Direct observation of 99942 Apophis with radar. A. Herique[1], D. Plettemeier[2], W. Kofman[1], S. Zine[1], O. Gassot[1], Y. Rogez[1], P. Michel[3], S. Ulamec[4], J. Biele[4], T.R Ho[5], J.T. Grundmann[5], D. Perna[6], H. Goldberg[7], A.K. Virkki[8], F.C.F. Venditti[8], S.E. Marshall[8] and D.C. Hickson[8], [1]Univ. Grenoble Alpes, CNRS, CNES, IPAG, Grenoble, France (alain.herique@univ-grenoble-alpes.fr), [2]Dresden University of Technology, Dresden, Germany, [3]OCA CNRS, Nice, France, [4]DLR, Köln, Germany, [5]DLR, Bremen, Germany, [6] INAF-OAR Monte Porzio Catone, Italy, [7] Gomspace, Luxemburg, [8]Arecibo Observatory, University of Central Florida, Arecibo, Puerto Rico

Science rational: Our knowledge of the internal structure of asteroids entirely relies on inferences from remote sensing observations of the surface and theoretical modeling [1]. Is Apophis a rubble-pile, as expected, or a monolithic rock, and how high is the porosity? What is the typical size of the constituent blocks? Are these blocks homogeneous or heterogeneous? The regolith covering Apophis remains largely unknown in terms of depth, size distribution and spatial variability. Is it resulting from fine particles re-accretion or from thermal fracturing?

After several asteroid orbiting missions, these crucial and yet basic questions remain open. Direct measurements of asteroid deep interior and regolith structure are needed to better understand the asteroid accretion and dynamical evolution and to provide answers that will directly improve our ability to understand structures and dynamical processes. Probing of the interior is also crucial for determining material composition and mineralogy while space weathering and thermal cycling alter surface properties as observed by optical remote sensing.

Direct observations of asteroid subsurface are also required to better model mechanics of such kind of granular materials in low gravity, to study stability conditions and to monitor the response of Apophis to the gravitational constraints induced by its close approach to the Earth. This is also crucial to plan any interaction of a spacecraft with Apophis especially for Planetary Defense purposes.

Radar observation: Radar observation of Apophis from a spacecraft is the most mature technique capable of achieving these objectives, by providing a direct measurement of its interior, giving a context for remote measurements of surfaces, and the stratigraphic connection of the observed terrain units. Earth-based radar has been used for decades now. While space-borne radar is now a classical method for surface and shallow subsurface investigation of planets and satellites, it is still new when applied to small bodies. However, CONSERT onboard Rosetta/ESA [2] has fathomed a limited part of the 67P/ Churyumov–Gerasimenko comet nucleus.

Radar performances in terms of investigation depth, sensitivity and resolution are highly dependent on the considered wave frequency band. Performances are also strongly dependent on the geometry of observation: incidence angles, measurement orbit arcs, multi-sensor geometry [3]. For such reasons, a radar dedicated to small bodies deviates significantly from such instruments designed for planets or large satellites, benefiting from small relative speeds but requiring versatility by-design to cover a large range of operation geometries.

Covering the whole investigation objectives requires a minimum of two frequency channels: a low frequency channel to investigate Apophis' deep interior with a limited spatial resolution and a higher frequency channel to image the near surface regolith with the highest resolution.

Observing regolith and near surface: Imaging the first tens of meters of Apophis' subsurface with a decimetric resolution can be achieved with a monostatic radar with a typical 300MHz – 800MHz frequency range [3]. Such radar operates on a single spacecraft, transmits radar signals and measures the wave reflected or scattered by the first tens of meters of Apophis.

Channel at 300MHz-800MHz. With one acquisition sequence, the measured scattered-power map provides the 2D distribution of geomorphological features (rocks, boulders, cavities, layers, etc.) that are embedded in the shallow subsurface while multipass acquisition is required for a 3D tomography of the regolith.

This radar channel allows to identify layering, to characterize the spatial variation of the regolith texture, (related to macroporosity and the size of the constituting grains) and then to reconnect surface measurements to internal structure. Apophis subsurface dielectric properties can be estimated from the scattered power or from the spatial signature of reflectors.

Channel at 2.3 GHz. An additional channel at higher frequency like S-band (2.3 GHz) allows to map surfaces with a lower penetration depth. Associated with multipass observation, it is a unique opportunity to map the surface at an accuracy equal to a fraction of wavelength ($\lambda \approx$12cm), to support shape modeling by interferometry as done in Earth observation, determination of the dynamical state with identification of excited modes, and to support gravimetric measurement with a direct ranging of the Spacecraft-Apophis distance. On Apophis, it is a unique way to accurately quantify mass redistribution and shape modification induced by gravitational constraints at Earth closest approach.

Observing deep interior: Deep interior tomography requires a low-frequency radar to penetrate throughout the complete body. The instrument could be then a monostatic, with a single spacecraft, or a bistatic radar, using two platforms or more to measure the signal transmitted throughout Apophis, as CONSERT did onboard Rosetta orbiter and Philae lander [1], [2], [4], [5].

Monostatic radar. A low frequency channel like 60 MHz offers a larger penetration (up to 100 meters or more) with a limited resolution (≈5 m). It corresponds to the instrument under implementation for the Juventas Cubesat on Hera/ESA mission [11].

As for the regolith, multipass tomography allows to rebuild a 3D tomography of the interior to identify internal structure like layers, voids and sub-aggregates to bring out the aggregate structure and to characterize its constituent blocks in terms of size distribution and heterogeneity at different scales (from submetric to global).

Shallow subsurface characterization and support to shape modeling are also possible in this configuration, with degraded performance due to a limited resolution.

Bistatic radar. Beneficing of daughter platforms like a nanolander or cubesats [12], the bistatic radar is measuring the signal in transmission, allowing to achieve a direct measurement of the dielectric permittivity, which is related to composition and microporosity [4]. The received power is related to meter-scale heterogeneities (size, distribution of constitutive material and porosity) [5], while the spatial variation of the signal and the multiple paths provide information on the presence of large heterogeneities, voids or layers.

Bistatic radar is less demanding in terms of data volume and operation: a partial coverage will provide slices of the body with average characterization and its special variability, while only a dense coverage will allow a complete tomography.

Bistatic measurement with Arecibo. Apophis is an opportunity to have bistatic measurement with Earth-based radiotelescopes and in particular with Arecibo (c.f. A. K. Virkki's presentation).

At higher frequency range (2380 MHz and 430 MHz), the signal sent by Arecibo is recoded by the spacecraft receiver. The SNR benefits then of the large transmitted power (900 and 100 kW respectively). So, the signal is mainly coming from the shallow subsurface with expected penetration depth from meters to ten meters depending on the carrier frequency. This configuration will provide additional geometries and permit joint inversion of ground-based and space-borne data.

The same configuration with Arecibo transmitting can be used at 8.1MHz for a full tomography in transmission. On the other hand, the possible implementation of a 60MHz receiver at Arecibo could allow a tomography in transmission with the spacecraft transmitting and Arecibo receiving. This configuration would be complementary to a monostatic radar onboard a mission without lander.

A proposed radar package. The payload on a future Apophis 2029 mission would carry a radar package with channels at 60MHz, 300-800MHz and 2.3GHz. The 60MHz channel will operate in monostatic and also in bistatic mode if a lander or any daughtercraft provides the opportunity of measurement in transmission. This 3 channels offer the capability to to operate combined bistatic measurements with Arecibo. Required performances and resources are listed in the following table.

Such a dedicated radar suite has been developed for asteroid investigation, especially in the frame of an engineering study of an Apophis 2029 mission by CNES [6], then in the frame of the ESA AIM proposed mission [7] and is now studied in the frame of the NEOMAP H2020 European program. This suite has been proposed to the M-class cosmic vision ESA mission [1], [8]–[10] and more recently for NEST (F-Class) and Chimera (Discovery). A 60MHz monostatic radar is under implementation for Juventas on the Hera mission and is inheriting from this work. All configurations are now TRL 4 or higher.

	Regolith	Deep interior Bistatic	
	Monostatic	Orbiter part	lander part
BW (MHz)	300-800	50-70	50-70
Ext.. BW	300-2500	45-75	45-75
Polar (MHz)	circular	Circular	Linear
Antenna	Vivaldi	Dipoles	Dipoles
Penetration (m)	10 to 20	≈100 (mono)	≈400
Sensitivity(*)	-40 dB.m^2/m^2	-40 dB.m^2/m^2	180 dB
PRF (Hz)	0.1-5	0.1-0.3	0.1-0.3
Tx power (W)	10	5	5
Mass (g) Electronic Antenna	 830 1560	 920 470	 920 230+100

* Monostatic radars: NEσ0 = -40 dB.m^2/m^2,
bistatic: 180dB absorption losses

Acknowledgments: We acknowledge support from CNES, ESA and from the European Union's Horizon 2020 research and innovation programme under grant agreement No 870377 (NEO-MAPP).

References: [1] A.Herique et al. (2018) ASR 62, 2141-2162. [2] W.Kofman et al. (2015) Science 349, aab0639. [3] A. Herique et al. (2019) Acta Astro. 156, 317-329. [4] Herique et al. (2016) MNRAS 462, S516-S532. [5] A. Herique et al. (2019) A&A 630, A6. [6] P. Michel et al. (2012) Proc. IAU 10, 481-482, [7] P. Michel et al. (2016) ASR 57, 2529-2547. [8] I. A. Franchi,et al. (2017) LPSC 48, 2667. [9] J. Oberst et al. (2018) ASR 62, 2220-2238. [10] C. Snodgrass et al. (2018) ASR 62, 1947-1976. [11] Goldberg et al. (2019) SSC19-WKIV-05. [12] C. Lange et al. (2018) ASR 62, 2055-2083