

PLANETARY SUBSURFACE EXPLORATION WITH SMART SEISMIC NETWORKS. W. Song¹, F. Li¹, M. Panning², S. Kedar², R. Weber³, C. Neal⁴, ¹University of Georgia, Athens, GA 30602, wsong@uga.edu, fangyu.li@uga.edu, ²Jet Propulsion Laboratory, Pasadena, CA 91109, mark.p.panning@jpl.nasa.gov, sharon.Kedar@jpl.nasa.gov; ³Marshall Space Flight Center, Huntsville, AL 35805, renee.c.weber@nasa.gov, ⁴University of Notre Dame, neal.1@nd.edu

Summary: We design a smart seismic network that can sense and compute planetary subsurface image and activity in-situ, providing 3-4 orders of magnitude reduction in data volume (e.g., 10 Gbit/sol to 10 Mbit/sol). This innovative approach and significant data reduction will have significant impacts that can (1) enable future science mission with a network of seismic instruments for high-resolution planetary subsurface exploration; (2) enable discovery of subsurface structures and activities of icy ocean worlds to constrain planetary evolution models and potential habitability.

Introduction: Subsurface imaging can map geological structures and monitor underground activities, shown in Fig. 1. The icy ocean moons of the outer planets are dynamic bodies of high interest for future science missions, which produce seismic waves. In particular, the moons Enceladus, Titan, and Europa all show signs of dynamic activity and potential for life. Observations of cryovolcanic plumes have been made for both Europa and Enceladus [1, 2]. Identifying these active processes and determining the subsurface location of liquid water are both excellent targets for planetary seismology. Cryovolcanic processes generate vibrations that can be detected by seismic instruments, while important subsurface structure on icy ocean worlds can be determined with seismic data.

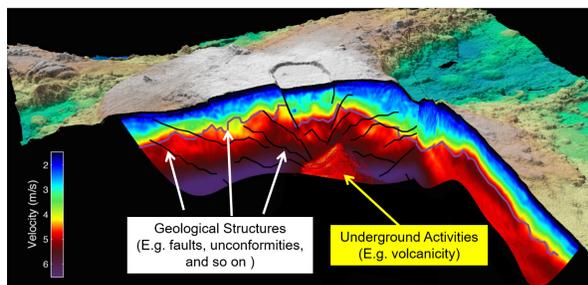


Fig. 1 Subsurface imaging can map geological structures and monitor underground activities.

In order to solve the complicated problem, we propose innovations and modifications to include: (1) a distributed ambient noise seismic imaging algorithm to image planetary subsurface structures and variations; (2) a distributed microseismic imaging algorithm to track dynamic planetary subsurface activities; (3) smart in-situ computing and networking software that integrates the aforementioned algorithms and self-adapts to the sensor network resource fluctuations.

We will demonstrate the system prototype in relevant environments and validate with synthetic planetary data sets for candidate worlds.

Methods: We design smart seismic network that can image planetary subsurface structure and activity in-situ in real-time. The proposed system computes subsurface structure and activity based on ambient noise imaging (Fig. 2) and microseismic imaging (Fig. 3) principles, respectively. It enables cost-effective delivery of key planetary subsurface features to earth and avoids costly raw data transmission over satellite links. We will develop and demonstrate a software system prototype in the laboratory emulation environment and validate with synthetic planetary data sets for candidate worlds.

Ambient Noise Seismic Imaging. Ambient Noise Seismic Imaging (ANSI) is particularly useful in resolving shallow earth structure [3], because the persistent nature of the seismic background noise, spatial and temporal variations of subsurface structure can be evaluated and monitored. Using this approach to determine internal structure in the ice shells of icy ocean worlds has high potential to return structure vital to understanding formation of features like chaos terrane, and assessing proximity of liquid water to the surface, which has been assessed as a vital science goal for addressing astrobiological potential.

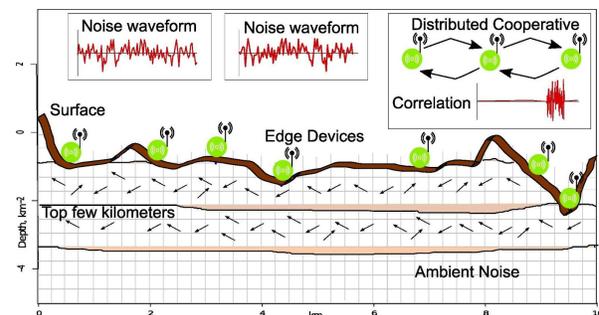


Fig. 2 Ambient noise seismic imaging process.

Microseismic Imaging. Microseismic monitoring is currently the most effective technique to track the geometry of stimulated fracture networks, shown in Fig. 3, which is analogous to icy world sources related to cracking from cryovolcanic processes. Recently, we proposed a Time-Reversal and Migration Imaging (TRMI) approach for microseismic imaging [4]. The key principle of TRMI is that the imaged hypocenters

must correspond to locations where all the wave-fields individually backward-propagated from each receiver coincide in both space and time, which is capable of producing high-resolution images of multiple source locations, even when signal-to-noise ratio (SNR) is low. On icy ocean worlds, the progress of cryovolcanic activity and fluid progress can be imaged and assessed through such systems, as well as locating anticipated frequent ice cracking events, which have potential for illuminating ice shell response to tidal cycling.

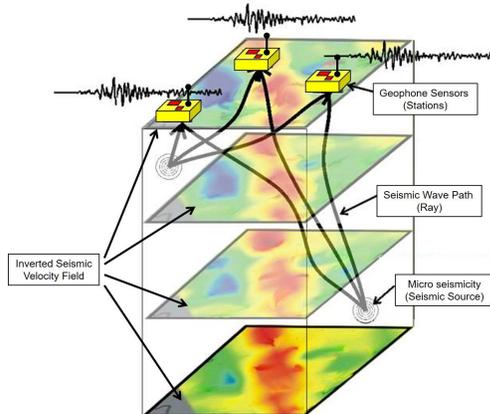


Fig. 3 Microseismic imaging process.

Integration. Some signal processing algorithms may be used on both ANSI and TRMI algorithms and the design will consider that and avoid duplicated tasks to improve the efficiency. In addition, they are also complementary as ANSI is for shallow subsurface static structure imaging while TRMI is for tracking dynamic subsurface microseismic events. TRMI requires an initial velocity model of the subsurface, which is hard to be optimal using the data from Earth, while ANSI can provide the velocity model based on body wave inversion from the surface wave data. Thus the proposed integration of ANSI and TRMI will be a nicely integrated subsurface image computing software, which is extremely valuable for science missions. In the event that the network and computing resources are severely limited in planet (because of limited energy supplies and significant harsh environment), the smart seismic network may self-adapt and scale back. For example, the ANSI can scale back to the spatial autocorrelation that calculates the 1D vertical velocity model under each smart seismometer, and TRMI can scale back to the classical beamforming approach for tracking source location.

Modeling synthetic planetary data. In order to demonstrate this approach will work in the relevant planetary environment, we need to create a synthetic planetary dataset of relevant signals and modeled noise. Recent work has enabled the creation of

thermodynamically self-consistent models for icy worlds [5], provided numerical tools for calculation and interpretation of seismic waveforms in icy ocean worlds [6], and modeling of continuous noise generation due to tidal ice-cracking events [7]. Using these, we can generate realistic datasets to test these networks in a virtual environment.

Conclusions: We propose to compute real-time seismic imaging through distributed in-situ computing algorithms, which largely avoids the logging and transmission of raw data from sensors. The sensor network has the ability to extract meaningful information from the raw seismic data at each node in real time, while minimizing radio bandwidth and energy consumption. For the scientific evaluation of distributed seismic imaging algorithm, we compare it with the result derived from centralized processing and the ground truth of synthetic data. Intermediate snapshot images of evolving features are saved and compared. We also scientifically evaluate the impact of the frequency of microseismic events on the ANSI and TRMI image quality.

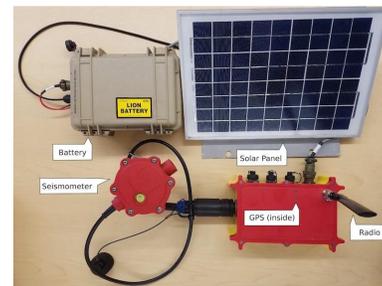


Fig. 4 Prototype Smart Seismic Node.

On hardware side, we have designed prototype smart node consisting of a geophone and a small box housing a processor and a low power communication device in Fig. 4 that can run the proposed software. Future hardware engineering will be required to minimize mass and power requirements for space mission, but transmission power requirements are naturally minimized as each sensor package only needs to be able to communicate with neighboring packages and not to any central hub, indicating this is a feasible path to future mission planning.

References: [1] Sparks W. E. et al. (2017) *ApJL*, 839, L18. [2] Waite J. H. et al. (2017) *Science*, 356, 155-159. [3] Lin F. C et al. (2008) *GJI*, 173, 281-298. [4] Sun J. et al. (2015) *SEG*, 2485-2490. [5] Vance, S.D. et al. (2017), *JGR*, doi: 10.1002/2017JE005341. [6] Stähler, S.C. et al. (2017), *JGR*, doi: 10.1002/2017JE005338, [7] Panning et al. (2017), *JGR*, doi: 10.1002/2017JE005332.