Electromagnetic Scattering Analysis of Large Size Asteroids/Comets for Reflection/Transmission Tomography (RTT)

Manohar Deshpande,
Microwave Instrument Technology Branch
NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
manohar.d.deshpande@nasa.gov

Abstract: A precise knowledge of the interior structure of asteroids, comets, and Near Earth Objects (NEO) is important to assess the consequences of their impacts with the Earth and develop efficient mitigation strategies. Knowledge of their interior structure also provides opportunities for extraction of raw materials for future space activities. Low frequency radio sounding is often proposed for investigating interior structures of asteroids and NEOs. For designing and optimizing radio sounding instrument it is advantageous to have an accurate and efficient numerical simulation model of radio reflection and transmission through large size bodies of asteroid shapes. In this presentation we will present electromagnetic (EM) scattering analysis of electrically large size asteroids using (1) a weak form formulation and (2) also a more accurate hybrid finite element method/method of moments (FEM/MOM) to help estimate their internal structures. Assuming the internal structure with known electrical properties of a sample asteroid, we first develop its forward EM scattering model. From the knowledge of EM scattering as a function of frequency and look angle we will then present the inverse scattering procedure to extract its interior structure image. Validity of the inverse scattering procedure will be presented through few simulation examples.

Keywords: RF Sounding, EM Scattering, Radio Frequency Tomography

1. Introduction

NASA has been mandated by the US Congress to plan, develop, and implement a Near-Earth Object (NEO) Survey program to detect, track, catalogue, and characterize the physical characteristics of NEOs in order to assess the threat as well as opportunities offered by such NEOs. These NEOs are usually monitored from the ground using optical, infrared, and radar sensors which help get information about their size, shape, brightness, and more importantly their path and future trajectories. In case of these objects' high probability of impact with the Earth, it is important to have knowledge of their internal structure which would be helpful in destroying or changing their trajectory to avoid an impact. For extracting internal structural images of these NEOs, low frequency wideband radars are being proposed [1-3] in the scenario shown in Figure 1.

In the setting shown in Figure 1, the Orbiter, placed at a distance from the small body, will illuminate the target with low frequency radio waves and will record the reflected signal. Part of the transmitted signal will also pass through the interior of the small body and will be detected by the receiver on the Lander. The resulting measurements will then be processed in real time or post processed on the ground to extract interior structure of the target. An EM scattering model of an asteroid body will be an important tool for designing an optimum RTT instrument for such application. A forward EM scattering model of an asteroid body is also essential for extracting its interior structural image using the inverse scattering procedure. In this work, we will present a very low frequency EM scattering model of an asteroid to generate synthetic raw radar data that emulates what would be received by the radio tomography instrument depicted in Figure 1.

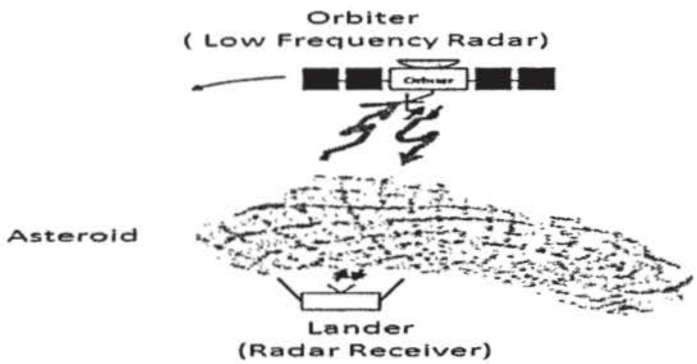

Figure 1: deployment of low frequency radars for reflection/transmission tomography of asteroid.

2. Theory

To develop EM scattering model, it is assumed that an asteroid target is illuminated by the far field radiated by a dipole antenna excited by a train of RF chirp pulse given by

$$s(t) = Cos(2\pi f_c t + \kappa\pi t^2) \; , \; 0 \le t \le \tau$$
$$= 0 \, , \; \tau \le t \le T \tag{1}$$

where f_c, κ, τ, T are, respectively, carrier frequency, chirp rate, pulse width, and pulse repetition interval. The far field generated by the dipole will illuminate and induce surface as well as volumetric currents on the target. The induced current will then cause the secondary radiation which will be received by the dipole and will be the synthetic raw radar data. The scenario described above is depicted in Figure 2.

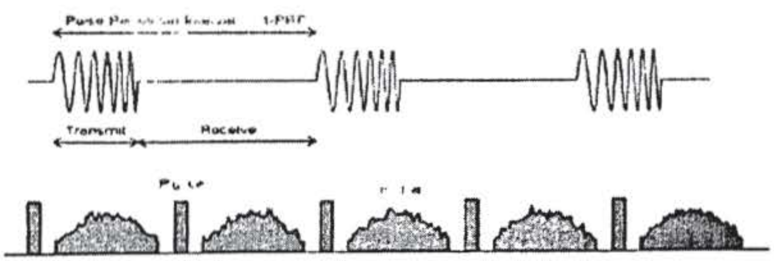

Figure 2: Transmit and receive signal timing diagram

To generate synthetic raw radar data following steps will be followed and will be implemented in the EM scattering model.

1. The complex amplitudes of frequency components present in (1) are first estimated using the Fourier transform of (1).
2. For each frequency component of (1), EM analysis of dipole antenna is then performed to estimate its far field incident on the target.

3. From the incident field for each frequency calculated in Step 2, and using EM scattering model (as explained in the next section) of a large size asteroid, the scattered electromagnetic fields are estimated.
4. Induced current on the dipole (also induced voltage) due to the scattered field from the target incident on the dipole is then determined using EM analysis of the dipole antenna.
5. Repetition of Steps 2-4 for each frequency component of (1) yields antenna received signal for each frequency component of transmitted signal.
6. Performing the inverse Fourier transform on the signal estimated in Step 5 results in the received time domain signal (synthetic raw radar data)

3. EM Scattering Model

In this section the two methods (weak form formulation and FEM/MoM) that will be discussed in details during presentation are briefly described for the mathematical modeling of EM scattering.

***A. Weak Form Formulation*:** For development of the forward EM scattering model we will assume an arbitrarily shaped asteroid with known electrical properties. Numerical scattering model can then be developed by discretizing the interior volume into tetrahedron and replacing them by an equivalent polarization current distribution with unknown incident field. The unknown total incident field has two components: one set up by the transmitting dipole and another due to the scattering by all other tetrahedron elements. Contribution to the incident field from other tetrahedron elements must be considered to take into account the mutual coupling. However, earlier observations [4] have shown that the dielectric contrast within the volumetric region of asteroid targets is very low and hence the mutual coupling between elements may be neglected for the first cut solution. Under this assumption the polarization current is completely known in terms of the incident field due to the transmitting antenna and the scattered EM field can be estimated using

$$\vec{E}_s(\vec{r}) = \frac{k_0^2}{4\pi\varepsilon_0}\sum_{n=1}^{N}\vec{E}_{inc}(\vec{r}_{nc})\left[\varepsilon(n)-\varepsilon_0\right]\frac{e^{-jk_0(|\vec{r}-\vec{r}_{nc}|}}{|\vec{r}-\vec{r}_{nc}|}dV_n \tag{2}$$

where $\vec{r},\vec{r}_{nc}$ are the coordinates of field point and the centriod of nth tetrahedron, $dV_n, \varepsilon(n)$ are the volume and dielectric constant of nth tetrahedron.

B. FEM/MoM Formulation:

In order to obtain more accurate EM scattering model we use FEM/MoM hybrid approach. In this approach, the scattered EM field is solved using the well known FEM approach and the field in the region exterior to the target is solved using the Integral Equation Method. The two approaches are properly matched at the common boundary by enforcing continuity of tangential fields at the boundary. The application of FEM approach for the interior region makes it more suitable to account for inhomogeuity of the inside medium. The mathematical details involved in the FEM/MoM formulation will not be repeated here due to page limitation and can be found in many text books on electromagnetic.

In order estimate received time domain signal, the EM scattering from a large size target must be calculated at number of frequencies associated with the transmit signal. Consequently, the proposed scattering computation would take prohibitively large computational time. Hence, asymptotic waveform evaluation technique or appropriate interpolation technique in conjunction with the FEM/MoM method are used to speed up the scattering computation.

4. Conclusion

To investigate/probe the interior structure of asteroids, comets, and Near Earth Objects (NEO) a new radio reflection/transmission tomography instrument is proposed. A computer simulation model that will emulate the functionality of the proposed RTT instrument has been proposed. One of the important aspects of the proposed simulation is successful development of efficient and accurate method of computing EM scattering due to electrically large targets of asteroid shapes. To meet this requirement a weak form formulation is presented to estimate EM scattering from a large size target. More rigorous and accurate approach such as the hybrid FEM/MoM has been proposed to estimate the EM scattering from a large size objects. Simple numerical examples will be discussed during the presentation.

5. References

[1] A. Safaeinili, et al., "Comet/Asteroid Radio Reflection Tomography," Presentation, http://trs-new.jpl.nasa.gov/dspace/bitstream/2014/13056/1/01-1554.pdf

[2] A. Safaeinili, et al. " Probing the Interior of Asteroids and Comets using Radio Reflection Tomography," Meteorites & Planetary Science, Volume 37, 12, pp. 1953-1963, December 2002