

CONSTRAINING MARS CRUST AND MANTLE STRUCTURE FROM WAVEFORM INVERSION OF FUNDAMENTAL AND HIGHER MODE SURFACE WAVES. C. Beghein^{1,2}, H. Xu¹, J. Irving³, M. Drilleau⁴, B. Kenda⁴, P. Lognonné⁴, N. Murdoch⁵, M. Panning⁶, M. Bose⁷, N. Brinkman⁷, S. Ceylan⁷, J. Clinton⁷, F. Euchner⁷, D. Giardini⁷, A. Horleston⁸, T. Kawamura⁴, A. Khan⁷, S. Stahler⁷, M. van Driel⁷, ¹Department of Earth, Planetary, and Space Sciences, University of California Los Angeles, 595 Charles Young Drive East, Box 951567, Los Angeles, CA 90095, USA (cbeghein@epss.ucla, htxu@ucla.edu), ²Visting scientist at Lunar and Planetary Institute, USRA, 3600 Bay Area Blvd., Houston TX 77058, USA, ³Department of Geosciences, Princeton University, USA, ⁴Institut de Physique du Globe de Paris, Paris, France, ⁵Ecole nationale supérieure de l'aéronautique et de l'espace, Toulouse, France, ⁶Jet Propulsion Lab, California Institute of Technology, Pasadena, CA 91109, USA, ⁷ETH Zürich, 8092 Zürich, Switzerland, ⁸School of Earth Sciences, University of Bristol, Queens Road, Bristol BS8 1RJ, UK

Introduction: One of InSight's primary objectives is to constrain the crustal and mantle structure of Mars. To achieve this goal, we plan to use long-period seismic waveforms recorded by InSight's seismometer, SEIS, and to measure the dispersion of the fundamental and, when available, the higher mode surface waves. The advantage of using surface waves lies in their dispersive properties. They thus have greater depth sensitivity to shear-wave velocity (V_s) structure than body wave travel times. While measurements of fundamental mode surface waves will help constrain the crust and the shallow part of the mantle, determining the dispersion of higher mode surface waves will provide additional and unique constraints on mid-to-deep mantle structure since they are sensitive to deeper structure than fundamental modes at the same periods.

Measuring higher mode dispersion is challenging because the different modes arrive at similar times on the seismogram and tend to overlap. One way to deal with this problem is by performing waveform modeling. To prepare for the mission, we tested our technique on a blind waveform data set generated by members of the Mars Structure Service (MSS) team. Here, we present our method, which is based on a reversible jump Markov Chain Monte Carlo (rj-MCMC) method [1] within a hierarchical Bayesian framework, and its application to the blind test data.

Method: Our method relies on waveform fitting of long-period fundamental and/or higher mode surface waves [2] and a Bayesian approach to represent the model parameters with posterior probability density functions (PPDFs). Synthetic seismograms are calculated in a fully non-linear manner by normal mode summation using a starting prior Mars model and Fortran code MINEOS [3] modified for Mars. New models are generated iteratively with a rj-MCMC method, and new synthetic seismograms are calculated for the models generated along the Markov Chains using perturbation theory. The rj-MCMC enables us to infer model parameters and model dimensionality, thereby letting the data themselves constrain the complexity of the model. The hierarchical nature of the technique allows the algorithm

to estimate unknown data noise in addition to the model parameters while being parsimonious, yielding models that are not too simple and not overfitting the data.

After convergence, our technique results in two outcomes: (1) PPDFs for V_s models of Mars interior that represent the average structure for the source-receiver path, and (2) fundamental and higher mode dispersion curves with uncertainties calculated from the V_s models. These can be seen as secondary data that can be inverted jointly with other datasets to further constrain Mars internal structure.

Application to Blind Data Set: A blind waveform data set was generated by members of the MSS team and distributed to the rest of the InSight science team in October 2018. The location, source parameters, noise level, and interior model were unknown to the rest of the team. The Mars Quake Service (MQS) team identified an event using this blind dataset, with a location estimated at 26°S latitude and 53°E longitude (Fig. 1). We used this event to test our algorithm. Since no clear higher modes were visible in the waveform at periods

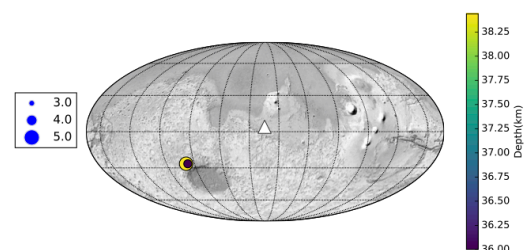


Figure 1. Triangle denotes SEIS location for the blind test. Yellow circle represents true location and M_w ; Dark circle is for MQS location and surface wave magnitude (M_sM) estimates. Magnitude and epicentral distance were later updated by the MQS using a Metropolis-Hastings algorithm.

above 25s, we decided to focus on the 25-50s period fundamental mode Rayleigh wave only.

Because waveform modeling requires knowledge of the source parameters, we employed the estimates of focal depth, moment magnitude, strike, rake, and dip made by the MQS with a Metropolis-Hastings algorithm fitting the first arriving P- and S-body wave coda. Those parameters were represented by PPDFs. We ran two sets of inversions: one for which we employed the mean values of these PPDFs as input for the source parameters, and one for which the strike, dip, rake, and scalar moment magnitude were allowed to vary uniformly around those mean values and within bounds based on the width of the PPDFs. For each case, we tested different starting models, including one with a lithospheric low velocity

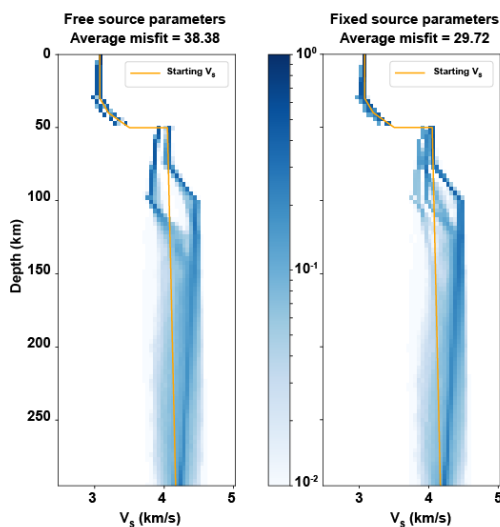


Figure 2. Resulting V_s models obtained when the source parameters vary (left) and are fixed (right).

zone (LVZ) [4]. The resulting V_s models and measured phase and group velocities were then compared (Fig. 2).

Our preliminary results showed that the measured data enabled us to constrain V_s down to 150 km depth. While we cannot constrain the source parameters and

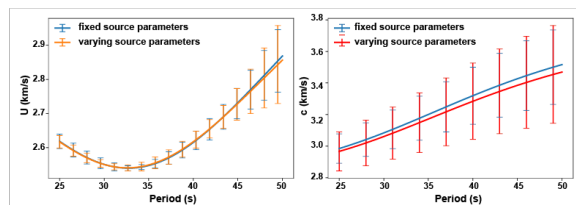


Figure 3. Group (left) and phase (right) velocities determined for the fundamental mode Rayleigh wave with and without source parameters included in the inversion.

trade-offs are visible between structure and source, the range of V_s models and corresponding group and phase velocities do not significantly depend on whether the source parameters are included in the inversion (Figs. 2 and 3). The presence of trade-offs between source and structure demonstrates that the inverse problem is highly non-unique and that it is important to include the source parameters among the unknowns to determine reliable posterior model uncertainties. This will be es-

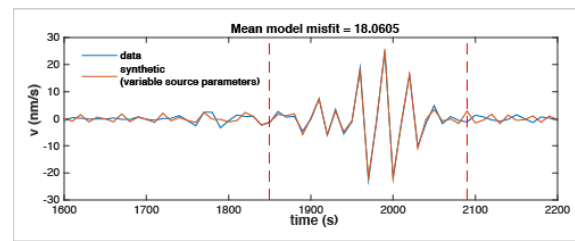


Figure 4. Waveform fit based on the mean model obtained when the source parameters are allowed to vary. The dashed lines represent the selected time-window. The waveform was filtered between 25s and 50s.

pecially important when dealing with real data as we may not always get reliable source parameter estimates.

Discussion: We tested our waveform fitting algorithm on blind test data and measured fundamental mode surface wave dispersion. The resulting group velocities and V_s models are in good agreement with those made by other InSight team members with other techniques. Our measurements, taken together with their uncertainties, do not depend on whether the source parameters inverted jointly with V_s . This is promising since source parameter may sometimes be difficult to obtain on Mars. While we were unable to detect overtones in the blind data set at the periods of interest, previous application of our technique to Earth data has allowed us to reliably measure the first few overtones and thus provide constraints on deeper mantle structure than with fundamental modes alone [2]. We are thus optimistic that we will be able to constrain deep Mars mantle structure if higher modes are detected by SEIS. Further tests will be performed to assess the detectability of such long-period higher modes on Mars.

References: [1] Bodin T., Sambridge M., Tkalčić H., Arroucau P., Gallagher K., and Rawlison N. (2012) *JGR*, 117, 1151–1154, B02301. [2] Xu H. and Beghein C. (2017), *Fall Meeting, AGU*, Abstract #S23A-2303. [3] Masters G., Woodhouse J.H., and Freeman G. (2011), *Computational Infrastructure for Geodynamics*, <https://geodynamics.org/cig/software/mineos>. [4] Zheng Y., Nimmo F., and Lay T. (2015) *PEPI*, 240, 132–141.