A MARTIAN IMPACT FULL RAYLEIGH WAVEFORM INVERSION TECHNIQUE FOR 1D IDENTIFICATION OF CRUSTAL STRUCTURE. F. Karakostas1,2, P. Lognonné2, C. Larmat1 and N. Schmerr3,  
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Introduction: During the nominal period of operations of the InSight mission (1 Martian year) several meteoroid impacts are expected to generate Rayleigh waves which will be recorded by the VBB seismometer of the Seismic Experiment of Internal Structure (SEIS) [1][2]. Impacts are important for the InSight mission as additional seismic sources than tectonic events. However, as their magnitude range is expected to be limited [1][3], they will be most useful for identification of the crustal structure at local or (in an optimistic case) regional scale. Furthermore, their importance is enhanced as their location and occurrence time (in some cases) can be known from optical observations of Martian orbiters. Therefore, an inversion technique is needed, in order to provide solutions for the internal structure, based on previous constraints and the Rayleigh waveforms. Impacts are very good generator of surface waves as they are seismic sources situated on the surface.

We consider a model where the impact is an isotropic source on the ground, following a series of isotropic explosions in the atmosphere. Previous works showed that we can correlate the absolute value of the seismic moment with the energy which is released by the procedure of entry and impact of the meteoroid [4]. It was also shown that the released energy can be associated to the density of the ambient atmosphere or the solid part [1]. In the case of Mars, with the presence of a relatively thin atmosphere, this means that the seismic energy released in the atmosphere will be negligible compared to the energy generated at the impact for most cases, at the exception of events occurring very close to the seismometer.

Methodology: Our approach is based on the use of two numerical methods for the modeling of Rayleigh waves. The first method is normal modes summation [5] whereas the second one is a spectral element method software, SPECFEM-3D [6]. The same techniques were previously used for the characterization of the seismic source of an Chelyabinsk airburst [1]. In the case of Chelyabinsk, the inversion of the seismic source benefited from well constrained models of the Earth atmosphere and solid subsurface. In order to determine the magnitude of the impact event, in terms of seismic moment, we use a full waveform inversion technique, developed by [7] and used for the airburst inversion of Chelyabinsk event by [1]. The input is the synthetic seismogram calculated with any of the two techniques mentioned above, which corresponds to the synt of the following equations. The observed waveform is noted as sobs. With the use of an a priori model of the Martian internal structure, we can obtain an estimation of the absolute value of the moment tensor by searching the value which minimizes the residue of the following expression:

\[ \frac{\partial}{\partial M_{\text{ratio}}} \left( \int_{t_1}^{t_2} (s_{\text{synt}}(t) - s_{\text{obs}}(t))^2 \, dt \right) = 0 \]

where \( M_{\text{ratio}} \) is the relative value of the true moment tensor, \( M_{\text{real}} \), compared to a moment tensor used for the modeling of the input synthetic seismograms, \( M_{\text{synt}} \), as described by the following equation:

\[ M_{\text{ratio}} = \frac{M_{\text{real}}}{M_{\text{synt}}} \Rightarrow M_{\text{real}} = M_{\text{synt}} \cdot M_{\text{ratio}} \]

The result provided from this inversion technique should correspond to only one model. Therefore, every assumption for the internal structure, expressed in terms of a proposed velocity model, including depths of discontinuities and the seismic velocities in each layer, in this case of the 1D structure identification, is accompanied by a proposed seismic magnitude. The quality of this result, which is numerically found to be the best fit for each model, can be qualitatively reviewed based on two factors: the time-delay of the Rayleigh waves arrivals and the correlation coefficient of the synthetic and recorded waveforms.

Results: The results of this inversion technique should be obviously obtained after the use of real Martian seismic data, associated to impact events. The best result in terms of waveform should be the modeling based on a 1D model, which provides the best fit. Therefore, every assumption for the internal structure, expressed in terms of a proposed model, comprising the depths of discontinuities and the seismic velocities of the layers, in this case of the 1D structure identification, is accompanied by a proposed seismic moment magnitude. The quality of this result, which is numerically found to be the best fit for each model, can be qualitatively reviewed based on two factors: the time-delay of the Rayleigh waves arrivals and the correlation coefficient of the synthetic and recorded waveforms.
However, preliminary modeling results, with the use of a preliminary model of the atmosphere [8] and the internal structure [9] of Mars, provide evidence for the amplitudes of Rayleigh waves, capable to be detected in different epicentral distances and their association with the magnitude of the event.

The figure depicts the synthetic seismograms calculated for an impact equivalent to a seismic event of \( M_w = 1.3 \), for detections in several epicentral distances on Mars. These seismograms are computed with the summation of the fundamental Martian spheroidal mode in frequencies up to 0.16 Hz. A seismic signal of such event can be detected by the InSight VBB seismometer if it has an amplitude greater than the noise level, which is estimated equal to \( 10^{-9} \text{ m.s}^{-2} \). As it can be observed, such small impacts can only contribute to the identification of the local lithospheric structure, in epicentral distances of about 5\(^\circ\). In larger distances and in frequencies that correspond to the Rayleigh waves, this signal seems to be lower than the noise and therefore undetectable. However, larger impactors may generate waves which can be used in order to perform such an analysis in larger scale.

The attenuation which is observed in the synthetic seismograms corresponds to a quality factor in the crust equal to \( Q=500 \). This is also an assumption of the model, therefore, an inversion technique which can provide numerical results for the magnitude of the seismic event and permits the qualitative analysis of these results, as referred above, based on the time and waveform correlation between recordings and synthetics, can be useful in order to provide constraints on the quality factor of the Martian crust through the analysis of more than one impact events. Furthermore, this inversion technique is able to provide results for a series of models tested by the InSight mission Mars Structure Service. Even if the event magnitude is dependent to the internal structure, the correlation coefficient can provide evidence for the model which is more efficient to describe the detected signals.

**Conclusion:** We developed an inversion technique which is planned to be applied immediately when an impact event occurs on Mars during the operations of InSight mission.

The inversion technique has been validated on the Chelyabinsk event on Earth and the forward modeling has been used for estimating the detectability of the seismic signal generated by an impact on Mars. These results have been already published. We propose a way to use the inversion technique, developed as a source characterization, as a structure characterization technique. The mathematical and numerical tools can be used for a qualitative analysis of the fit of waveforms modeling assuming a 1D model, and thus provide useful constraints to the Mars Structure Service of the InSight mission. Several properties of the event (epicentral distance from the SEIS VBB seismometer, size of the meteoroid, entry angle etc.) are variables that control the quality of the expected results, as well as the number of the impact events during the InSight mission operations on Mars.

**References:**