THE EUROPA SEISMIC PACKAGE (ESP) CONCEPT: 1. SELECTING A BROADBAND MICROSEISMOMETER FOR OCEAN WORLDS. W. T. Pike[1], I. M. Standley[2], S. Calcutt[3], S. Kedar[4], S. D. Vance[4], B. G. Bills[4], [1]Dept. of Electrical and Electronic Engineering, Imperial College, London, UK, [2]Standley Technology Consulting, Claremont, CA, [3]Dept. of Physics, Oxford University, UK, [4]Jet Propulsion Laboratory, Caltech, Pasadena, CA w.t.pike@imperial.ac.uk

Introduction: NASA is currently studying a potential Europa lander mission with instrumentation required to be ready within 3-4 years. The mission would search for life and habitability by probing and analyzing the chemistry of the surface ice in pursuit of evidence for microbiological markers. The Europa Lander concept and subsequent Ocean Worlds landers would also carry seismometers to map the shallow and deep interiors of the moons, which hold the keys to understanding their planetary evolution, their thermal and chemical make-up, and thus their long-term habitability. We summarize the instrument requirements that would enable a seismic system to provide a probe of the habitability of Europa and introduce a candidate microseismometer for a Europa Seismic Package (ESP) concept that meets those requirements, comparing to potential competitor technologies.

Seismology as a Probe of Habitability: Sensitive seismometers are critical for detecting faint motions deep within planetary bodies that can be used to reconstruct composition and temperature structure, while also revealing fundamental processes such as plate and ice tectonics, volcanism, ocean waves, ice flow, geysers and more. Moreover, a seismometer for Europa and other Ocean Worlds will listen for the moons' distinct "vital signs": fluid motion in the shallow subsurface, cryovolcanos, and sub-glacial ocean circulation (Fig. 1).

Prior investigations [1, 2, 3, 4] have considered primary seismic sources, their likely occurrence rates and magnitudes, and how they might be used to measure the thickness of the ice shell and underlying ocean. Europa's internal structure controls its prospects for life by governing the cycling of redox materials, which is key to habitability [5]. A hot metallic core or silicate melts [6] would be strong evidence for an active interior [e.g., 3] and of continued hydrothermal activity producing hydrogen and other electron donors needed to sustain chemical energy for life. The amplitude and frequencies of these expected sources in plotted in Fig. 1.

The SP microseismometer: The measured noise floor of the microseismometer that was successfully delivered to the InSight Mars 2018 mission is also shown in Fig. 1, demonstrating sufficient sensitivity to detect a broad range of Europa's expected seismic activity. While this seismometer is designated as "short period" (in comparison to the CNES-designed very broadband (VBB) seismometer), the SP provides a sensitivity and dynamic range comparable to significantly more massive broadband terrestrial instruments. The sensor is micromachined from single-crystal silicon by through-wafer deep reactive-ion etching to produce a non-magnetic suspension and proof mass with a resonance of 6 Hz [7].

The SP is well suited for accommodation on a potential Europa Lander. It is robust to high shock (> 1000 g) and vibration (> 30 g_{rms}). For qualification SP units have undergone the full thermal cycles of the InSight mission and noise tested down to 208K, with no degradation in the performance in both cases. In addition, the sensor has been tested as functional down to 77K, below the lowest expected temperatures on Europa. All three axes deliver full performance over a tilt range of ±15° on Mars, allowing operation on Europa without leveling. The SP operates in feedback automatically initiated with power on of the electronics, achieving a noise floor

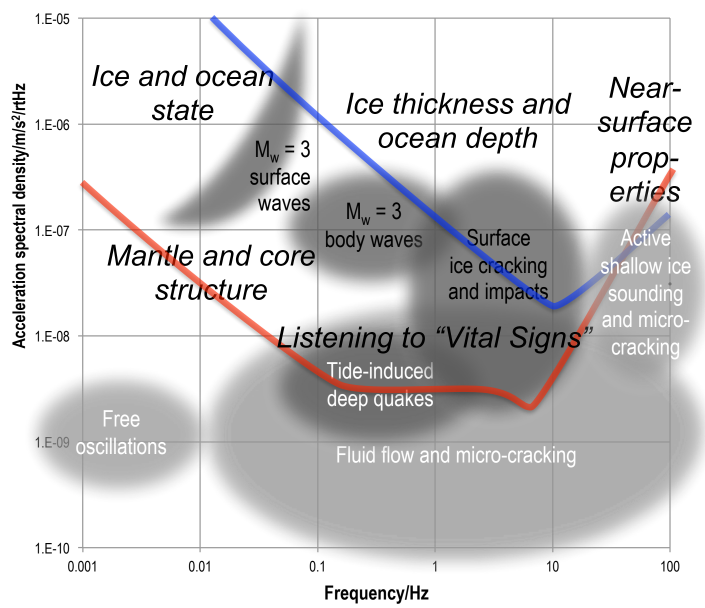

Figure 1: Europa is expected to be seismically active *[2,4] requiring a sensitive, broad-band, high-dynamic-range seismometer such as the SP (red). The expected sources are located in their relevant frequency and amplitude ranges, based on Earth analog (black text) and models (white text), with italicized text indicating the science investigations that are enabled by recording these sources. The sensitivity of a 10 Hz geophone is shown in blue for comparison.*

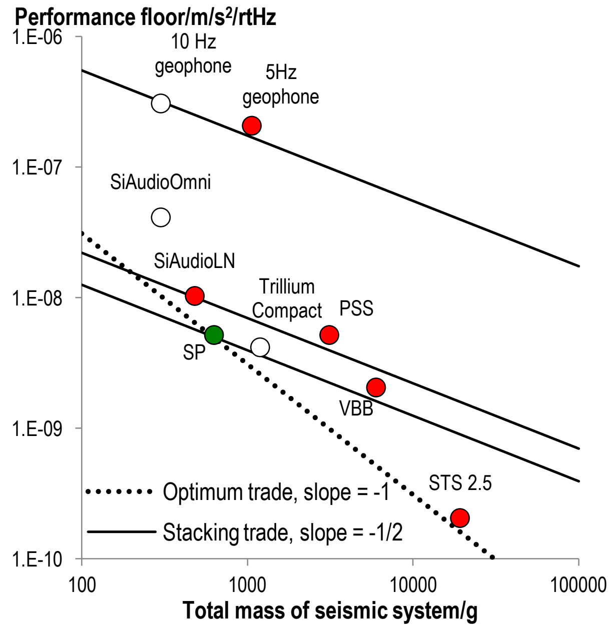

Figure 2: Comparison of sensor performance/mass parameter space. *The SP is the most mature and best suited for Europa: it is the only non-magnetic seismic system delivered for flight (marked in green), with most comparators also requiring leveling (marked in red).*

below 1 ng/√Hz in less than a minute. The total mass for the three-axis SP delivery is 635g while the power requirement is 360 mW.

Comparative Technology Assessment: We have compared the SP with a variety of other possible seismic technologies in terms of performance (noise floor), mass and power:

- Conventional 10 Hz (Fig. 1) and 5 Hz geophones (noise data from [8])
- Two optically sensed miniature seismometers, one requiring tilt [8]
- A geophone developed in Japan for a lunar penetrator, PSS [9]
- A conventional broad-band seismometer, the Trillium Compact [10]
- The Streckeisen STS 2.5, a high sensitivity seismometer with performance designed to match the lowest ambient noise floor of Earth [11]
- The CNES VBB under development for InSight 2018 [12]

The noise floor accounts for the peaked response of the geophones by selecting the lowest noise sensitivity at the extremes of a frequency bandwidth of two orders of magnitude. The mass requirements are estimated for a three-axis seismic system. If the sensor requires tilt under Europa gravity, an additional 75% is added for the mechanism, based on the InSight VBB system. The critical trade for these seismic systems is between performance and mass as their power budgets are comparable. The relationship between these two parameters (fig. 2) gives the general trend of the instrument locations, with a slope of ~ -1. The SP has the highest figure of merit: compared to its nearest neighbors it has twice the performance of the non-flight Silicon Audio Low Noise, 50% the mass of the non-flight Trillium Compact, and 20% the mass of the PSS. Geophones fare poorly in this trade, with lower performance without any mass advantage. One option to improve performance is to use multiple, n, units to push down the noise by $\sqrt{n}$. However, this comes at an increase of n in the mass and hence such "stacked" systems will be distributed along lines of slope -1/2, pushing them away from the optimal trade line.

Two other critical parameters for selection are the deployment and calibration requirements, and the technology maturity. Leveling requires additional mass and more complicated deployment, and introduces additional failure modes, some of which may be hard to predict in the Europa environment. The SP does not need leveling unlike most other competing technologies. It also requires no magnetic calibration from additional sensors, unlike all its comparators. These are important advantages given the strong slopes [13] and variable magnetic environment at Europa [14]. Finally, only the SP has the fully flight-qualified heritage.

Conclusion: The SP stands out as the strongest candidate for development for a Europa payload. We are now adapting its design to meet the environmental challenges of Europa.

Acknowledgments: A portion of this work was funded by the UK Space Agency, and a portion performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA. U.S. Government sponsorship is acknowledged.

References: [1] Kovach & Chyba. (2001) *Icarus*, **150**(2):279– 287 [2] Lee et al. (2003), *Icarus* **165**, 144–167 [3] Cammarano et al. (2006) *J. Geophys. Res.,* E12009 [4] Panning et al. (2006) *J. Geophys. Res.*, E12008 [5] Vance et al. (2016) *Geophys. Res. Lett.*, **43**, 4871–4879 [6] Chantel et al. (2016) *Science Advances*, **2**, 5, e1600246 [7] Pike et al. (2013). *Proc. Transducers & Eurosensors XXVII,* 622-625 [8] http://www.siaudio.com/uploads/common/10-15-SA-product-flyer-updates-v2.pdf [9] Yamada et al. (2009) *Planetary Space Science* 57, no. 7: 751-763 [10]http://www.nanometrics.ca/ckfinder/userfiles/files/NMX-TrilliumCompact-%20WEB.pdf [11] http://www.kinemetrics.com/uploads/PDFs/STS-2_5.pdf [12] Robert et al. (2012) *LPSC*, vol. 43 2025 [13] Schenk (2009) *Geophys. Res. Lett.*, 36(15):L15204 [14] Kivelson et al. (2009) *Europa*, ISBN: 9780816528448, 545-570.