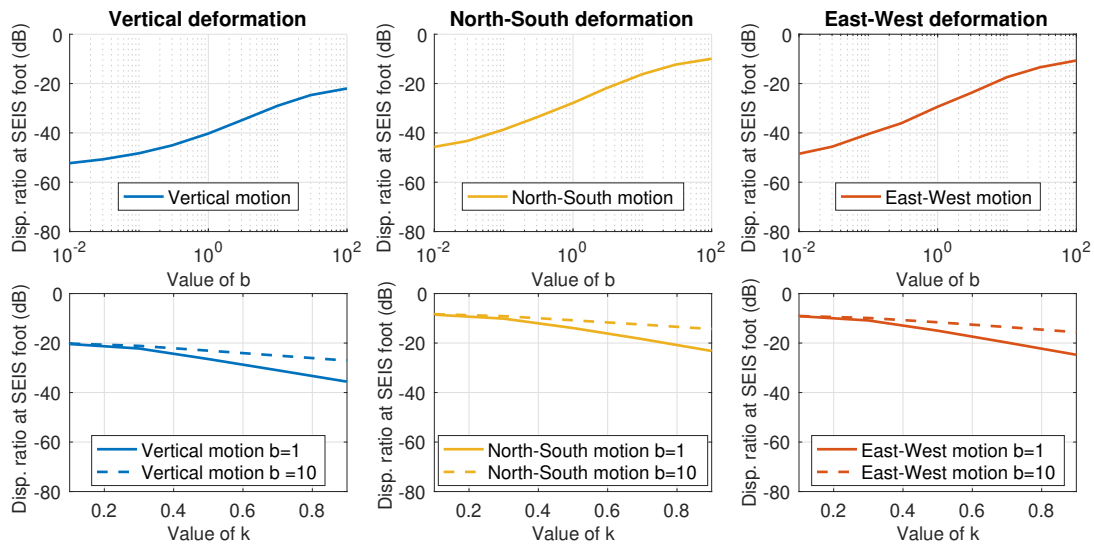


Figure 11. Average displacement of the three SEIS feet as a ratio of the lander feet displacement (the transfer coefficient) from the FEA where the Young's modulus is given by $E = E_0(b + z/r_f)^k$ (5) over different k and b parameters where k corresponds to the depth variation and b is linked to the surface confining stress. Each column shows the displacement amplitude attenuation for vertical, north-south and east-west deformations from left to right. The attenuation for the vertical deformation is the corresponding vertical motion of the lander and the horizontal motions are the respective in-plane motion to the deformation. The top row gives the transfer coefficient for a fixed $k = 0.9$ over a range of values of b and the bottom row shows the transfer coefficient for the fixed values of $b = 1$ and $b = 10$ over a range of k .

632 Conclusion

633 Two algorithms were proposed to derive the tilt from the SP mass position data. The first of these
 634 took the mass position value of both the horizontal SP sensors when SP2 reached a reference
 635 temperature. The second algorithm removed the fitted thermal response model proposed in [Stott
 636 et al. \(2018a\)](#) for each sensor. These algorithms calculate the tilt on a Sol to Sol basis and so provide
 637 an estimate of the relative, delta tilt. This makes them reasonably robust to data gaps/outlying data.

638 The two tilt extraction algorithms were applied to the deployment data, from when SEIS was
 639 on the deck to when it was fully covered by the WTS on the ground. The tilt estimates over
 640 this period show the overall settling of the sensor after site modifications such as levelling and

641 the effect of actions including the TSB release, LSA release, pinning mass adjustments and WTS
642 deployment itself. The tilt estimation algorithms were then applied over 667 Sols (one Martian
643 year) of data throughout the science monitoring phase. This showed that the SEIS assembly has
644 remained extremely stable to a change in tilt of <0.007 degrees throughout.

645 The SP data from deployment is also useful to examine the local noise sources at InSight. To do
646 so, we compared the acceleration observed by the SP seismometer on and off the deck. Vibrations
647 from robotic arm motions are found to be attenuated by -52 ± 6 dB and -54 ± 10 dB for the vertical
648 and north components respectively. These values are estimates of the amplitude attenuation of
649 lander generated signals to SEIS, that is, the transfer coefficient.

650 The wind induced vibrations are decomposed for attenuation between moving SEIS to the
651 ground and then by the WTS. For frequencies above 1 Hz, moving SEIS to the ground from the
652 deck reduces wind induced signals by ~ -28 dB. Below 1 Hz the attenuation is slightly lower at
653 ~ -12 dB. For frequencies below 10 Hz, the emplacement of the WTS attenuates wind induced vi-
654 brations by ~ -16 dB for vertical and ~ -25 dB for horizontal components. Above 10 Hz, the WTS
655 only has an effect on the vertical component with an attenuation of -10 ± 2 dB. This means that
656 the horizontal components may not have been affected by direct wind forcing on SEIS at these
657 frequencies before the WTS was deployed. Wind induced vibrations under the WTS on the ground
658 are ~ -49 dB lower than on the deck in the 1.5–3.5 Hz and 5–9 Hz bandwidths. These total attenu-
659 ation values are of a similar order to the robot arm estimates, a known source from the lander. This
660 suggests they are also estimates of the transfer coefficient and that wind induced lander vibrations
661 are the dominant source of ambient noise, as expected in the pre-landing studies of [Mimoun et al.](#)
662 [\(2017\)](#); [Murdoch et al. \(2017\)](#). Below 1 Hz, the full attenuation is by ~ -30 dB and ~ -41 dB for
663 the vertical and horizontal components respectively. Above 10 Hz, the full attenuation is by ~ -35
664 dB for each component. The background wind noise could also be generated by the lander in these
665 bandwidths as frequency dependent factors may play a part.

666 The transfer coefficients provide a broad indication of the attenuation between the lander deck
667 and SEIS on the ground. An FEM was implemented to explore the contribution of geometric
668 attenuation in the regolith. To explain the observed attenuation of ~ -49 dB, a fast Young's modulus
669 increase with depth is required, of a similar value to those seen in terrestrial studies. However, the
670 parameter describing the surface confining stress is required to be a factor of ~ 100 lower than

671 that for a calculation for directly under the lander feet. The FEM also cannot explain the change
672 in attenuation with frequency observed in the wind induced signal attenuation values, should they
673 be taken as transfer coefficient estimates. Several other factors not considered by the FEM may
674 contribute to the transfer coefficient estimates. These include: attenuation from the lander legs,
675 local ground discontinuities, the inertial response of the regolith, elastic anisotropy and anelasticity.

676 Considering the regolith as a homogeneous elastic half space, the effective Young's modulus
677 is estimated to be $E = 62\text{--}81$ MPa based on the vertical acceleration below 1 Hz, the equation
678 of motion for the lander and the candidate wind forcing. This value is close to the duricrust
679 estimate of 47 ± 10 MPa (Lognonné et al., 2020) and lower than the pressure forcing estimates
680 of 239 ± 140 MPa (Murdoch et al., 2020). Our approach is sensitive to a shallower depth than the
681 pressure forcing estimates and so this can be reconciled.

682 This work uses the data from SP sensor during the deployment phase of the InSight Mission to
683 provide data-centric context for the SEIS experiment's observations. The tilt estimates are useful
684 to examine long period variation at InSight and also provide a story of the SEIS deployment. The
685 tilt algorithms are designed for high noise environments, where temperature is the dominant fac-
686 tor. Future developments could incorporate other factors such as pressure. The transfer coefficient
687 estimates are important to understand the noise injection at InSight. They can be incorporated
688 into the mission noise models of Mimoun et al. (2017); Murdoch et al. (2017) and used to update
689 the forward model for decorrelation attempts such as in Hurley et al. (2018). The lack of anthro-
690 pogenic/cultural sources or an ocean microseism mean that the the affect of wind in seismic data
691 can be better isolated on Mars in comparison to Earth data, where it is also a concern. For example,
692 Dybing et al. (2019) observed similar a relationship to wind. The field of planetary seismology is
693 set to grow with seismometers planned on missions to the Moon (Nunn et al., 2021) and Titan
694 (Lorenz et al., 2019) along with further concepts for ocean worlds (Vance et al., 2021). To that
695 end, this study yields information about operating a seismometer on Mars both on a lander deck
696 and on the surface. The approaches used could also be extended for terrestrial data, in particular
697 for lesser isolated stations.

698 **Data and Resources**

699 The InSight SEIS (seismic sensor) and TWINS (wind speed) data used in this paper are available
700 from the IPGP Datacenter and IRIS-DMC ([InSight Mars SEIS Data Service, 2019b](#)) and are also
701 available from the NASA PDS (National Aeronautics and Space Administration Planetary Data
702 System, <https://pds.nasa.gov/>, ([InSight Mars SEIS Data Service, 2019a](#))).

703 The finite element model was adapted from ([Myhill et al., 2018](#)) using the FEniCS Project
704 Python package ([Alnæs et al., 2015](#); [Logg et al., 2012](#)). The code will be made available on
705 Github.

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713

714 **References**

- 715 Alnæs, M., J. Blechta, J. Hake, A. Johansson, B. Kehlet, A. Logg, C. Richardson, J. Ring, M.
716 E. Rognes, and G. N. Wells (2015). The FEniCS project version 1.5, *Archive of Numerical*
717 *Software*, 3(100).
- 718 Banerdt, W. B., S. E. Smrekar, D. Banfield, D. Giardini, M. Golombek, C. L. Johnson, P.
719 Lognonné, A. Spiga, T. Spohn, C. Perrin, et al. (2020). Initial results from the InSight mis-
720 sion on Mars, *Nat. Geosci.*, 13(3) 183-189.
- 721 Banfield, D., A. Spiga, C. Newman, F. Forget, M. Lemmon, R. Lorenz, N. Murdoch, D. Viudez-
722 Moreiras, J. Pla-Garcia, R. F. Garcia, et al. (2020). The atmosphere of Mars as observed by
723 InSight, *Nat. Geosci.*, 13(3) 190-198.

724 Bierwirth, M., A. Kramer, M. Eberhardt, and F. IJpelaan (2019). Leveling the SEIS instrument
725 on NASA's InSight mission to Mars, Proceedings of the European Space Mechanisms and
726 Tribology Symposium

727 Ceylan, S., J. F. Clinton, D. Giardini, M. Böse, C. Charalambous, M. van Driel, A. Horleston,
728 T. Kawamura, A. Khan, G. Orhand-Mainsant, J.-R. Scholz, S. C. Stähler, F. Euchner, W. B.
729 Banerdt, P. Lognonné, D. Banfield, E. Beucler, R. F. Garcia, S. Kedar, M. Panning, W. T. Pike,
730 S. E. Smrekar, A. Spiga, N. L. Dahmen, K. Hurst, A. E. Stott, R. D. Lorenz, M. Schimmel, E.
731 Stutzmann, J. ten Pierick, V. Conejero, C. Pardo, and C. Perrin (2021). Companion guide to the
732 Marsquake Catalog from InSight, Sols 0-478: data content and non-seismic events, Phys. Earth
733 Planet. In., 310 106597.

734 Charalambous, C., A. E. Stott, W. T. Pike, J. McClean, T. Warren, A. Spiga, D. Banfield, D.,
735 R. F. Garcia, J. Clinton, S. C. Stähler, et al. (2020). A comodulation analysis of atmospheric
736 energy injection into the ground motion at insight, Mars, J. Geophys. Res.: Planets, 126
737 e2020JE006538.

738 Clinton, J. F., S. Ceylan, M. van Driel, D. Giardini, S. C. Stähler, M. Böse, C. Charalambous, N. L.
739 Dahmen, A. Horleston, T. Kawamura, A. Khan, G. Orhand-Mainsant, J.-R. Scholz, F. Euchner,
740 W. B. Banerdt, P. Lognonné, D. Banfield, E. Beucler, S. Kedar, M. Panning, C. Perrin, W. T.
741 Pike, S. E. Smrekar, A. Spiga, and A. E. Stott (2021). The Marsquake Catalogue from InSight,
742 Sols 0-478, Phys. Earth Planet. In., 310 106595

743 De Angelis, S. and P. Bodin (2012). Watching the wind: Seismic data contamination at long periods
744 due to atmospheric pressure-field-induced tilting, Bull. Seism. Soc. Am., 102(3) 1255–1265.

745 DeGroot, M. H. and M. J. Schervish (2012). Probability and statistics, Pearson Education.

746 Delage, P., F. Karakostas, A. Dhemaied, M. Belmokhtar, P. Lognonné, M. Golombek, E. De Laure,
747 K. Hurst, J.-C. Dupla, S. Kedar, Sharon, et al. (2017). An investigation of the mechanical
748 properties of some Martian regolith simulants with respect to the surface properties at the InSight
749 mission landing site, Space. Sci. Rev., 211(1-4) 191–213.

750 Dybing, S. N., A. T. Ringler, D. C. Wilson, and R. E. Anthony (2019). Characteristics and Spatial
751 Variability of Wind Noise on Near-Surface Broadband Seismometers, *Bull. Seism. Soc. Am.*,
752 109(3) 1082–1098.

753 Garcia, R. F., B. Kenda, T. Kawamura, A. Spiga, N. Murdoch, P. Lognonné, R. Widmer-
754 Schnidrig, N. Compaire, G. Orhand-Mainsant, D. Banfield, et al. (2020). Pressure Effects on
755 the SEIS-InSight Instrument, Improvement of Seismic Records, and Characterization of Long
756 Period Atmospheric Waves From Ground Displacements, *J. Geophys. Res.: Planets*, 125(7)
757 e2019JE006278.

758 Giardini, D., P. Lognonné, W. B. Banerdt, W. T. Pike, U. Christensen, S. Ceylan, J. F. Clinton, M.
759 van Driel, S. C. Stähler, M. Böse, et al. (2020). The seismicity of Mars, *Nat. Geosci.*, 13(3)
760 205–212.

761 Golombek, M., D. Kipp, N. Warner, I. Daubar, R. Fergason, R. L. Kirk, R. Beyer, A. Huertas, S.
762 Piqueux, N. E. Putzig, et al. (2017). Selection of the InSight landing site, *Space. Sci. Rev.*,
763 211(1) 5–95.

764 Hurley, J., N. Murdoch, N. A. Teanby, N. Bowles, T. Warren, S. B. Calcutt, D. Mimoun, and W.
765 T. Pike (2018). Isolation of Seismic Signal from InSight/SEIS-SP Microseismometer Measure-
766 ments, *Space. Sci. Rev.*, 214(5) 95.

767 InSight Mars SEIS Data Service (2019a). InSight SEIS Data Bundle. PDS Geosciences (GEO)
768 Node, <https://doi.org/10.17189/1517570>.

769 InSight Mars SEIS Data Service (2019b). SEIS raw data, Insight Mission. IPGP, JPL, CNES,
770 ETHZ, ICL, MPS, ISAE-Supaero, LPG, MFSC, [https://doi.org/10.18715/SEIS.INSIGHT.XB_](https://doi.org/10.18715/SEIS.INSIGHT.XB_2016)
771 [2016](https://doi.org/10.18715/SEIS.INSIGHT.XB_2016).

772 Kenda, B., M. Drilleau, R. F. Garcia, T. Kawamura, N. Murdoch, N. Compaire, P. Lognonné, A.
773 Spiga, R. Widmer-Schnidrig, P. Delage, et al. (2020). Subsurface structure at the InSight landing
774 site from compliance measurements by seismic and meteorological experiments, *J. Geophys.*
775 *Res.: Planets*, 125(6) e2020JE006387.

776 Kämpel, H.-J., K. Lehmann, M. Fabian, and G. Mentés (2001). Point stability at shallow depths:
777 experience from tilt measurements in the Lower Rhine Embayment, Germany, and implications
778 for high-resolution GPS and gravity recordings, *Geophys. J. Int.*, 146(3) 699–713.

779 Liu, H., W. T. Pike, C. Charalambous and A. E. Stott (2019). Passive Method for Reducing Tem-
780 perature Sensitivity of a Microelectromechanical Seismic Accelerometer for Marsquake Moni-
781 toring Below 1 Nano-g, *Physical Review Applied*, 12(6) 064057.

782 Logg, A., K.-A. Mardal, and G. N. Wells (2012). Automated solution of differential equations by
783 the finite element method: The FEniCS book, Springer Science & Business Media.

784 Lognonné, P., W. B. Banerdt, D. Giardini, W. T. Pike, U. Christensen, P. Laudet, S. De Raucourt, P.
785 Zweifel, S. Calcutt, M. Bierwirth, et al. (2019). SEIS: Insight’s seismic experiment for internal
786 structure of Mars, *Space. Sci. Rev.*, 215(1):12.

787 Lognonné, P., W. B. Banerdt, W. T. Pike, D. Giardini, U. Christensen, R. F. Garcia, T. Kawamura,
788 S. Kedar, B. Knapmeyer-Endrun, B., L. Margerin, F. Nimmo, M. Panning, B. Tauzin, J.-R.
789 Scholz, et al. (2020). Constraints on the shallow elastic and anelastic structure of Mars from
790 InSight seismic data, *Nat. Geosci.* 13(3): 213-220.

791 Lorenz, R. D., M. Panning, S. C. Stähler, H. Shiraishi, R. Yamada, and E. P. Turtle (2019). Titan
792 Seismology with Dragonfly: Probing the Internal Structure of the Most Accessible Ocean World,
793 51st Lunar and Planetary Science Conference.

794 Maki, J. N., M. Golombek, R. Deen, H. Abarca, C. Sorice, T. Goodsall, M. Schwochert, M. Lem-
795 mon, A. Trebi-Ollennu, and W. B. Banerdt (2018). The color cameras on the InSight lander,
796 *Space. Sci. Rev.*, 214(6) 105.

797 McClean, J. B., W. T. Pike, C. Charalambous, A. E. Stott, T. Warren, S. Calcutt, I. M. Standley, P.
798 Lognonné, and W. B. Banerdt (2019). Operation of the InSight Short Period (SP) Seismometers
799 During Cruise, 51st Lunar and Planetary Science Conference.

800 Mimoun, D., N. Murdoch, P. Lognonné, K. Hurst, W. T. Pike, J. Hurley, T. Nébut, W. B. Banerdt,
801 et al. (2017). The noise model of the SEIS seismometer of the InSight mission to Mars, *Space.*
802 *Sci. Rev.*, 211(1-4) 383–428.

803 Morgan, P., M. Grott, B. Knapmeyer-Endrun, M. Golombek, P. Delage, P. Lognonné, S. Piqueux,
804 I. Daubar, N. Murdoch, C. Charalambous, et al. (2018). A pre-landing assessment of regolith
805 properties at the InSight landing site, *Space. Sci. Rev.*, 214(6) 104.

806 Murdoch, N., D. Alazard, B. Knapmeyer-Endrun, N. Teanby, and R. Myhill (2018). Flexible mode
807 modelling of the InSight lander and consequences for the SEIS instrument, *Space. Sci. Rev.*,
808 214(8) 117.

809 Murdoch, N., D. Mimoun, R. F. Garcia, W. Rapin, T. Kawamura, P. Lognonné, D. Banfield, and W.
810 B. Banerdt (2017). Evaluating the Wind-Induced Mechanical Noise on the InSight Seismome-
811 ters, *Space. Sci. Rev.*, 211(1) 429–455.

812 Murdoch, N., A. Spiga, R. D. Lorenz, R. F. Garcia, C. Perrin, R. Widmer-Schmidrig, S. Rodriguez,
813 N. Compaire, N. H. Warner, D. Mimoun, D. Banfield, P. Lognonné, and W. B. Banerdt (2020).
814 Constraining Martian regolith parameters and vortex trajectories from combined seismic and
815 meteorological measurements, *J. Geophys. Res.: Planets*, 126(2) e2020JE006410.

816 Myhill, R., N. Teanby, J. Wookey, and N. Murdoch (2018). Near-field seismic propagation and
817 coupling through Mars’ regolith: implications for the InSight Mission, *Space. Sci. Rev.*, 214(5)
818 85.

819 Nunn, C., W. T. Pike, I. M. Standley, S. Calcutt, S. Kedar, and M. Panning (2021). Standing on
820 Apollo’s Shoulders: a Microseismometer for the Moon, *The Planetary Science Journal*, 2(1)
821 36.

822 Panning, M. P., W. T. Pike, P. Lognonné, W. B. Banerdt, N. Murdoch, D. Banfield, C. Charalam-
823 bous, S. Kedar, R. D. Lorenz, A. G. Marusiak, J. B. McClean, C. Nunn, S. C. Stähler, A. E.
824 Stott, and T. Warren (2020). On-Deck Seismology: Lessons from InSight for Future Planetary
825 Seismology, *J. Geophys. Res.: Planets*, 125(4) 1–13.

826 Petrosino, S., C. Ricco, E. De Lauro, I. Aquino, and M. Falanga (2020). Time evolution of medium
827 and long-period ground tilting at Campi Flegrei caldera, *ADGEO*, 52 9–17.

828 Pike, W. T., S. Calcutt, I. M. Standley, A. G. Mukherjee, J. Temple, T. Warren, C. Charalambous,

- 829 H. Liu, A. E. Stott, and J. B. McClean (2016). A silicon seismic package (SSP) for planetary
830 geophysics, 47th Lunar and Planetary Science Conference.
- 831 Ringler, A. T., J. Steim, D. C. Wilson, R. Widmer-Schmidrig, and R. E. Anthony (2020). Im-
832 provedments in seismic resolution and current limitations in the Global Seismographic Network,
833 *Geophys. J. Int.*, 220(1) 508–521.
- 834 Rodgers, P. W. (1968). The response of the horizontal pendulum seismometer to Rayleigh and
835 Love waves, tilt, and free oscillations of the Earth. *Bull. Seism. Soc. Am.*, 58(5) 1385–1406.
- 836 Santamarina, J. C., K. A. Klein, and M. A. Fam (2001). *Soils and waves*, J. Wiley & Sons New
837 York.
- 838 Sorrells, G. G. (1971). A preliminary investigation into the relationship between long-period seis-
839 mic noise and local fluctuations in the atmospheric pressure field. *Geophys. J. Int.*, 26(1-4)
840 71–82.
- 841 Stott, A. E., C. Charalambous, J. B. McClean, T. Warren, A. Trebi-Ollennu, G. Lim, N. A. Teanby,
842 R. Myhill, A. Horleston, S. Kedar, et al. (2020). Using InSight’s Robotic Arm Motion to Ex-
843 amine the Martian Regolith’s Response to Short Period Vibrations, 51st Lunar and Planetary
844 Science Conference.
- 845 Stott, A. E., C. Charalambous, T. Warren and W. T. Pike (2018). Full-band signal extraction from
846 sensors in extreme environments: the NASA InSight microseismometer, *IEEE Sensor J.*, 18(22)
847 9382–9392.
- 848 Stott, A. E. (2018). Latent variable regression and applications to planetary seismic instrumenta-
849 tion, Imperial College London Thesis.
- 850 Teanby, N. A., J. Stevanović, J. Wookey, N. Murdoch, J. Hurley, R. Myhill, N. Bowles, S. Calcutt,
851 and W. T. Pike (2017). Seismic coupling of short-period wind noise through Mars’ regolith for
852 NASA’s InSight lander, *Space. Sci. Rev.*, 211(1-4) 485–500.
- 853 Trebi-Ollennu, A., W. Kim, K. Ali, O. Khan, C. Sorice, P. Bailey, J. Umland, et al. (2018). InSight
854 Mars Lander Robotics Instrument Deployment System, *Space. Sci. Rev.*, 214(5) 93.

- 855 Vance, S., M. Behoukova, B. G. Bills, P. Byrne, O. Cadek, J. Castillo-Rogez, G. Choblet, K.
856 Hughson, S. Hurford, J. Keane, et al. (2021). Distributed Geophysical Exploration of Enceladus
857 and Other Ocean Worlds, *Bull. Am. Astron. Soc.*, 53(4) 127.
- 858 Wielandt, E., and G. Streckeisen (1982). The leaf-spring seismometer: Design and performance,
859 *Bull. Seism. Soc. Am.*, 72(6A) 2349–2367.
- 860 Wolin, E., S. van der Lee, T. A. Bollmann, D. A. Wiens, J. Revenaugh, F. A. Darbyshire, A. W.
861 Frederiksen, S. Stein, and M. E. Wysession (2015). Seasonal and diurnal variations in long-
862 period noise at SPREE stations: The influence of soil characteristics on shallow stations' per-
863 formance, *Bull. Seism. Soc. Am.*, 105(5) 2433–2452.