FREQUENCY CONTENT OF IMPACT-GENERATED SEISMIC WAVES. N. Wójcicka[1], G. S. Collins[1], I. D. Bastow[1], N.A. Teanby[2], K. Miljković[3] and A. Rajšić[3]. [1]Department of Earth Science and Engineering, Imperial College London, London, SW7 2AZ, United Kingdom; [2]School of Earth Sciences, University of Bristol, Bristol BS8 1RJ, United Kingdom; [3]Space Science and Technology Centre, School of Earth and Planetary Sciences, Curtin University, Perth, Australia; (E-mail: n.wojcicka18@imperial.ac.uk).

Introduction: The InSight mission has been recording seismic signals on the surface of Mars since early 2019 and whilst meteorite impacts were expected to contribute significantly to Martian seismicity, identifying impact-generated signals in the data and distinguishing them from other sources has proven challenging. The seismic signature of impacts, including the frequency content of the seismic waves they may produce, have so far been poorly constrained, primarily due to lack of observed data.

In this work we constrain the frequency content of meteorite impacts at short distances (∼780 m, ∼10-100 crater radii), as a function of impact properties, using a small uniform asteroid as a target. Our results will aid the efforts to identify impacts in InSight seismic data and, in the case of a candidate crater image being captured, to connect the crater properties to the seismic signal.

Modelling: We used iSALE2D [1–3] to simulate a suite of impacts onto a small, uniform asteroid. Whilst impacts onto planetary surfaces are often modelled in a half-space mesh geometry, using a spherical target allows us to track the seismic wave for a longer period of time, without producing reflections from a nonphysical boundary. We measured the displacement of a virtual seismometer at the equator of the asteroid and used the signal to produce a frequency spectrum and examine its sensitivity to several impact parameters: impactor size and velocity and target material.

We simulated three impactor diameters at 100 m/s: 4 m, 16 m and 60 m. The slow impact speed was chosen based on the numerical experiments of [4], where the elastic response of the target was examined. Additionally, to examine the sensitivity to impact velocity, the 4 m impactor was simulated at 800 m/s and 6400 m/s.

The asteroid and the impactor were both modelled as uniform spherical bodies. The typical resolution of the impactor was 10 cells per projectile radius (cppr). The asteroid's diameter was kept constant at 1 km, and hence the total number of cells in the simulation domain was dependent on the size of the impactor. An example simulation setup is shown in Fig.1.

To test the frequency spectrum response we adopted three target materials: bedrock (non-porous), fractured bedrock (25% porosity) and regolith (44% porosity). All three material models were previously used to model small impacts onto planetary surfaces [5, 6].

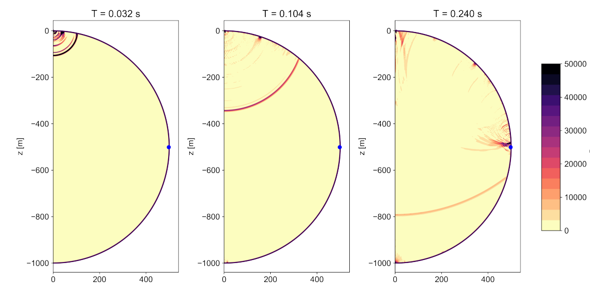

Figure 1: The seismic wave propagating through the simulation mesh for one of impact scenarios of a 4 m impactor striking a 1 km rocky asteroid at 100 m/s. The probe (seismometer) is marked with a blue dot at the equator.

All materials were modelled using a Tillotson equation of state for basalt [7] with reference density of $\rho_0 = 2860\,\mathrm{kgm^{-3}}$ paired with an $\epsilon - \alpha$ compaction model to describe porosity in the porous materials. Additionally, the ROCK strength model [2] was used in the intact and fractured bedrock cases, and Lundborg strength model [8] was used in the porous regolith case. The impactor was modelled using the intact bedrock material model in all simulations.

Results: We calculated the frequency spectra using a Fast Fourier Transform of the displacement time series recorded 2 m under the surface at the equator of the asteroid (∼780 m from the source).

We fitted each displacement amplitude spectrum with the following expression [9, 10]:

$$A(f) = \frac{A_0}{1 + \frac{f^2}{f_c^2}}, \quad (1)$$

where A_0 is the low frequency limit of the amplitude spectrum and f_c is the corner frequency of the spectrum. A_0 and f_c are found for each impact scenario using a least squares fit.

The effects of each of the impact properties investigated are shown in Fig. 2. We make the following observations:

- Increasing impactor size reduces the corner frequency.
- Increasing impact velocity also reduces the corner frequency.
- Impacts onto more porous targets produce lower frequency spectra.

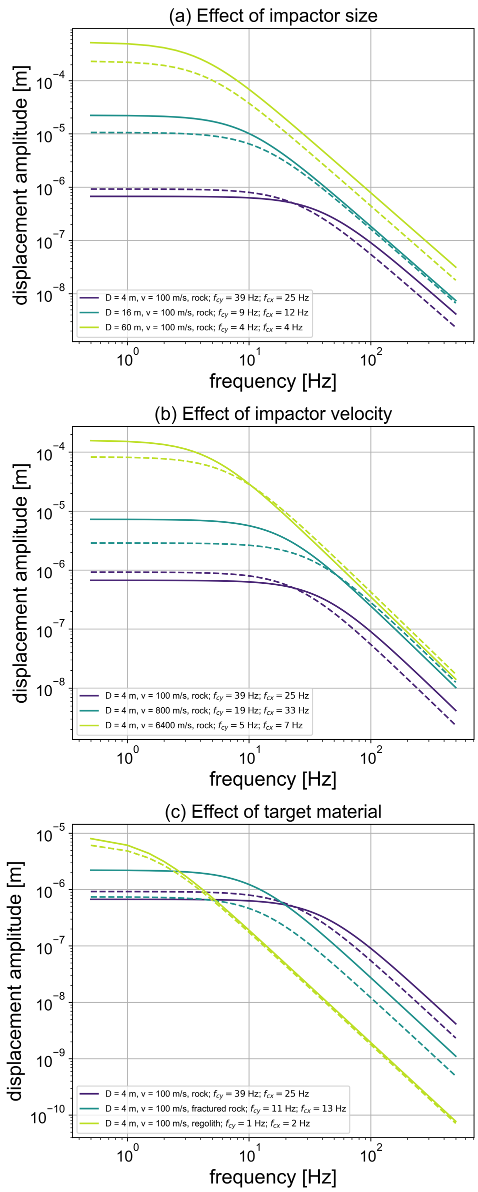

Figure 2: The effect of: (a) impactor size, (b) impact speed and (c) target material, on the frequency content of the near-field signal produced by simulated impacts. The solid lines represent the vertical component and dashed lines represent the horizontal component.

The spectra for the horizontal (parallel to the surface) and vertical (perpendicular to the surface) components are very similar, with slightly more energy in the vertical direction (with the exception of the 4 m impactor where the opposite is true).

Discussion and Conclusions: The impact scenarios we modelled here produce frequencies up to 100 Hz in the near field, with large portion of the energy at frequencies above the bandwidth of SEIS [11]. However, in comparison to scenarios most likely to occur on Mars they are considerably larger and slower - the range of diameters expected to occur most frequently is sub-metre and average meteorite velocity at the top of Martian atmosphere is ∼11 km/s. The passage through the atmosphere significantly reduces both the mass and speed of the impactor, resulting in impact velocities between 1 - 6 km/s [5]. Hence the impacts of the most interest for InSight produce craters between few - few tens of metres in diameter. For example, for an impact of a ∼20 cm wide projectile at 4 km/s onto porous regolith (crater diameter ∼5-7 m), we can expect the corner frequency to be reduced ∼40 times due to the effect of increased velocity, and increased ∼20 times, due to the decreased impactor size. Overall the vertical corner frequency can be expected to be approximately half the corner frequency for the simulated scenario of a 4 m wide impactor at 100 m/s onto regolith target - approximately 0.75 Hz. For the same impact in bedrock, the estimated corner frequency at short distances would be approximately 12.5 Hz. Propagation over large distances will attenuate the highest frequencies, so the signal recorded at a receiver such as InSight is likely to mostly contain lower frequencies.

Preliminary results show that the frequency content of seismic signals generated by meteorite impacts is strongly related to the impact parameters. We have introduced a two-parameter approximation of a near-field signal, and further work will allow us to constrain the dependence of each parameter on impact properties. This will allow us to generate synthetic signals for other impact scenarios.

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References: [1] Amsden, A. A. et al. (1980) tech. rep. June Los Alamos, NM (United States): Los Alamos National Laboratory (LANL), 101p. [2] Collins, G. S. et al. (2004) *Meteorit. Planet. Sci.* 39:217–231. [3] Wünnemann, K. et al. (2006) *Icarus*, 180:514–527. [4] Richardson, J. E. et al. (2020) *Icarus*, 347:113811. [5] Wójcicka, N. et al. (2020) *J. Geophys. Res. Planets*, 125. [6] Rajšić, A. et al. (2021) *J. Geophys. Res.: Planets*, 126:e2020JE006662. [7] Tillotson, J. H. (1962) *Rep. No. GA-3216, Gen. At. San Diego, CA*,43. [8] Lundborg, N. (1968) *Int. J. Rock Mech. Min. Sci.* 5:427–454. [9] Brune, J. N. (1970) *J. Geophys. Res.* 75:4997–5009. [10] Böse, M. et al. (2021) *Bulletin of the Seismological Society of America*, [11] Lognonné, P. et al. (2019) *Space Sci. Rev.* 215:12.