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Single-station and single-event marsquake location and inversion for structure using synthetic Martian waveforms

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A B S T R A C T

In anticipation of the upcoming InSight mission, which is expected to deploy a single seismic station on the Martian surface in November 2018, we describe a methodology that enables locating marsquakes and obtaining information on the interior structure of Mars. The method works sequentially and is illustrated using single representative 3-component seismograms from two separate events: a relatively large teleseismic event (M_w5.1) and a small-to-moderate-sized regional event (M_w3.8). Location and origin time of the event is determined probabilistically from observations of Rayleigh waves and body-wave arrivals. From the recording of surface waves, averaged fundamental-mode group velocity dispersion data can be extracted and, in combination with body-wave arrival picks, inverted for crust and mantle structure. In the absence of Martian seismic data, we performed full waveform computations using a spectral element method (AxiSEM) to compute seismograms down to a period of 1 s. The model (radial profiles of density, P- and S-wave-speed, and attenuation) used for this purpose is constructed on the basis of an average Martian mantle composition and model areotherm using thermodynamic principles, mineral physics data, and viscoelastic modeling. Noise was added to the synthetic seismic data using an up-to-date noise model that considers a whole series of possible noise sources generated in instrument and lander, including wind-, thermal-, and pressure-induced effects and electromagnetic noise. The examples studied here, which are based on the assumption of spherical symmetry, show that we are able to determine epicentral distance and origin time to accuracies of ~0.5–1° and ±3–6 s, respectively. For the events and the particular noise level chosen, information on Rayleigh-wave group velocity dispersion in the period range ~14–48 s (M_w5.1) and ~14–34 s (M_w3.8) could be determined. Stochastic inversion of dispersion data in combination with body-wave travel time information for interior structure, allows us to constrain mantle velocity structure to an uncertainty of ~5%. Employing the travel times obtained with the initially inverted models, we are able to locate additional body-wave arrivals including depth phases, surface and Moho (multiple) reflections that may otherwise elude visual identification. This expanded data set is reinverted to refine interior structure models and source parameters (epicentral distance and origin time).

1. Introduction

Seismology, because of its higher resolving power relative to other geophysical methods for sounding the interior of a planetary body, has played a prominent role in the study of Earth's interior (e.g., Dziewonski and Romanowicz, 2007). For example, many of the parameters that are important for understanding the dynamic behavior of planetary interiors are determined by seismology (e.g., Lognonné and Johnson, 2007, Khan et al., 2013). This is one of the primary reasons for landing a seismometer on Mars with the upcoming InSight (Interior Exploration using Seismic Investiga-

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tions, Geodesy and Heat Transport) mission (Banerdt et al., 2013). The InSight mission is currently expected to be launched in May 2018 with deployment on the Martian surface expected the following November. The InSight lander will be the first planetary seismology mission in nearly four decades since the Apollo and Viking missions (e.g., Nakamura, 2015; Anderson et al., 1977; Lognonné and Johnson, 2007) and is expected to provide seismic data from which the internal structure of Mars can be elucidated.

Extra-terrestrial seismology saw its advent with the U.S. Apollo missions which were undertaken from July 1969 to December 1972. Seismic stations were deployed at five locations as part of an integrated set of geophysical experiments. Interpretation and analysis of lunar seismic data proved difficult, because of paucity of stations, limited spatio-temporal configuration, restricted instrument bandwidth, and limited number of usable seismic events (e.g., Lognonné and Johnson, 2007; Khan et al., 2013; Nakamura, 1983, 2015; Kawamura et al., 2015; Knapmeyer and Weber, 2015). In spite of this complexity, it has nonetheless been possible to make first-order inferences on the internal structure that showed the Moon to be a differentiated body, stratified into a crust, mantle, and possibly liquid core (e.g., Nakamura, 1983; Williams et al., 2001; Khan and Mosegaard, 2002; Khan et al., 2004; Lognonné et al., 2003; Gagnepain-Beyneix et al., 2006; Weber et al., 2011; Garcia et al., 2011; Yamada et al., 2014). Continued analysis of this and other data sets keeps refining this picture and, as a consequence, our understanding of lunar structure and its implications for lunar origin and evolution (e.g., Nimmo et al., 2012; Grimm, 2013; Karato, 2013; Yamada et al., 2013; Khan et al., 2014; Pommier et al., 2015; Williams and Boggs, 2015).

InSight will land a single station including a 3-component broadband and short-period seismometer within Elysium Planitia with a nominal lifetime of 1 Martian year (~2 Earth years). For seismometer details see Lognonné et al. (2012), Mimoun et al. (2012) and Lognonné and Pike (2015). In addition to the seismic experiment, InSight will carry a probe for measuring heat flow, enable very high-precision measurements of the rotation and precession of Mars, a magnetometer for measuring the magnetic environment around the landing site including crustal and induced fields, and pressure and wind sensors (Banerdt et al., 2013). These data hold the potential of providing significant constraints on the interior structure of Mars much of which remains to be ascertained beyond the first-order picture that currently prevails (e.g., Longhi et al., 1992; Kuskov and Panferov, 1993; Mocquet et al., 1996; Smith and Zuber, 2002; Yoder et al., 2003; Neumann et al., 2004; Wieczorek and Zuber, 2004; Sohl et al., 2005; Verhoeven et al., 2005; Zharkov and Gudkova, 2005; Khan and Connolly, 2008; Rivoldini et al., 2011; Nimmo and Faul, 2013; Wang et al., 2013). From a physical point of view, this includes: 1) crustal structure and thickness; 2) mantle discontinuities; 3) core size, constitution, and state. From knowledge of these parameters, inferences on Mars' bulk chemical composition and thermal state can be drawn, which, in turn, are crucial for constraining its origin and evolution (e.g., Bertka and Fei, 1998; Khan and Connolly, 2008; Taylor, 2013).

Locating marsquakes with a single station is a challenging task as demonstrated by Panning et al. (2015), who tested single-station methods using terrestrial seismic data. Here, we build upon and extend this work by employing the single-station-single-event probabilistic location algorithm developed by Böse et al. (2016) in a purely Martian context. This method estimates source location and uncertainty from observations of surface-wave and body-wave arrivals and their polarization. Surface-wave dispersion data are automatically output as part of the algorithm, which are inverted in combination with body-wave travel time data for radial structure. We illustrate the methodology using two events with different source characteristics to highlight its ability of adapting to different conditions, i.e., data sets, for locating marsquakes.

This study is based on purely radial models and complexities related to anisotropy and three-dimensional structure, particularly in the crust and lithosphere, will undoubtedly complicate the simplified picture envisaged here. However, as the present study seeks to promote a methodology, second-order effects arising from e.g., lateral variations in structure are neglected here and will be the focus of forthcoming analyses. In what follows, the scheme is presented step-by-step, starting with the construction of models of Mars' internal structure, followed by computation of seismograms, including addition of noise, probabilistic marsquake location, and finally inversion for structure. The single-station-single-event probabilistic location algorithm is detailed in our companion paper (Böse et al., 2016).

2. Brief overview of joint location and interior structure determination

The scheme is outlined in Fig. 1 and is divided into four main stages that work as follows.

Input stage (white box): We construct a model of the interior structure of Mars (Section 3) to compute seismic waveforms (Section 4) for two representative events. Waveforms are combined with a realistic noise model (Murdoch et al., 2015a,b) to produce "real" (synthetic) Martian seismic data that form the input for our analysis. The input stage will be replaced with seismic data from Mars as these become available.

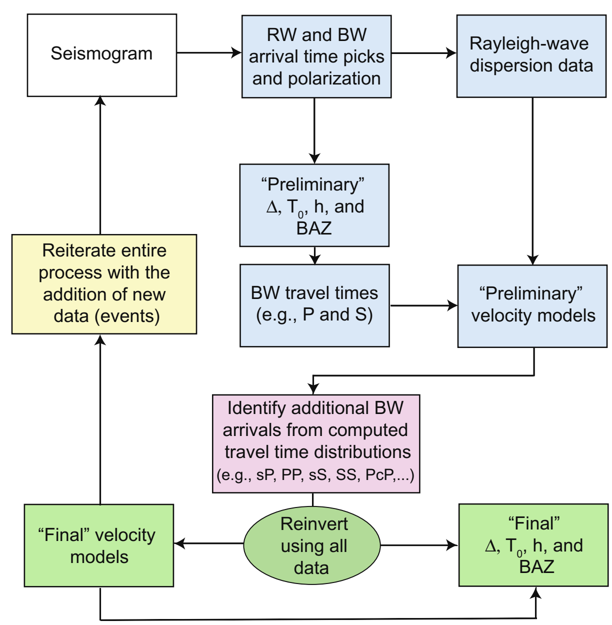

Fig. 1. Joint seismic event-location and structure-inversion scheme. The procedure is divided into four stages. Stage 1 (blue boxes): Rayleigh-wave (RW) and body-wave (BW) arrival time picks and polarization information are obtained from event data (seismogram) and used for "Preliminary" location (here epicentral distance Δ, origin time T_0, source depth h, and back-azimuth BAZ) determination. For large events both minor- and major-arc Rayleigh wave passages are considered, whereas for small events only the minor-arc surface wave passage is available. Dispersion data are obtained from the surface-wave arrivals and inverted in combination with body-wave arrival picks for a set of "Preliminary" models of interior structure. Stage 2 (red box): Using the "Preliminary" set of inverted models, travel time distributions for other seismic phases (e.g., crustal, depth or core-related phases) can be computed. These distributions can be used as an aid in identifying small-amplitude arrivals that are otherwise difficult to pick visually. Stage 3 (green boxes): Reinversion of refined/updated data set results in "Final" structure models and location estimates. Stage 4 (yellow box): The entire process works iteratively with the addition of new event data. See main text for further details. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this article.)