**USING INSIGHT'S ROBOTIC ARM MOTION TO EXAMINE THE MARTIAN REGOLITH'S RESPONSE TO SHORT PERIOD VIBRATIONS.** A. E. Stott[1], C. Charalambous[1], J. B. McClean[1], T. Warren[2], A. Trebi-Ollennu[3], G. Lim[3], N. Teanby[4], R. Myhill[4], A. Horleston[4], S. Kedar[3], K. Hurst[3], N. Murdoch[5], P. Lognonné[6], S. Calcutt[2] and W. T. Pike[1], [1]Imperial College London, UK (alexander.stott10@imperial.ac.uk), [2]University of Oxford, UK, [3]JPL Caltech, USA, [4]University of Bristol, UK, [5]ISAE, FR, [6]IPGP, FR

**Introduction:** A rich set of data has been recorded by the NASA InSight mission's seismometers, following its arrival and subsequent deployment on Elysium Planitia [1,2]. In particular, the SEIS experiment [2] has recorded vibrations generated by the InSight robotic instrument deployment arm (IDA) [3]. Here, we compare the acceleration response recorded on and off the lander deck to examine the Martian regolith.

**Method:** The Short Period (SP) seismometer was able to operate on the deck of the lander owing to its high dynamic operating range [4,5]. This enables the comparison of the observed acceleration response between IDA motions recorded while on the deck and on the ground. Given a similar motion in each scenario, the two data sets can be compared to establish the coupling from the lander to SEIS.

Previous experiments [6,7] were performed in an analogue environment in Iceland using wind excitation. The coupling through the regolith is quantified by the transfer coefficient, which is the ratio of the acceleration response of the output over the input and indicates the level of attenuation.

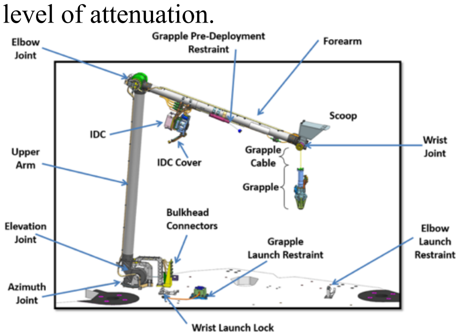


**Figure 1: Diagram of the IDA.**

**Data:** Arm motion causes vibrations which are sensed by the SEIS seismometers. Fig. 2 shows the spectrograms of a set of arm motions observed by the SP from on and off the deck. These spectrograms show the response across the full 50 Hz bandwidth. During a motion, the arm vibration injects energy across a broad band of frequencies, most significantly above 4 Hz, including a series of lander modes [2]. On the deck this is often swamped by environmental excitation, more so for increasing frequency. A notable excitation is the mode around 4 Hz. This is seen to chirp to 6 Hz depending on the arm motor positions and is observed in most arm motions on and off the deck. Here we examine the vertical displacement but a horizontal response is also observed.

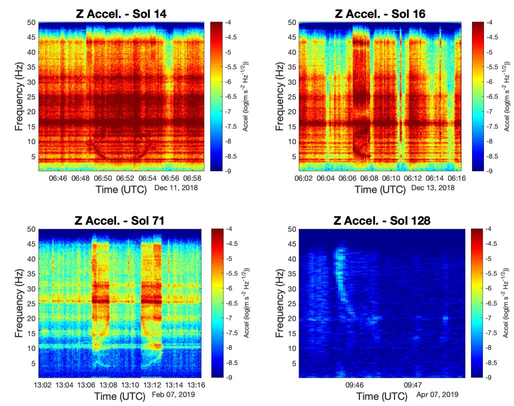


**Figure 2: Example IDA motions sensed by InSight's SP seismometer on the deck for Sol 14 and 16 and off the deck for Sols 71 and 128.**

**Results:** In order to determine the attenuation in the regolith we must identify and compare similar motion sequences from on and off the deck. One such sequence is the tau pose (shown in Fig. 3) which raises the arm to the sky and back to estimate the optical depth. This was performed on both sol 14 and 71. The motor angle positions and the acceleration response of the SP for both is shown in Fig. 4.

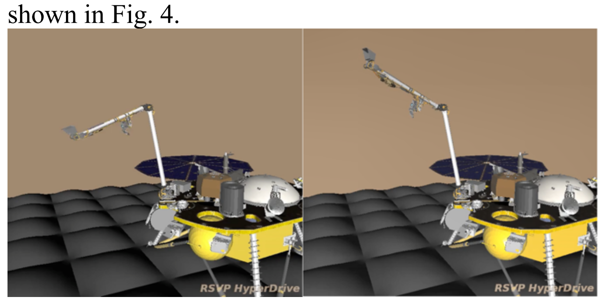


**Figure 3: Arm position of start and end of a tau pose.**

To compare the different acceleration responses for each motion, we plot the rtPSD for each slice of the spectrogram across the arm sequence and take the maximum value for each frequency. The ratio of this maximum excited acceleration for sol 71 over 14 then yields an estimate of the transfer coefficient across frequency.

**Analysis and discussion:** The transfer coefficient is determined in the bandwidth 4-9 Hz. This is because the IDA produces a clear excitation above the ambient in both the on and off-deck motions, as seen in Fig. 5. The average transfer coefficient in this bandwidth is 0.004.

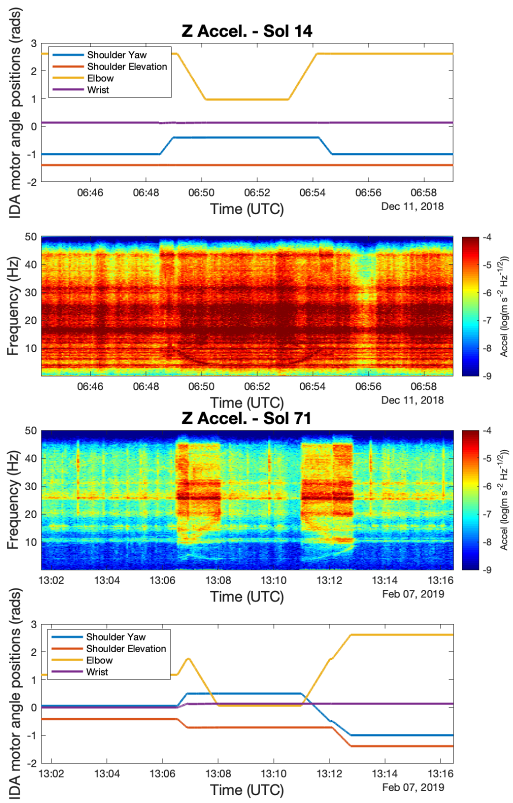


**Figure 4: Arm motor positions and spectrogram of the acceleration response observed from a tau pose performed on the deck (sol 14) and off the deck (sol 71).**

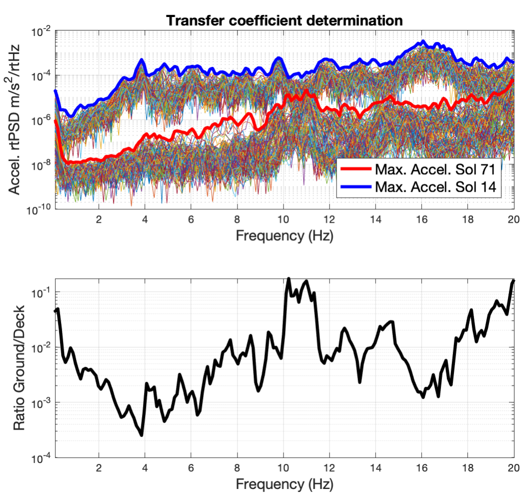


**Figure 5: Plot of each slice of the spectrograms for sol 14 and 71 with the maximum value for each frequency highlighted. The ratio of these maxima gives an estimate of the transfer coefficient.**

To assess the implications for the near surface regolith properties we next compare this value to a theoretical calculation. To this end, we use a straightforward regolith model of a homogenous elastic half-space, as proposed in [6,7]. In this case, the ratio of the measured (normalised) displacement at a distance $r$ to the displacement from a disc of radius $a$ is given by

$$d(r) = \frac{2}{\pi}\sin^{-1}\frac{a}{r}$$

Assuming that the deformation at each of the SEIS assembly feet is an additive sum of the contributions from each of the lander feet (for $i = 1,2,3$) then the total deformation ratio at each foot $j = 1,2,3$ can be approximated as

$$D_j = \frac{2}{\pi}\sum_{i=1}^{3}\sin^{-1}\frac{a}{r_{ij}}$$

The lander footpads each have radius $a = 14.50\,cm$ and $r_{11} = 1.74\,m, r_{21} = 2.26\,m,\ r_{31} = 3.52m$, $r_{12} = 1.94\,m,\ r_{22} = 2.44\,m,\ r_{32} = 3.73\,m,\ r_{13} = 1.77\,m,\ r_{23} = 2.47\,m$ and $r_{33} = 3.63\,m$. This yields theoretical transfer coefficients for the north, south and west SEIS feet $D_1 = 0.12, D_2 = 0.11$ and $D_3 = 0.12$.

The observed attenuation through the regolith is ~30 times lower than this theoretical calculation showing that the regolith cannot be well modelled as a homogenous elastic medium. A more complex model is required incorporating energy loss and regolith inhomogeneity.

**Conclusion:** Here we have presented an analysis of InSight data to show a dynamic experiment of the regolith using the IDA movements. We have established an attenuation level of 0.004 in the 4-9 Hz band which is an order of magnitude below that predicted from a homogeneous elastic half-space. Additional attenuation to this model was also observed in analogue experiments [6,7]. Future work has two components: (*i*) to increase the estimation robustness through a modelling of the robot arm induced forces and (*ii*) to examine more complex models of the regolith and lander to SEIS coupling as in [7], incorporating the horizontal motions as a further constraint. A transfer function can be developed and compared to environmental injections for an in-depth analysis of the near surface seismic propagation and the features observed in the InSight seismic data.

**Acknowledgments:** Thanks to the UK Space agency, IDS team and InSight Mars SEIS Data https://doi.org/10.18715/SEIS.INSIGHT.XB_2016.

**References:** [1] InSight Mars SEIS Data Service (2019). [2] Lognonné et al. (2019) *SSR,* 215:12. [3] Trebi-Ollennu et al. (2018) *SSR,* 214:93. [4] Pike et al. (2018) *IEEE MEMS*, 2160-1968. [5] Pike et al. (2016) *LPSC* 47, Abstract #2081. [6] Teanby et al. (2017), *SSR*, 211:485-500. [7] Myhill et al. (2018), *SSR*, 214: 85.