SHORT APERTURE SEISMIC ARRAYS ON ICY SATELLITES. N. C. Schmerr[1], E. Garnero[2], T. Hurford[3], V. Lekic[2], M. Panning,[4] A. Rhoden[2], H. Yu[2]. [1]University of Maryland, Department of Geology, College Park MD 20742 USA, nschmerr@umd.edu, [2]Arizona State University, School of Earth and Space Exploration, [3]NASA Goddard Space Flight Center, [4]University of Florida, Dept. of Geological Sciences.

Introduction: The icy moons of Europa and Enceladus are thought to have global subsurface oceans in contact with silicate interiors, and may host environments capable of providing the ingredients essential for life [1, 2]. Investigating the relationship between the sub-ice oceans and underlying silicate core require knowledge of ice thickness and liquid water depths. In a future lander-based experiments, seismic measurements will be a key geophysical tool for obtaining this critical knowledge. Here we present the advantages and capabilities to address these topics of a short aperture seismic array, defined as a multi-instrument seismic deployment with an aperture < 10 meters.

There are currently no measurements of the level of seismicity and ground motion occurring on Europa, so the required specifications of any deployed instruments must be derived from theoretical studies of the types of seismic signals that should be present [e.g., 3, 4, 5]. The most likely sources of seismic energy relevant for a lander mission are icequakes, caused by tidally induced motion along faults in the ice shell of Europa [6]. Icequakes are expected to efficiently radiate seismic energy in the realm of 0.1 to 100 Hz, with ground motions on the order of 10 $\mu m/s^2/Hz^{0.5}$ at 5° (~137 km) from a 5.0 moment magnitude (M_w) event [4].

Despite the relevant differences between terrestrial and Europan settings, Earth analog sites do exist with ice hundreds of meters to kilometers thick (compared to tens of kilometers on Europa) whose motion is influenced by diurnal tides and can serve as locations to study icequake seismicity [7]. Earth is host to many kilometer-scale regions of coexisting ice, water, and silicate material, thereby providing areas with the desired analog seismic contrasts. However, differences exist, with colder ice possessing lower attenuation (Q ~100), while warmer ice or ice closer to an ice-water interface has greater attenuation (Q ~10) [8]. It is therefore anticipated that attenuation will play a large role in the difference between Earth analog sites and Europa ice. Seismic waves traveling through water columns on either world should experience similar attenuation [9].

Methods: We demonstrated the science potential of a short aperture seismic array on an icy world in a pilot study conducted on the southeastern Greenland ice sheet [10]. This site is located approximately 40 km to the west of Helheim glacier, and overlies a shallow firn aquifer at 10-20 m depth [11] with 800-1200 m of ice to the glacier-bedrock interface (**Fig. 1**).

Experimental Design: The experiment used twenty-four 40-Hz vertical component geophones and a Geometrics ES-3000 multichannel recorder to log active source signals generated by swinging a 8-kg hammer into a half-inch thick aluminum plate. Active source experiments were necessary as the ES-3000 can only record 2 minutes of continuous seismic data at a 2 ms sampling rate. For this experiment, 17 test shots were recorded at 62.5 μs sampling rate over a 4 second duration.

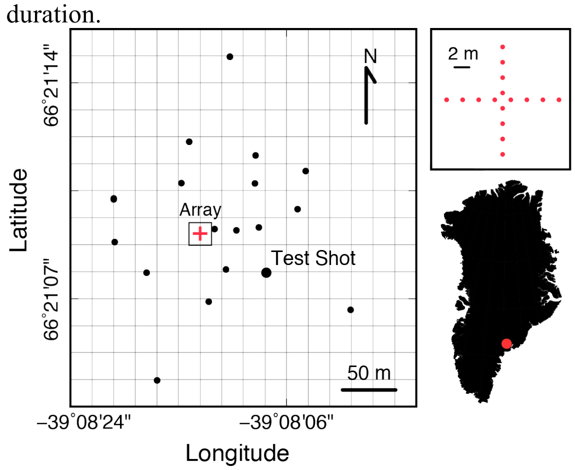

Figure 1. Location of the 2016 Greenland study region ~40 km upstream of the terminus of Helheim glacier (location shown in lower right; red dot). The geophone array geometry (upper right) and location of active source test shots (left) were designed to allow us to image ice properties with various short apertures and source distances.

Results: P-waves, S-waves and surface waves are visible in nearly all shots collected by the array. Unfiltered active source seismograms are shown in **(Fig. 2)** demonstrate the coherency of waveforms. Sources of noise were designed to be present in some of the test shots, including wind gusts of 10-15 kph, the operation of generators 100-150 m away, and sporadic episodes of cultural noise (people walking) during some shots. These are typically well below the source signal in the seismograms. Given the short recording durations, we did not detect any natural icequakes or glacial seismicity—monitoring over several days to weeks is needed to maximize detection of natural seismic events. We applied standard array processing techniques (backazimuth, vespagrams, polarization filtering) to the data to determine source locations and subsurface structure. The short aperture array could accurately reconstruct the ray parameter and backazimuth of incoming P and S waves, locate sources within 5-10 meters of the actual location, and determine the near surface velocity of the waves [10].

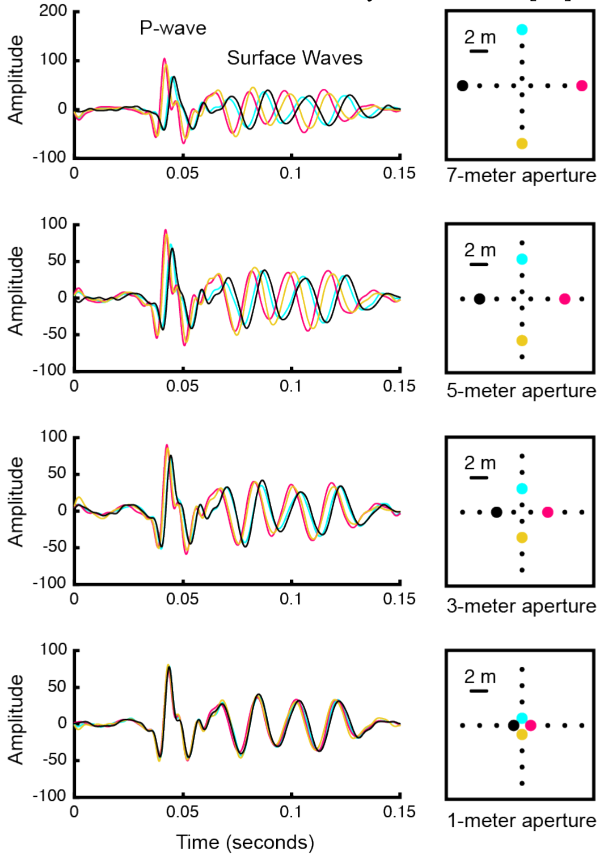

Figure 2. Seismograms recorded at the short aperture array in Greenland. The geometry of the array is indicated to the right and seismic waveforms to the left. Color is used to indicate corresponding station and waveforms.

Modeling: We demonstrate the efficacy of a short aperture seismic array through high frequency synthetic seismograms calculated for both 1-D velocity structures using the reflectivity method [12] and for 3-D structures using Serpentine Wave Propagation [13] **(Fig. 3)**. In each modeling scenario, we implement simple background structures with ice overlying water and/or rock, as appropriate for each field locale. The resulting synthetic seismograms are then processed identically to the data. This allows us to construct predictions for background models of varying thicknesses of ice overlying water and rock that could be recorded by a short aperture array on Europa [e.g., 14]. From our modeling we can draw several recommendations for future Europa seismic missions. For example, the large ice thickness beneath the array is best determined at shorter epicentral distances where the surface waves do not overlap with ice reflections. Another prediction is that the short aperture array can also be used to identify body waves from surface waves given their large differences in slowness – this analysis would be difficult with only a single 3-component station.

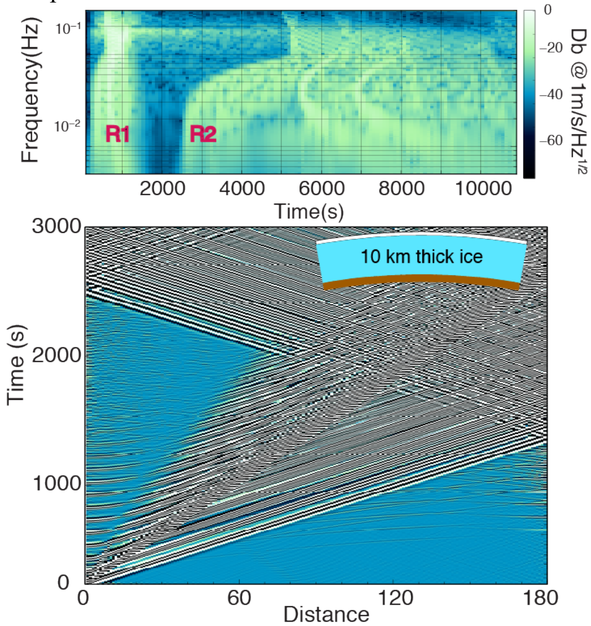

Figure 3. Simulated seismic waves within a 10 km thick ice shell overlying a liquid ocean. The top panel is a spectrogram for a station 500 km from the source and shows the expected surface wave orbits. The lower panel shows the expected waveforms, including a number of ice-water interface reverberations.

Conclusions: Short aperture seismic arrays deployed on the legs of a 2-3 m wide spacecraft would improve the science return of a single lander mission to the surface of an icy world. The arrays can be used to independently identify and locate seismicity, distinguish key body wave and surface wave arrivals, and provide the local properties ice of the near surface.

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