MEASURING THE ELECTRIC PROPERTIES OF SUB-SURFACE MATERIALS WITH MUTUAL IMPEDANCE (MI) PROBES

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ABSTRACT

Mutual Impedance Probes measure the complex permittivity of materials in the ELF to LF frequency range. MI instruments have been developed for a number of terrestrial and space applications. On earth, MI probes are used for non-invasive conductivity and permittivity measurements in application areas such as geology and archeology. The main features of MI probes are recapitulated. Results from recent field test campaigns in various harsh environments are shown. The measurement range and accuracy of MI probes are presented, and new configurations of future instruments and their applications are discussed.

INTRODUCTION

The ground permittivity measurement through MI impedance probes has been used first in geophysical prospection with DC currents at the beginning of the XXth century [1]. For DC (or extremely low frequencies), the conduction in geophysical materials is mainly set by the ion conductivity in regolith interstitial water and then it is dependent on both porosity and ionic content. Rock materials are generally semi-conductors but can also involve metallic conduction. Then, at high frequencies, the displacement conductivity will dominate. The range of conductivity of the geophysical materials is extremely large, over about 12 orders of magnitude. This work, motivated by planetary surface investigations, will not include DC measurements. Metallic electrodes are used, which are free to exchange electrons with the surrounding medium. In these conditions, the expected range of constitutive materials resistivity is ~ $[10^{-7} – 10^{2}$ Ωm] and [1-100] for the dielectric constant. With AC sources, a perfect contact between the electrode and the ground is not mandatory [2,3]. The mixture of several components, especially in the case of metallic components can also modify considerably the conductivity as measured at macroscopic scale with respect to the conductivity of the constituents. The MI probe will measure the apparent complex permittivity, as if the whole material was homogeneous.

In practice, MI measurements are often performed on the interface between a half space of vacuum and a half space of a homogeneous material. The apparent permittivity is then the mean of vacuum and material permittivities. More complex geometries as for the Huygens probe on the surface of Titan can also be used [4,5]. In our present work, after a description of the MI probe principle, the architecture and performance of a Huygens-type laboratory instrument is described. The measurement range and accuracy of the instrument is studied. Finally, we present alternative MI configurations for measurements on a surface or in a borehole, which could be used both for terrestrial applications and on planetary space missions.

MI PROBE PRINCIPLE

A mutual impedance probe consists essentially of a sensor array, a current generator and a voltmeter as shown in Fig.1. An alternating (sinusoidal) current I, of frequency ω, is injected between two transmitting electrodes, TX1 and TX2, and induces a voltage A between two receiving electrodes, RX1 and RX2. The frequency is chosen such that the wavelength is much larger than the size of the electrode array. The complex ratio A/I is the mutual impedance of the circuit.

If the amplitude and phase of the measured voltage are

$$A_0, \varphi_0 \quad \text{in a vacuum, and}$$
$$A, \varphi \quad \text{in a given environment,}$$

the apparent conductivity σ and relative permittivity ε_r of the medium are given by

$$\sigma = \frac{A_0}{A} * \omega * \varepsilon_0 * \sin(\varphi - \varphi_0) \quad \text{and} \quad \varepsilon_r = \frac{A_0}{A} * \cos(\varphi - \varphi_0), \tag{1}$$

where ε_0 is the relative permittivity of vacuum.

The mutual impedance reflects the bulk properties of the medium. Analytical solutions exist also for configurations where the electrode array is placed on the surface of a liquid or on a locally planar ground, and for intermediate configurations [6].

LABORATORY INSTRUMENTS AND MEASUREMENT RESULTS

A laboratory instrument, which closely resembles the MI probe on board the Huygens spacecraft, has been built and tested in the field. The architecture of the instrument is illustrated in Fig. 2. It consists of a data processing unit which employs a digital signal processor, analogue electronics including ADC and DAC converters and high impedance preamplifiers, an array of wire electrodes mounted on fiberglass booms and batteries for power supply. The instrument is controlled by a laptop computer, which determines the instrument's operating mode and stores the measurement data. The frequency range used is 45 Hz to 5670 Hz. The instrument is accommodated in a housing similar to the body of the Huygens probe. The geometry of the electrode array (RX1 – RX2 electrode distance 1.4m, TX1-TX2 distance 1.1m) determines the spatial resolution of the instrument in the range of ~ 1.5m.

A series of field tests have been conducted in order to compare MI measurement results, MI error model predictions and measurement results from an alternative method (plate capacitor technique). The results for both conductivity and relative permittivity are in good agreement with the results from alternative measurement methods [7]. The difference in the results is well within the predicted measurement error ranges, which confirms both the performance of the instrument and the suitability of the models used for data calibration.

MEASUREMENT RANGE AND ACCURACY

MI probes determine the complex permittivity of a material by measuring at a time both magnitude and phase of the receiver electrode potentials. The measurement range and accuracy for both conductivity and relative permittivity are interdependent.

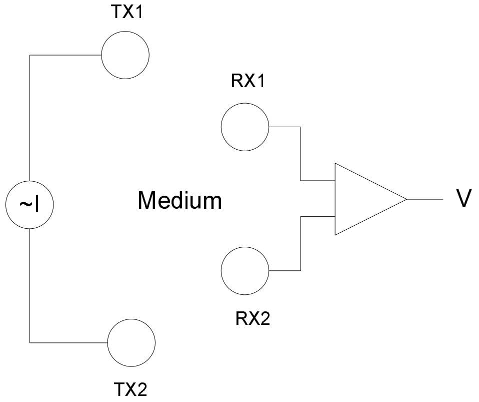


Fig. 1. MI probe principle

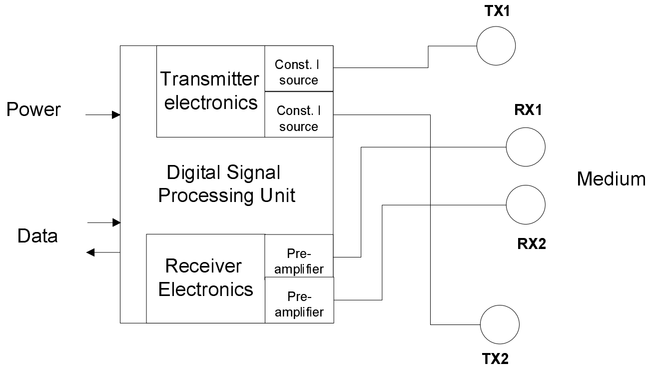
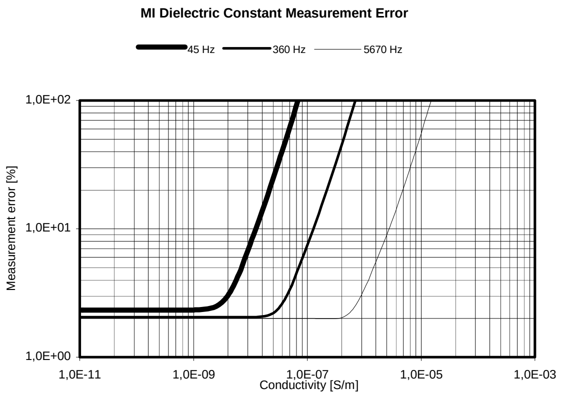


Fig. 2. Instrument Architecture



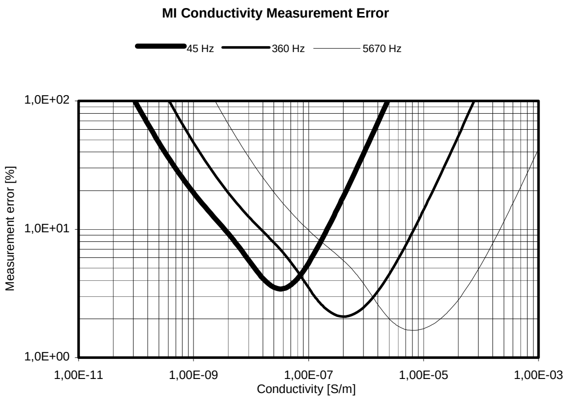


Figure 3: Measurement accuracy (dielectric constant)

Figure 4: Measurement accuracy (conductivity)

The most important factors for measurement range and accuracy of MI probes are

- Operating frequency range
- Transmitter signal magnitude range
- Transmitter signal spectral cleanliness
- Receiver signal to noise ratio
- Digital signal processing capabilities
- Sensitivity to environmental parameters (temperature etc.)

While the relative permittivity of most materials is not different by more than two orders of magnitude, the conductivities of common materials often differ by more than 15 orders of magnitude. It is therefore most of all the conductivity of the material investigated by a MI probe that determines the receiver signal quality and hence the measurement precision. Consequently, it is reasonable to assess the measurement accuracy of a MI probe as a function of the conductivity of the medium. The measurement accuracy has been modeled taking into account key parameters for the measurement such as magnitude and phase measurement precision, precision of component values used in the models for compensation of systematic errors (like parasitic transmitter current losses and receiver input currents) and electrode array geometry factors.

Fig. 3 and Fig. 4 illustrate the results of the accuracy analysis for the laboratory instrument for both conductivity and relative permittivity in a conductivity range of 10^{-3} S/m (example: wet sand) to 10^{-11} S/m (example: humid air). It is evident that for the measurement of relative permittivity the main constraint is the receiver signal to noise ratio at high conductivities for a given frequency. The measurement range can be extended towards higher conductivities by using higher measurement frequencies. For the conductivity measurements, the same restrictions apply for high material conductivities. For low material conductivities, the accuracy of the phase measurement at low frequencies is the most important factor limiting the measurement precision.

ALTERNATIVE CONFIGURATIONS

The configuration of a MI instrument consists of the electrode array and associated items such as the harness, electronics package and instrument housing. Our experimental example is similar to the MI instrument on board the Huygens probe, which is a relatively poor configuration as a result of severe accommodation constraints on the space probe (short booms) and due to the fact that it was optimized for atmospheric conductivity measurements. However, in the case of a homogeneous target we have shown that the measurements are accurate [7]. A major driver for alternative configurations for the investigation of surface or subsurface targets is to delimitate the volume involved in the measurement. Typically, the depth domain is commensurate with the size of the electrode array. For measurements on a surface one can use the feet of a (stationary) Lander or electrodes close to the wheels of a rover [6]. However, the most widely used geometry in terrestrial measurements is the Wenner array (4 electrodes in line, with equal intervals).

Such an array can be trailed behind a rover and an improved version with multiple electrodes could then give access to different depth ranges in the sub-surface [8]. Another type of MI instrument is used for borehole logging, with a Wenner array configuration installed on a drilling device or a penetrator.

CONCLUSIONS

Many subsurface materials and their physical state can be characterized by measuring their electric properties. The Conductivity and relative permittivity of materials in the ELF to LF frequency range can be accurately measured by MI probes. The shape and size of the electrodes are of minor importance, and the contact impedances between electrodes and medium are not important. Systematic errors caused by the electrode geometry and by parasitic effects can be modeled and compensated. The measurements are accurate in a wide range of material conductivities.

MI probes can be used in harsh terrestrial and in space environments. Static instruments can be used to monitor temporal variations of electric properties. Mobile probes can be used to map the complex permittivity along a track on a surface or as a depth profile along a bore hole. 2D and shallow 3D mapping can be performed using mobile probes on a surface.

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