

LUNAR INTERIOR PROPERTIES DERIVED FROM REANALYSIS OF APOLLO 12–EXPLORER 35 MAGNETIC TRANSFER FUNCTIONS. R.E. Grimm¹, ¹Southwest Research Institute, 1050 Walnut St. #300, Boulder, CO 80302 (robert.grimm@swri.org).

Introduction. Electromagnetic (EM) sounding of the Moon has placed upper limits on core size, determined the abundance of free iron in the mantle, and constrained the mantle temperature structure and global thermal evolution [e.g., 1-10]. All used the magnetic transfer function (TF) between the distantly orbiting Explorer 35 satellite and the Apollo 12 Lunar Surface Magnetometer in order to separate the frequency-dependent induced fields and solve for the electrical-conductivity profile of the interior. The most successful prior studies used a dataset [3,6] restricted to <1 mHz, so the lunar response could be modeled as a simple dipole. However, earlier efforts [1] produced data up to 36 mHz. The smaller electromagnetic skin depth at higher frequency would better resolve the uppermost mantle—where key information about early lunar evolution may still be preserved—but requires a multipole treatment.

I computed new profiles of electrical conductivity vs depth using the full bandwidth (0.01-36 mHz) of published Apollo-Explorer TFs. I derive a temperature profile at depths >400 km (<1 mHz) consistent with conductive heat loss and material properties within expectations of the iron (and possibly water) content of the mantle. In contrast, the full-bandwidth analysis produced a different conductivity profile that could not be realistically matched by conduction, convection, or partial melting. I conclude that the TF method at the Moon should be avoided >>1 mHz. Future EM sounding using the magnetotelluric (MT) method [11-13] can operate up to 100s Hz and is largely insensitive to multipole effects, resolving structure as shallow as 10s km.

Background. EM sounding was performed using the magnetic transfer function (TF), which compared the field at the surface (Apollo 12) to a distant reference (Explorer 35) (see [5] for a review). This is the ratio of the source+induced fields to the source field, from which the induced field and thence conductivity can be derived. The datasets treated here were obtained with the Moon in the solar wind and in particular use the transverse component in the colatitude direction with respect to the solar wind.

Hood et al. [3] produced the definitive “low-frequency” (LF) transfer-functions 0.01-1 mHz (the tabulation in [6] is most useful). However, Sonett et al. [1] previously reported TFs at “high frequency” (HF) 0.5-36 mHz. While the low-frequency data [3] have been analyzed for interior structure by several groups, the high-frequency data [1] have mostly languished. These data are potentially valuable because they probe to shallower depths.

Method. The TF “ A_{\min} ” in [1] was digitized, smoothed, and shifted by 0.4 to best match the LF TF [3] in the overlap region 0.5-1 mHz. The transfer function (**Fig. 1**) increases with frequency due to increased screening by eddy currents and solar-wind compression. When the wavelength of the plasma turbulence is comparable to the lunar radius (several mHz), the response can no longer be described as a simple dipole; multipoles cause the HF rollover of the TF.

The transfer functions were modeled using the multipole theory of lunar induction in the solar wind [14]. This theory is an approximation to the asymmetric confinement of induced fields experienced by the Moon in this environment. Multipoles to $n=3$ were treated. For $n>1$, the solar-wind velocity v and incidence colatitude θ must be specified. These parameters were set by trial-and-error to $v = 200$ km/s and $\theta = 150^\circ$, which agreed with the best inversion solutions of [1].

Monte Carlo inversions were carried out separately for HF and for all frequencies (AF). Each TF was sampled 45 times using a normal error distribution. Inversion for depth-dependent electrical conductivity $\sigma(z)$ from the frequency-dependent transfer functions was performed using the Levenberg-Marquardt method as implemented in Matlab® `lsqnonlin`. The conductivity was constrained to increase monotonically at 50-km intervals: spatial regularization was not required with this approach. **Fig. 1** plots the 68th percentile (approx. 1 std. dev.) error bounds on conductivity for the separate LF and AF inversions.

The depth limits of the inversions are truncated at 0.6 of the EM skin depth at the upper and lower frequency limits. This follows from combined theoretical and empirical limits in asymptotic inversion studies [15]. Some information can be gleaned deeper (say up to the maximum skin depth), but the minimum depth must be enforced as any shallower structure would require higher frequencies to resolve internally. The depth limits are 200-1200 km over the full 0.01-36 mHz bandwidth and 400-1200 km <1 mHz.

Results. The LF conductivity increases smoothly with depth and can be fit well to the function $\sigma[\text{S/m}] = 1.76 \times 10^{-4} \exp(z[\text{km}]/210)$ ($r^2 = 0.994$). While broadly in agreement with several prior studies [2,3,8], it closely matches the mean profile of Khan et al. [9]. I emphasize that both this result and [9] are valid only over the interval 400-1200 km.

The AF conductivity shows three distinct regions instead of the single trend at LF. Below 800 km depth the models agree well, but the AF conductivity is nearly

constant 400-700 km and then decreases sharply in the additional depth range 200-400 km.

Interpretation. Solid silicate electrical conductivity depends on temperature and composition. I modeled electrical conductivity as the sum of ionic (Mg), small-polaron, and proton-hopping conductivities in olivine [16,17]. The small-polaron conductivity is dominated by the iron fraction X_{Fe} , whereas the proton conductivity is entirely determined by the water abundance X_{H_2O} .

I solved for temperature at specified composition (joint inversion will be possible with a heat-flow constraint, [18]). The LF conductivity is a very good match to a conductive temperature profile [19] 500-1000 km at $X_{Fe} = 0.15$. The fit is improved at 400-500 km with $X_{H_2O} = 300$ ppm and at 1000-1200 km with $X_{Fe}=0.16$. These assignments are consistent with the bulk iron (or Mg#) [20] and water content [21] of the lunar mantle.

No satisfactory solution for interior properties was found for the AF model. The substantial departures of the upper segments from a conduction thermal model would require unrealistically large $X_{Fe}>0.25$ or $X_{H_2O}>1000$ ppm. The AF inflection at 400 km resembles the base of the stagnant lid in solid-state convection models [22], but the excess conductivity must still increase significantly <400 km depth. If instead the PKT (Apollo 12) upper mantle is partially molten [23], the conductivity at 200-500 km can be matched by just ~0.1% melt. This would imply the contemporary lunar interior is at a serendipitous last gasp at the solidus.

Conclusion. A model fitting the new full-bandwidth conductivity-depth profile might be found, but the fit to the established data <1 mHz matches simple temperature and composition models for the lunar interior. The conductivity slope is likely much steeper at shallow depths than can be recovered by the TF method. The magnetotelluric method can support a vastly larger bandwidth with minimal influence of multipoles [24] and thus reliably resolve much shallower depths in the resistive Moon.

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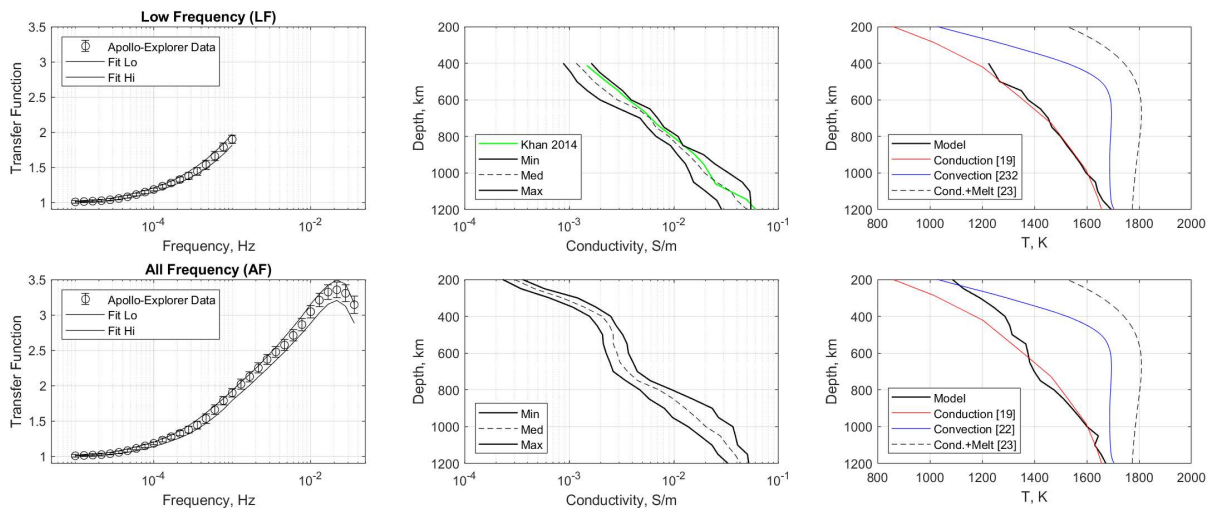


Fig. 1. Left Col: Explorer 35–Apollo 12 magnetic transfer functions for low-frequency (LF, <1 mHz, top) and all frequencies (AF, up to 36 mHz, bottom). Middle Col: Inversions for electrical conductivity as a function of depth. Solutions are truncated at the minimum and maximum depths supported by the data. Right Col: Interpretation for temperature and composition. LF is well-matched to a conductive thermal profile with bulk iron fraction $X_{Fe} = 0.15$, with depth >1000 km at $X_{Fe}=0.16$ and depth <500 km enhanced with $X_{H_2O} = 300$ ppm. AF profile uses same composition; large misfit at shallow depths indicates unrealistically large X_{Fe} or X_{H_2O} would be required there. See text for discussion of convection or partial melt. The AF model, and by extension the TF approach >> 1 mHz, is considered unreliable in lunar EM sounding.