THE SEISMIC SIGNATURES OF IMPACT EVENTS ON MARS: IMPLICATIONS FOR THE INSIGHT LANDER. N. C. Schmerr
1, M. E. Banks2, I. J. Daubar3, 1University of Maryland, Department of Geology, College Park MD 20742 USA, neschmerr@umd.edu, 2Planetary Science Institute, Tucson, AZ 85719, USA, 3Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109 USA.

Introduction: The detailed structure of the Martian interior is an essential constraint for understanding the formation, evolution, and dynamics of the planet. Impact events will serve as a key source of seismic waves for interrogating internal structure; e.g., the NASA Discovery Program lander InSight will be capable of detecting these events [1]. Recent, fresh craters formed by ongoing impacts into dust-covered regions are detectable in high-resolution orbital images of the Martian surface [2, 3]. Seismically detecting and subsequently spatially locating and orbitally imaging impacts will provide extremely accurate epicenters, and enable calibration of Martian seismic velocities and retrieval of internal structure.

To investigate recent impact-produced seismic activity on Mars, we use detailed characterizations of new, dated impacts, including measurements of crater diameter, morphometry, and geospatial information for individual craters in impacts occurring as clusters [4]. Measured parameters are converted to seismic predictions for the impact source using a scaling law [5] that relates crater diameter to the momentum and source duration, calibrated for Apollo recordings of meteoroid impacts on the Moon [6]. The resulting source function is dependent upon the target properties, impact angle, and the efficiency of conversion of impact momentum to seismic amplitudes [7]. We use a range of target properties (bedrock vs. regolith), that bound the seismic source for the observed crater distribution [8].

Impact Source Function: Impacts operate as a compressive point source at a collision point within a target medium. This is followed by a shockwave and excavation as momentum is transferred inefficiently from the bolide to the target materials and ejecta [5]. The relative efficiency of the momentum transfer depends upon the physical properties of the bolide and target materials [9]. In hypervelocity impacts, some momentum is transferred away from the target as ejecta. In terms of energy, only a small fraction (<< 1%) of the impact total energy goes into excitation of a seismic wave that propagates outward from the impact source [6].

This seismic wave takes the form of a time dependent force acting on the surface as an impulse, and can be written as:

\[ f(t, x) = F_0(t, x) \cdot g(t) \]

\[ g(t) = 1 + \cos(\omega_0 t) \quad \text{for} \ -\pi / \omega_0 < t < \pi / \omega_0 \]

\[ g(t) = 0 \quad \text{otherwise} \]

where \( F_0 \) is the seismic force, a fraction of the initial impact force (related to momentum of the bolide), \( t \) is the source duration, \( \omega_0 \) is the cutoff frequency \( (\omega_0 = \frac{2\pi}{r^3}) \) and \( x \) is the location relative to the center of the impact [8]. The resulting shape of an impact source time function is shown in Fig. 1.

The duration of the impact source is also tied to the size of the impact and amount of momentum transferred; this is calibrated using estimates from the Moon [8], (Fig. 1). Using crater size, we can then put a bound on the momentum released during impact, and thus estimate the size of the resulting seismic waves with some basic assumptions about target properties, efficiency of energy transfer to seismic waves, and Martian internal structure. Examples of source spectra for a range of impact sources are shown in Fig. 2.

![Fig. 1. Description of source time function used in impact seismic modeling. A) Time domain impulse source function \((t = 0.5 \text{ seconds})\). B) Source durations for the impacts recorded by the Apollo seismic experiments and a power law fit to the observed values [8].](image)

![Fig. 2. Seismic source spectra for a range of impact momentum values, similar to those in our dataset. Note the sharp cutoff at higher frequency and nonlinear behavior, and the sloping linear response at low frequency. A seismic efficiency of \( k=10^{-5} \) is used to scale the seismic energy [7].](image)
Synthetic Modeling: To study the seismic responses expected for the observed recent crater population, we use effective crater diameters, defined for crater clusters as $D_{\text{eff}} = (\Sigma D_i)^{1/3}$ [10]. For this initial study, we model craters from a database of 2774 craters detected at 56 separate impact sites. Target properties used to obtain an estimate of the impact seismic force were varied from hard rock ($Y=10$ MPa, $\rho=3.2$ g/cm$^3$) to soft sediments ($Y=20$ kPa, $\rho=1.7$ g/cm$^3$), where $Y$ is yield strength of the target materials, and $\rho$ is the target density [8]. We also investigate a range of bolide properties with bolide density ranging from 1-3 g/cm$^3$ (encompassing the range of densities for these impactors derived by [11]), and impact velocities of 5-10 km/s. Details of the source durations, momentums used, and distribution of crater sizes are in Fig. 3.

![Fig. 3. Distribution of source parameters for recent impact craters on Mars. A) Histogram of crater effective diameters, note the size cutoff is due to the resolution of the MRO cameras and not representative of the smallest crater sizes on Mars. (Thus we expect many additional small impacts to occur that may also be seismically detectable [4]). B) Impact momentum derived from empirically derived crater scaling laws in [5], C) equivalent seismic magnitudes of impact events, and D) impact source duration (Fig. 1).](image)

For the near field response, we model the expected seismic source(s) using 3-D Serpentine Wave Propagation [12] that predicts the full 3-D ground motion due to the impact. This code is accurate to frequencies of ~5 Hz. These calculations are computationally intensive, and require simplification of the velocity model to achieve efficient compute times. The background model used is a simple layered crust, with a 30 km thick layer of basalt, underlain by a 20 km thick layer of ultramafic mantle materials. We include the effect of small-scale heterogeneity and scattering in the shallower crust by introducing a 1 km thick layer of a von Karman-type random media with a Gaussian distribution of scatterers at 100 m scale-length and 10% velocity heterogeneity [13]. For some impact events, the bolide disintegrates in the atmosphere before impact, forming multiple craters of varying size; our code captures these more complex effects.

The far field response (> 500 km from the source) is modeled using the 1-D wave propagation code GEMINI [14]. We use the background model of Sohl and Spohn [15] for the deep Martian interior, and assume a moderately attenuating Martian mantle (Q=100). For impact clusters consisting of multiple craters, the source is modeled using the effective crater diameter in the cluster. Example results from the 1-D and 3-D methods for one impact are shown in Fig. 4.

![Fig. 4. Examples of synthetic seismograms for 9 separate, simultaneously-formed craters, the largest of which is 14.4 meters in diameter (M$_{cr}$=1.44) from HiRISE image PSP_006972_1710. A) 3-D synthetics for the clustered impact source region, B) 1-D synthetics, positive amplitudes are red, negative blue.](image)

Implications: The result of these efforts is a data-derived estimate for the amplitude of various seismic phases at different distances. This is essential for both the InSight mission and any future seismic studies of Mars: quantifying the detectable distances for body and surface wave phases, identifying the seismic signatures of impacts, and will enhance the ability of impact sources to recover Martian internal structure from a single 3-component seismometer.