A MAGNETOTELLURIC SOUNDER TO PROBE TERRESTRIAL PLANET AND SATELLITE INTERIORS. R. E. Grimm[1], G.T. Delory[2], J.R. Espley[3], D.E. Stillman[1], and EMS/LMS Teams, [1]Southwest Research Institute, 1050 Walnut St. #300, Boulder, CO 80302 (grimm@boulder.swri.edu), [2]Heliospace Corp., 932 Parker St. #2, Berkeley, CA 94710, [3]Goddard Space Flight Center, Code 695, Greenbelt, MD 20771.

Introduction. Electromagnetic (EM) sounding of the Earth, Moon, Galilean satellites, and Mercury has yielded important insights on the interior structures of these bodies [e.g., 1-10]. Extraterrestrial investigations have measured magnetic fields only and required auxiliary information on the nature of the source fields. The magnetotelluric (MT) method, by measuring both magnetic and *electric* fields, can perform soundings from a single platform, without separate information on source fields. MT requires only modest resources, can sense to depths of tens to hundreds of km, and can image through conductors. We are developing MT instrumention for Europa and lunar landers (pre-Phase A/ICEE-2 and flight/LSITP, respectively) and the same technology can be used on Mars and elsewhere.

Principles of MT. Time-varying natural or artificial EM fields induce eddy currents in planetary interiors, whose secondary EM fields are detected at or above the surface. These secondary fields shield the deeper interior according to the skin-depth effect, so that EM fields fall to 1/e amplitude over depth δ (km) = $0.5\sqrt{\rho/f}$, where ρ is the resistivity and f is the frequency. EM sounding exploits the skin-depth effect by measuring the complex impedance Z over a range of frequency to reconstruct resistivity over a range of depth [11,12]. Natural EM signals (waves in the solar wind, magnetospheric pulsations, ionospheric currents, lightning) are used instead of transmitters at the low frequencies necessary to penetrate kilometers to hundreds of km into the Earth.

MT uses orthogonal horizontal components of the local electric (E) and magnetic (B) fields to form $Z_{xy} = \mu E_x/B_y$ [13,14]. The subscripts are exchanged for Z_{yx}; together, these tensor components can map heterogeneity or anisotropy. Although several different methods are suitable for planetary deep-sounding measurements [see refs. 15, 16 for review], only MT can perform a complete sounding from a single station, without any supplementary source-field information. Multiple stations (e.g., a network) can assess lateral heterogeneity. MT is largely insensitive to changes in source-field structure introduced by plasma [15].

Instrumentation. MT requires vector measurements. Both fluxgates and searchcoils are used for B-field measurements, with the former generally used for low frequencies and the latter for high frequencies. The vertical component of B (magnetic tipper) is also useful in assessing heterogeneity. Because the magnetic-field amplitudes are not strongly affected by the subsurface, the source-field strength can be used to determine the magnetic-sensitivity requirement. This will typically be several pT near 1 Hz. On Earth, E-field measurements are galvanically coupled using conductive electrodes embedded into the ground, but the dry, resistive surfaces of other worlds calls for novel approaches. Many extraterrestrial environments have atmospheres or plasma environments with higher conductivity than the terrestrial atmosphere, enabling high input impedance active probes to measure the electric fields directly on the surface. Similar measurements have already been demonstrated on countless stratospheric balloons and on satellite space-physics investigations. On a planetary surface, this is analogous to seafloor MT, where the electrodes are embedded in a highly conductive medium over a more resistive interior. In the extreme case of negligible plasma, purely capactive measurements can be obtained with some sacrifice in low frequency performance. E-field sensitivity requirements ~μV/m near 1 Hz can be derived from E=cB, where c is the frequency-dependent effective propagation velocity determined by the subsurface structure.

Compact magnetometers can accomplish the measurement requirements for planetary exploration, so they can be easily deployed by a mast or boom to provide noise-reducing standoff from the lander. The electric-field measurements are made between pairs of electrodes on the surface, with signal-to-noise increasing with electrode separation. We have determined that 10-20 m separation is sufficient for planetary applications. Because this exceeds the reach of a boom, we have developed a spring-launched wireline mechanism to deploy the electrodes from the lander.

Europa. We have just completed a TRL 6 prototype for a Europa Magnetotelluric Sounder (EMS) under NASA COLDTech sponsorship. This system comprises central electronics, two remote-deployable electrodes, and a magnetometer on a mast. We performed functional data-acquisition testing (**Fig. 1**) and separately tested the deployments under Europa conditions. This protype is the basis for new development under ICEE-2, a pool of instruments selected for pre-Phase A development for a Europa Lander [17]. The updated EMS will requalify to TRL 6 but now incorporate 3 electrodes, robust cabling, and improved electronics.

The high sensitivity of EM sounding to saline water enabled the discovery of the Europa subsurface ocean [8], but a key Lander requirement is to detect any liquid water within 30 km—which could include dikes, sills, or diapirs within the ice shell. The source-field geometries at the higher frequencies needed for this shallower sounding would be unknown from a lander magnetometer alone, and comparision to an orbital magnetometer—if one was available—would be fraught with plasma effects. MT can readily achieve this goal [18].

Moon. EM sounding of the Moon has placed upper limits on core size, determined the abundance of free iron in the upper mantle, and constrained the mantle temperature structure and global thermal evolution [e.g., 3-7]. However, these inferences were made using an orbital-to-ground comparison at the Apollo 12 site, which lies within the anomalous Procellarum KREEP Terrane (PKT, ref. 19). Sounding outside PKT can determine if PKT has a hot or cold mantle [7], thus constraining the lateral differentiation of the Moon. Furthermore, MT has higher bandwidth, allowing shallower probing in the uppermost mantle. The Lunar Magnetotelluric Sounder (LMS) (**Fig. 2**) has been selected for flight under the NASA Lunar Science and Instrument Technology Payloads (LSITP) program. We have teamed with the heat-flow experiment [20] to request a landing site that is outside PKT, can be related to prior geophysical experiments, and is suitable for drilling. Mare Crisium is flat, has regions of thick regolith, and lies on a great circle to the Apollo 15 and 17 sites, where heat flow was previously measured. The mission is scheduled for 2022.

Mars and Venus. Prior work [21] enabled development of MT to TRL 4 for planetary exploration. On Mars, MT can determine the depth and salinity of groundwater to tens of kilometers depth [15]. The thickness of the cryosphere is an indicator of thermal gradient. On Venus, MT from a balloon may address the thickness of the lithosphere and its influence on geodynamical evolution, the thickness and differentiation of the crust, and the water content of the mantle [22].

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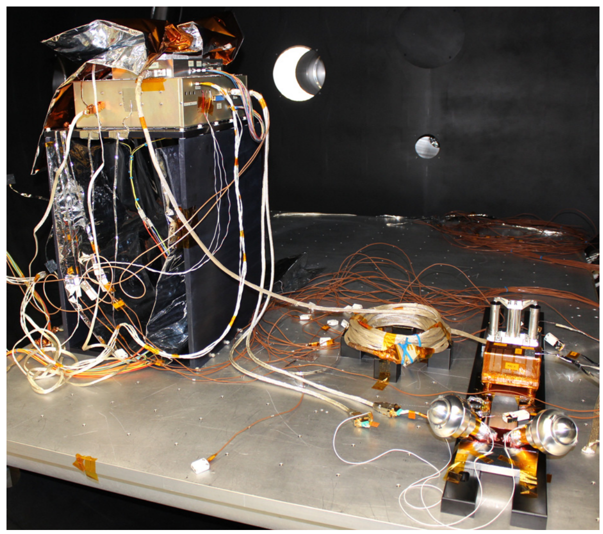

Fig. 1. Europa Magnetotelluric Sounder (EMS: COLDTech prototype) prepared for TVAC functional tests. Baseplate is held at Europa surface temperature and electronics (upper left) at vault temperature. Two electrodes are at lower right; magnetometer is separated from mast at middle right; all mechanisms undeployed.

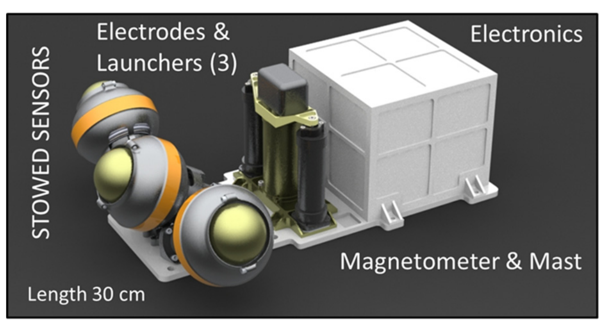

Fig. 2. Lunar Magnetotelluric Sounder (LMS) as proposed to LSITP. Flight version may add 4th electrode and distribute electrodes azimuthally around lander. EMS configures electrodes and magnetometer similar to figure, but electronics are in lander central vault.