MEASUREMENT OF THE THERMAL LITHOSPHERIC THICKNESS OF VENUS USING AERIAL ELECTROMAGNETIC SOUNDING. R.E. Grimm[1], A.C. Barr[1], K.P. Harrison[1], D.E. Stillman[1], K.L. Neal[2], M.A. Vincent[2], and G.T. Delory[3], [1]Department of Space Studies, [2]Department of Space Systems, Southwest Research Institute, 1050 Walnut St. #300, Boulder, CO 80302 (grimm@boulder.swri.edu), [2]Space Sciences Laboratory, University of California, Berkeley, CA 94720.

Introduction. Electromagnetic (EM) sounding has been widely used to reveal Earth structure from depths of meters to hundreds of kilometers and has also probed the deep interiors of the Moon and the Galilean satellites [see summary and refs in 1,2]. The *magnetotelluric* [MT: 3,4] and *wave-tilt* [WT: 5,6] methods enable natural-source soundings from a single platform. With lightning on Venus confirmed [7,8], the Schumann resonances are ready sources of EM energy that can penetrate tens of kilometers or more into the relatively dry interior, where electrical conductivity is sensitive to variations in temperature, and hence lithospheric structure. Properties of the ground-ionosphere waveguide allow subsurface conductivity to be inferred from the nominal 55-km altitude of a Venus balloon, after an ionospheric correction. Aerial EM sounding therefore can reveal a fundamental property controlling the geodynamics of Venus [9].

EM Sounding exploits the skin-depth effect by using measurements over a range of frequency to reconstruct resistivity over a range of depth [e.g., 3,4]. The response can be expressed as the apparent resistivity ρ_a, the resistivity of an equivalent halfspace. (Resistivity is the reciprocal of conductivity and is often preferred in geophysics because of its dimensional relation to impedance).

The conductive ionosphere precludes a solar-wind transfer-function approach using simultaneous orbital and near-surface measurements (although interplanetary coronal mass ejections may provide large, discrete signals [10], we seek continuous, reliable, subionospheric sources). To be complete using a single subionospheric platform, either the orthogonal horizontal electric E_{xy} and magnetic B_{yx} fields (MT) or the horizontal E_{xy} and vertical electric E_z fields (WT) must be measured. In both cases, properties of the ground-iono-sphere waveguide are exploited (see below) in which E_{xy} is the induced field containing the information on the subsurface and either B_{yx} or E_z is a reference field related by $E_z = cB_{yx}$, where c is the speed of light. Specifically, $\rho_a = (\mu_0/\omega)(E_{xy}/B_{yx})^2 = (1/\varepsilon_0\omega)(E_{xy}/E_z)^2$, where ω is the angular frequency and ε_0 and μ_0 are the free-space permittivity and permeability, respectively.

Whether E_z or B_{yx} is measured is a matter of sensor performance and local environment, but E_{xy} must be measured. This requires AC (capacitive) coupling in the resistive atmosphere of Venus, which in turn demands low amplifier input capacitance or high sensor capacitance.

Source and Waveguide Properties. The Venus Express magnetometer recorded bursts of field-aligned, circularly polarized energy that are consistent with whistler-mode lightning vertically refracted through the ionosphere [7,8]. The global lightning rate is inferred to be ~18/sec, or ~20% of Earth's. This will excite global interference patterns within the ground-ionosphere waveguide: the Schumann resonances. The fundamental resonance for Earth is at 8 Hz and for Venus is predicted to be 8-11 Hz [11-13]; harmonics lie approximately at multiples of $\sqrt{n(n+1)}$ [e.g., 14].

The Schumanns are transverse electromagnetic (TEM) waves that propagate *nearly* straight along the waveguide with Poynting vector $P_x = E_zB_y/\mu_0$. There is leakage because the boundaries are not perfect conductors. This is the origin of the horizontal electric field, with $E_x > 0$ near the surface tilting the wave into the ground, and $E_x < 0$ near the ionosphere tilting the wave upward. E_x at any altitude is a simple linear interpolant of the signed electric fields at the boundaries. Using the apparent-resistivity formulae above, the square root of the measured apparent resistivity $\sqrt{\rho_a^{meas}}$ is a linear interpolant between $-\sqrt{\rho_a^{iono}}$ and $+\sqrt{\rho_a^{ground}}$.

Because the variation of E_x is "locked" by the waveguide boundaries, sensitivity of TEM waves to the ground does not fall off sharply with altitude as occurs for vertically incident plane waves or higher-order TM modes. This also means that lateral resolution is comparable to the skin depth in the ground regardless of altitude, here, several tens of km.

We have confirmed these behaviors of leaky TEM waves analytically for constant-resistivity boundaries and numerically for continuous variations of resistivity in both the ground and ionosphere (Fig. 1).

Measurement Simulation. We have developed an analytical model for the recovery of subsurface resistivity as functions of instrument performance, altitude, and variations in the ionosphere. Here two WT sensor systems are considered: small (m-scale) using conventional booms and, large (10-m scale) using a novel design for incorporating electrodes into the balloon hull. This improves the E-field SNR by 20-100x.

A temperature-dependent, Newtonian-viscosity convection model [15] is used to develop physically plausible variations in lithospheric thickness about a mean. The ground conductivity as a function of depth

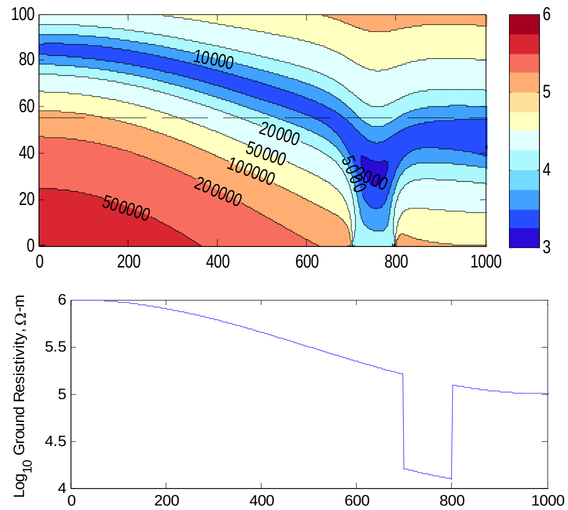

Fig. 1. Numerical model [23] of 10-Hz EM response (apparent resistivity, ρ_a) measured in the Venus atmosphere (log colorscale with contours in Ω-m). Variation in ground resistivity is illustrative of range derived from convection models, with an arbitrary 10x contrast superimposed (e.g., crustal plateau) to illustrate lateral resolution. Ionospheric resistivity is constant. Surface and ionobase (120 km) ρ_a closely track those media; apparent resistivity in atmosphere is a linear interpolant of signed $\sqrt{\rho_a}$ of boundaries and so experiences a null (blue band). Dashed line indicates 55-km balloon altitude. Interaction with ground can be detected at all points on this 1000-km profile.

(temperature) is specified from laboratory measurements of olivine with variable water content [16]. We consider endmembers of 0 and 5 ppm H_2O [17,18]. We optionally allow for a 30-km crust [19] with 10x higher conductivity. The vertical profile of ionospheric conductivity and the noon-to-midnight variation follow [13]; we take the mean conductivity profile but superimpose factors of two error in both random uncertainty (short wavelength or timescale) and bias (long wavelength or timescale). Plane-wave impedances [20] are used to calculate ρ_a^{ground} and ρ_a^{iono} for the first four Schumann resonances. The ionospheric bias is applied and $\rho(z)$ is derived from $\rho_a(\omega)$ using a simple asymptotic inversion [21]. For these preliminary models, instrument and random-ionospheric errors are propagated analytically [22].

The Schumann penetration is greatest, and recovery of subsurface conductivity is most robust, if the interior of Venus is dry. In this case, lithospheric thickness can be inferred to within ~20% when simultaneously inverting for the conductivity law and temperature gradient. A conductive crust has no effect if the Schumanns penetrate well through it. A "wet" mantle (several ppm H_2O) will "short-circuit" the sounding depth and can only recover lithospheric thickess in the absence of a conductive crust and iono-

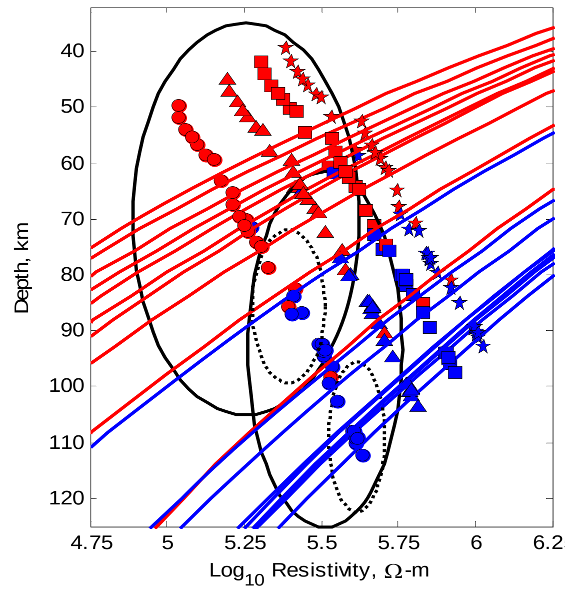

Fig. 2. Simulation of Venus aerial EM sounding. Red curves are dry resistivities from random sampling of temperature-dependent Newtonian convection model with Ra = 10^4 (250-km conductive lithosphere). Blue curves are Ra = 10^3 (360-km lithosphere). Symbols are recovered resistivity-depth using the first 4 Schumann resonances. There are 2 points per line to incorporate x½ to x2 unknown conductivity range of ionosphere. Representative error ellipses for fundamental Schumann are for nominal compact electrometer (solid) and for balloon-hull electrometer (dotted). Averaging over many individual soundings yields mean thermal gradient (lithospheric thickness) to within ~20%. 30-km conductive crust has no effect here because Schumanns penetrate much deeper.

spheric biases. These results would nonetheless indicate the presence of water in the Venus interior.

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