Internal probing of an asteroid analogue by electromagnetic method

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***Abstract*—The internal structure of small solar bodies are not well-known yet. The imaging of the interior of asteroids and comet will provide important information about their formation. In this paper, we aimed to provide a fast and efficient method to roughly image the shape and the interior of small bodies of the Solar system. We focused on monostatic measurements on two analogues of the 25143 Itokawa asteroid. The back-propagation technique was applied to promptly image the shape and internal structure of the analogues. The result shows the external shape of the analogue and that the inner void core can be reached and distinguished.**

***Index Terms*—3D imaging, measurements, asteroid analogues, inner structure.**

I. Introduction

Humans have always looked to the stars, but it is only in the last few decades that we have been able to send probes into Space. Our desire to understand Space also requires the development of new remote sensing and imaging methods. We are seeking to probe the interior of comets and asteroids, for which radar is widely used. Such investigations were first performed by the CONSERT (COmet Nucleus Sounding Experiment by Radiowave Transmission) radar during the Rosetta space mission to comet 67P/Churyumov-Gerasimenko. CONSERT led to several significant scientific findings ([1], [2]) and has given rise to new missions such as the Hera mission (launch in 2024) which will carry the Juventas Radar (JuRa) instrument to perform a tomographic radar investigation with the asteroid moon Dimorphos of the binary system 65803, Didymos as its target. To prepare the exploitation of the data, adequate imaging techniques have to be implemented and tested with laboratory measurements performed using analogue objects, which is the subject of this paper. However, asteroid imaging involves many challenges. Due to the large size of the objects studied, the computation time of the algorithms is often very long and must be optimized, as well as the computer memory required to perform such calculation. In this study, we seek to provide a fast qualitative method to reconstruct the global shape of a target and will so use a linear procedure that allows us to get away from the ill-conditions and the effects of noise.

II. Asteroid's sounding by a radar: Measurements on a analogue

A. Targets

As a realistic asteroid shape, we consider the 535 m diameter asteroid 25143 Itokawa, a rubble pile asteroid monitored during the space mission Hayabusa ([3]). We have manufactured two 20.5 cm diameter analogue models based on Hayabusa's accurate optical shape data[1] and studied them in high-frequency laboratory experiments. The effective permittivity of these 3D printed wireframe analogues is controlled via their relative spatial filling density, which has a layer-wise structure and has been set to match roughly the permittivities that are expected to be found inside a silicate asteroid. The manufacturing process has been described in [4]. One of these analogues, the homogeneous model (HM), has a constant permittivity while the other one, the detailed model (DM) is composed of three layers: a background part, a mantle in the vicinity of its surface and a void, deep in its interior. These targets have already been used to validate our full-wave time and frequency modelling with the measurements in [5] and [6].

B. Experimental configuration and parameters

The measurements were performed in laboratory in a controlled environment, the anechoic chamber of the C.C.R.M.-Marseille (Centre Commun de Ressources en Microonde) which allows to obtain a spherical experimental setup with a realistic measurement distance considering the analogue scale. To get the most information concerning the targets we perform the measurements on a sphere

[1] https://darts.isas.jaxa.jp/planet/project/hayabusa/shape.pl

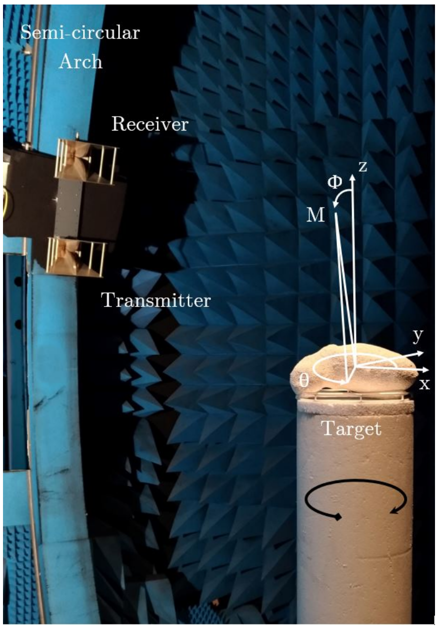

Fig. 1. A picture of the experimental setup of the anechoic chamber.

encircling the object using a quasi-monostatic setup that we have implemented in the anechoic chamber of the C.C.R.M.

As depicted in Fig.1, the target is placed at the origin of the coordinate system of the setup. The configuration of the chamber allows to measure the scattered field on a portion of sphere around the target. The antennas can rotate around the x and y-axis and the target around the z-axis. In the measurement, the receiving antenna is placed $12°$ ($-z$-axis direction) above the source antenna and follow the trajectory of the source antennas. This configuration is called quasi-monostatic since the receiving and transmitting antennas are not placed at the same exact position as a monostatic configuration would require. The distance between the center of the setup and the transmitting or receiving antenna is 1.849 m. The geometrical parameters have been chosen in such a way that the field is measured in a nonredundant manner according to [7]. Each source has a position (r^T, θ^T, ϕ^T), where $\theta^T \in [-180° : 178°]$ with a angular step properly chosen and $\phi^T \in [32° : 4° : 160°]$. The field is measured at the receiver positions (r^R, θ^R, ϕ^R), which differs from the source positions only by the elevation angle which is $\phi^R \in [32 - 12° : 4° : 160 - 12°]$. The measurements have been made considering a frequency bandwidth of $f \in [2 : 0.05 : 18]$ GHz.

III. Imaging

A. Imaging Techniques

In this paper, we aimed to obtain direct qualitative imaging in order to be able to have a fast first global observation of our object. The imaging techniques implemented in this study are based on the observation equation (1) of the scattered field:

$$\mathbf{E}_{\text{sca}}(\mathbf{r}_\Gamma) = \int_\Omega \boldsymbol{\mathcal{G}}(\mathbf{r}_\Gamma, \mathbf{r}_\Omega)\mathbf{J}(\mathbf{r}_\Omega)\,\mathrm{d}\mathbf{r}_\Omega \ , \qquad (1)$$

where $\boldsymbol{\mathcal{G}}$ is the dyadic free-space Green's function between the object zone Ω and the receiver zone Γ. This equation is used to retrieve a retro propagated map of the induced current:

$$\mathbf{J}(\mathbf{r}_\Omega) = \boldsymbol{\chi}(\mathbf{r}_\Omega)\mathbf{E}_{\text{tot}}(\mathbf{r}_\Omega) \ , \qquad (2)$$

where $\mathbf{E}_{\text{tot}}$ and $\boldsymbol{\chi}$ are respectively the total field and the contrast in the Ω domain. The observation equation allows us to visualize the external shape of the object and to have a global idea of the internal structure. We consider that the far-field conditions are realized:

$$k_0 r_\Gamma \gg 1, \ r_\Gamma \gg r_\Omega, \ \frac{k_0 r_\Omega^2}{2 r_\Gamma} \gg 1, \forall r_\Gamma \in \Gamma, \ \forall r_\Omega \in \Omega \ , \qquad (3)$$

with the temporal convention $-\mathrm{i}\omega t$, the dyadic free-space Green's function in spherical coordinates can be approximated [8] by:

$$\boldsymbol{\mathcal{G}}(\mathbf{r}_\Gamma, \mathbf{r}_\Omega) \approx \frac{e^{\mathrm{i}\mathbf{k}_\mathrm{s}(\mathbf{r}_\Gamma - \mathbf{r}_\Omega)}}{4\pi(\mathbf{r}_\Gamma - \mathbf{r}_\Omega)} \left[\mathbf{I} - \mathbf{e}_{r_\Gamma} \otimes \mathbf{e}_{r_\Gamma}\right] \ . \qquad (4)$$

$\mathbf{r}_\Gamma$ and $\mathbf{r}_\Omega$ are respectively the reception position of the antenna and the position of our object zone, $\mathbf{k}_\mathrm{s}$ is the scattered wave vector, $\mathbf{I}$ the identity operator and $\mathbf{e}_{r_\Gamma}$ is the unit vector of the spherical basis.

In order to obtain the induced current we used the back-propagation method which will provide a qualitative image of our object. Back-propagation is one of the most classical method to obtain the induced current. This technique gives an approaching solution of the induced current using (1), since the Green function is a low-pass filter. The idea is to retro-propagate the scattered field, using the Green function, into the target zone.

With the back-propagation method we retrieve the induced current by using the transpose conjugate of the dyadic free-space Green's function:

$$\mathbf{J}'(\mathbf{r}_\Omega, f) = \boldsymbol{\mathcal{G}}^*(\mathbf{r}_\Omega, f, \mathbf{r}_\Gamma)\mathbf{E}_{\text{sca}}(\mathbf{r}_\Gamma) \ , \qquad (5)$$

where f the number of frequency and $\boldsymbol{\mathcal{G}}^*$ is the transpose-conjugate matrix of $\boldsymbol{\mathcal{G}}$. The back-propagation algorithms gives us an approximation of the induced current for each voxel of the target domain. For each frequency we have a 3D map

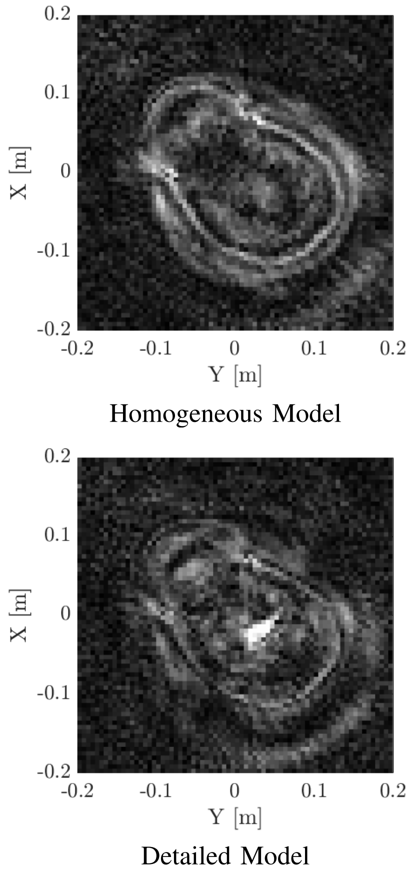

Fig. 2. Slice at $z = 0$ m of the 3D imaging map, reconstructed from measurement scattered field.

of the induced current. Then, the maps for each frequency are summed together in order to obtain one 3D reconstruction.

B. Results

In this study the object zone is define as a $40 \times 40 \times 40$ cm^3 cube. As a result a first reconstruction of the analogue containing an inner void core and the homogeneous one using the back-propagation method is presented in Fig. 2 . It appears that the external shape of the asteroid is visible and that it is possible to see the internal structure (here the void).

IV. CONCLUSION

In this study, the scattering of two analogues of the asteroid 25143 Itokowa was measured. Imaging was performed from quasi-monostatic measurements via back-propagation which provides a fast global reconstruction of the target and especially distinguishes the void included in the analogue. This is our first promising result for the probing of inner structure of asteroids from data of quasi-monostatic radar using a multipoint signal setting.

ACKNOWLEDGMENT

The authors acknowledge the opportunity provided by the Centre Commun de Ressources en Microonde to use its fully equipped anechoic chamber and the Mesocentre of Aix-Marseille University for its support for these numerical simulations.

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