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A DIRECT OBSERVATION OF THE ASTEROID'S STRUCTURE FROM DEEP INTERIOR TO REGOLITH: WHY AND HOW?

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Abstract

Our knowledge of the internal structure of asteroids is, so far, indirect – relying entirely on inferences from remote sensing observations of the surface, and theoretical modeling. What are the bulk properties of the regolith and deep interior? And what are the physical processes that shape their internal structures? After several asteroids orbiting missions, theses crucial questions remain open.

Direct measurements are needed to provide answers that will directly improve our ability to understand and model the mechanisms driving Near Earth Asteroids (NEA) for the benefit of science as well as for planetary defense or exploration. Radar tomography is the only technique to characterize internal structure from decimetric scale to global scale.

This paper reviews the benefits of direct measurement of the asteroid interior. Then the radar concepts for both deep interior and shallow subsurface are shown and the radar payload proposed for the AIDA/AIM mission is outlined.

Why?

Characterize the deep interior and physical properties of the asteroid

The internal structure of small bodies has never been explored through direct measurements. Classical optical remote sensing observations falls short, to determine whether a body is monolithic or a rubble pile. Similarly, there is no surface remote sensing technique to estimate a small body's bulk porosity, or how that porosity is distributed in the form of small (micro-) and large (macro-) porosities or voids. Intuition and inference are applied, along with elaborate simulations and modeling, leading to a situation in which a lot of science is built upon hypotheses. Collisional evolution models and measured bulk densities of some asteroids suggest that a significant number of small asteroids (typically smaller than 50 km and larger than a few hundred meters in diameters) have a rubble pile structure. However, only a geophysical sounding investigation, such with FANTINA, will constrain the ambiguities on these hypotheses (Herique et al, 2011). As we have no a priori knowledge of the detailed internal structure of any asteroid, the results of radar tomography investigation may require revision of our ideas about the origin of such small bodies.

Such information is crucial to understand and model the evolution of an asteroid since its formation in the primitive solar nebula. For example, the internal structure of an asteroid determines its response to impacts by other small bodies and, consequently, its collisional lifetime. Collision modeling depends strongly on the assumptions made about the asteroids internal structure. Similarly, mitigation strategies aimed for deflecting a threatening object, using a kinetic impactor, require a far better knowledge of the potential internal structure of such an object.

Rubble pile structures are also invoked to explain the large fraction of binary systems (15%) observed in asteroid populations. Direct measurement of the inner structure for an asteroid is indeed needed to discriminate between the different possible formation models for binaries by YORP acceleration (Walsh et al. 2008) or post collisional gravitational re-accretion remains (Jacobson and Scheeres 2011).

Characterize the regolith and its formation processes

These airless bodies are covered by a blanket of fractured rocks, dust, and other fine granular materials that are collectively called regolith. Its properties can differ dramatically from one small body to another (for ex. gravels and pebbles on Itokawa, fine dust on Eros). However, the depth and structure of this regolith lack direct measurements and are only inferred from surface observations.

Direct measurements of the regolith depth, structure and of its lateral variations would give better constraints on the process of regolith formation and evolution on asteroid surfaces, and help to understand how such small bodies can retain loose material while their gravitational attraction is so low. Having direct information would help to improve our understanding and refine our ability to model asteroid surfaces. Regolith properties depend on the regolith formation process for which different not-exclusive processes have been invoked (retention of ejecta resulting from impact cratering, Richardson et al. 2011; thermal fragmentation, Delbo et al. 2014). Having direct measurements of the regolith properties (size distribution) and abundance (depth) will allow us to better constrain how it forms and how it evolves and is transported in a low-gravity environment. These measurements will also allow us to infer other regolith properties that are important for modeling and interpretation of surface features such as the frictional and cohesive properties. By combining observations of the surface and interior with numerical modeling, we can constrain those properties, to more accurately predict the effects of surface processes on small bodies and the interaction with their surface of future spacecraft: for example, in the context of asteroid deflection, the impactor energy transfer and the surface stability for a gravity tractor.

Because of its high porosity, the regolith is also a thermally insulating layer. The knowledge of the regolith thickness and its lateral variations allows also better modeling of the thermal state of the asteroid surface and, therefore, the magnitude of the Yarkosvky thermal effect, which is another approach envisaged for risk mitigation.

How?

Radar sounding is the only technique capable of achieving our objective of characterizing the internal structure and heterogeneity of an asteroid. The radar capability and performances are determined mainly by the choice of the frequency and bandwidth of the transmitted radio signal: the frequency drives the penetration depth with lower attenuation of the lowest frequencies and the bandwidth drives the resolution while the bandwidth is necessary lower than the highest frequency. This is the main trade-off for instrument specification, which has to take into account technical constraints as antenna accommodation or operation scenarios.

Deep interior

The deep interior structure tomography requires low-frequency radar to reduce the dielectric and scattering losses and to penetrate throughout the complete body. The radar wave propagation delay and the received power are related to the complex dielectric permittivity (i.e to the composition and microporosity) and the small scale heterogeneities (scattering losses) while the spatial variation of the signal and the multiple paths provide information on the presence of heterogeneities (variations in composition or porosity), layers, voids or large blocks. A partial coverage will provide "cuts" of the body when a dense coverage will allow a complete tomography. Two instruments concepts can be considered (figure 1):

- a monostatic radar like Marsis on board of Mars Express / ESA (Picardi, 2005) that will analyze radar waves transmitted by the orbiter and received after reflection by the asteroid, its surface and its internal structures;
- a bistatic radar like Consert on board of Philae and Rosetta/ESA,DLR,CNES (Kofman, 2008) that analyzes radar waves transmitted by a lander, propagated through the body and received by the orbiter.

Monostatic radar requires very low frequencies necessitating the use of large antennas and is more consuming in term of mission resources (mass, data flow), driving all the mission specification. On the other hand, bistatic radar can use slightly higher frequencies, simplifying the accommodation on mission carrying a surface package. This concept is fully compliant with medium class planetary missions like Marco Polo CV/ESA or AIDA-AIM/ESA.

Regolith and shallow subsurface

Imaging the first ~10 meters of the subsurface with a ~1 m resolution or better to identify layering and to reconnect surface measurements to internal structure requires higher frequencies and higher bandwidth. It can be achieved with a monostatic radar on Orbiter only, with a 300MHz – 800MHz frequency range typically.

An enlarged frequency range up to 3GHz, like Wisdom developed for ExoMars Rover / ESA (Ciarletti, 2010) would add valuable science return contributing into the shape modeling, mass estimation and close asteroid navigation with an altimeter mode. This frequency range is also a unique opportunity of ground-based radar observation cross-validation.

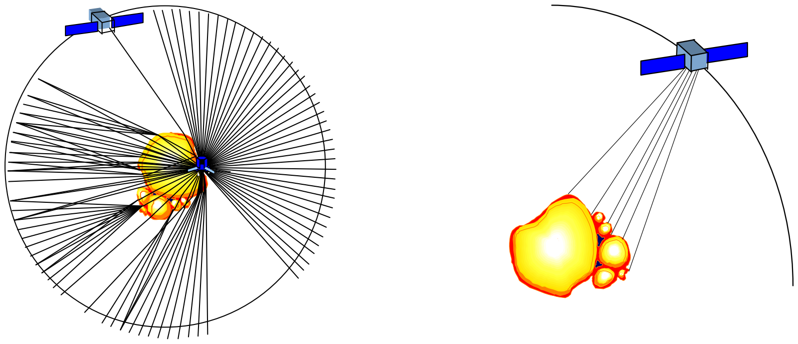

Figure 1: Illustrations of Bistatic (i.e., Consert-like) tomographic investigation and Monostatic (Marsis-like) sounding radar,

Payload

FANTINA for Marco Polo – Cosmic Vision

In the frame of the Marco Polo mission, a medium scale mission proposed to Cosmic Vision /ESA, the FANTINA instrument suite has been designed with a deep interior bistatic radar inheriting from Consert/Rosetta, a shallow subsurface high frequency radar inheriting from Wisdom/ExoMars in combination with a visible imaging system identical to CAM on Mascot/Hayabusa-2 (Schmitz, 2015) and an accelerometer to characterize the structure and physical properties of the near surface.

AIDA/AIM Mission

Both radars are presently under study in the frame of the ESA's Asteroid Impact Monitoring mission: AIM would be a stand-alone mission or constitute the Asteroid Impact & Deflection Assessment (AIDA) with the Double Asteroid Redirection Test (DART) mission under study by APL. AIM mission is to characterize "Didymoon", the secondary body of the binary NEA (65803) Didymos and to contribute to the evaluation of impact mitigation strategies (Michel, 2015).

AIM will carry Mascot2, a lander inheriting from Mascot/Hayabusa2 (Ulamec, 2014) to land on Didymoon. On Mascot2 and AIM, the bistatic radar will probe the Didymoon's internal structure, with a typical resolution of 30 meters to characterize the structural homogeneity of the interior. The objective is to discriminate monolithic structure vs. building blocks, to derive the possible presence of various constituting blocks and to derive an estimate of the average complex dielectric permittivity, which relates to the mineralogy and porosity of the constituting material. Assuming a full 3D coverage of the body, the radar will determine Didymoon’s 3D structure: deep layering, spatial variability of the density, of the block size distribution, of the average permittivity.

When the AIM is combined with DART, bistatic radar will be used to characterize possible structural modification induced by DART impact. It will also support mass determination and orbit characterization with range measurements during and after descent. Finally, it will contribute to the characterization of the primary body of the Didymos system (referred to as "Didymain").

On AIM mothership, the shallow subsurface radar objective is to determine the structure and layering of Didymoon and Didymain shallow sub-surfaces down to a few meters with a metric resolution. The radar will map also spatial variation of the regolith texture which is related to the size and mineralogy of the constituting grains and macro-porosity and spatial distribution of geomorphological elements (rocks, boulders, etc) that are embedded in the subsurface.

With DART, the radar is a key instrument to assess the regolith tomography before and after impact in order to characterize the crater topography, the internal structure modifications and the mass loss. The radar would also monitor the impact ejecta, generated by the collision with the DART spacecraft, in the vicinity of the secondary asteroid in order to estimate size distribution, speed, and total mass.

It will also contribute to shape modeling, mass determination and orbital characterization with altimeter mode. And finally, more prospective objectives will be considered, such as the support to ground-based radar measurements like Arecibo or Goldstone: orbital radar measurement is indeed a unique opportunity to cross-validate ground-based NEA characterization with radar signal in the same frequency range and with better resolution, better SNR and more favorable geometry.

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