A RADIO SCIENCE EXPERIMENT TO STUDY THE INTERIOR OF THE URANIAN MOONS.

Valerio Filice[1,2] (v.filice@observatory.be), Gael Cascioli[3,4], Sébastien Le Maistre[1,2], Rose-Marie Baland[2], Erwan Mazarico[4] and Sander J. Goossens[4], [1]Université Catholique de Louvain, [2]Royal Observatory of Belgium (v.filice@observatory.be), [3]University of Maryland Baltimore County, [4]NASA Goddard Space Flight Center

Introduction: The five largest moons of Uranus, as well as Uranus itself, have mostly been studied through ground-based observations [e.g., 1]. Only Voyager 2 provided in situ measurements that significantly enhanced our understanding of the system [2,3]. As a ten-year launch window approaches, the scientific community has agreed on the importance of prioritizing a robotic mission to Uranus, proposing it as the next NASA flagship-class mission [4]. In response to this, NASA is reviewing the Uranus Orbiter and Probe (UOP) mission concept [5]. The concept was evaluated by the most recent Planetary Science and Astrobiology Decadal Survey [4] as a low-risk, relatively low-cost, and high-reward mission. Upon arrival, the mission would deploy an atmospheric probe, settle into orbit around Uranus for 4.5 Earth years, and conduct flybys of several moons. A Radio Science (RS) experiment that includes multiple satellite flybys (in addition to the orbital phase around Uranus) can provide valuable information about the interior properties, formation, evolution, and potential habitability of the planetary bodies in the Uranian system, as previously demonstrated [6-7]. An RS experiment can answer key science questions regarding the internal structure and rock-to-ice ratios of the large satellites of Uranus, and help identifying significant internal heat sources or possible oceans.

Target observables: In addition to magnetic field observations, static gravity field, tides, libration amplitude, and obliquity measurements are commonly considered to probe the interior of planets and moons. These observables may be highly sensitive to the presence of a global liquid layer inside the body. Based on [8-10], we first model the moons as two-layer solid bodies consisting of an ice mantle and a rock core and compute the values of the gravity coefficients J_2 and $C_{2,2}$ as a function of the normalized polar moment of inertia C/MR^2, assuming hydrostatic equilibrium and using Radau's equation. We compute the expected libration amplitude and obliquity for such solid bodies. Then, we replace the ice mantle by an ice shell and a liquid subsurface ocean in contact with the rocky core, based on [10]. Realistic ranges of values for the water and rock densities are considered. For each moon, the ocean thickness is varied from 5 to 50 km. The libration amplitude and obliquity of the ice shell are calculated as a function of the shell and ocean thicknesses, respectively. We confirm the level of accuracy required on the determination of the $C_{2,2}$ gravity coefficient to determine whether a moon is differentiated or not, as well as the accuracy required on the normalized moment of inertia (±0.005) to determine the hydrosphere thickness with an accuracy of ±50 km, as specified by [10]. For realistic ice shell thicknesses, the libration amplitude ranges from around 5 meters (Oberon) to around 60 meters (Miranda). The presence of a liquid ocean does not change the order of magnitude of the obliquity of the shell of the five large satellites, which is between approximately 0.0001° and 0.01°.

Parameters determination: A covariance analysis is conducted using the MONTE orbit determination software package [11] to determine if the target observables can be measured with sufficient precision to improve our knowledge of the main Uranian moons. Specifically, we simulated standard X-band Doppler tracking data with a noise level of 0.1 mm/s at 60-s integration time over 8-hour tracking windows centered on the closest approach of each flyby. The radio measurements are processed using a multi-arc Precise Orbit Determination approach [12]. We estimate the static gravity field, tidal Love number, libration amplitude, and obliquity of Uranian moons, along with the initial states of the orbiter and a solar radiation pressure scaling factor for each arc. Additionally, we investigate the benefits of combining optical data with the radiometric dataset. The JANUS camera model [13] is assumed. Landmarks in optical images define a control point network (CPN), with an expected noise level of 1 pixel. We estimate the rotation parameters to minimize the predicted sample and line offsets of any sunlit landmark observed within the camera's field of view. This technique is also referred to as 'landmark tracking' [14]. The nominal strategy of four pictures per flyby is simulated (two during ingress and two during egress) and we define a total of 50 landmarks randomly distributed over the surface.

UOP nominal tour: The current UOP orbit consists of two phases: the equatorialization phase, which occurs immediately after the Uranus Orbit Insertion (UOI), and the equatorial science phase. During these two phases, the spacecraft will perform a total of 34 flybys of the satellites: 14 for Ariel, 16 for Titania, 2 for Oberon, 1 for Umbriel, and 1 for Miranda. Our covariance analysis shows that the degree two coefficients J_2 and $C_{2,2}$ of Oberon, Umbriel, and Miranda cannot be measured independently due to the reduced number of passes and large distances at closest approach (see Fig.1). However, for Ariel and Titania, it is possible to measure the normalized moment of inertia, but not with enough precision to constrain the hydrosphere thickness at the 50 km level (see Fig.2). The optimization of the existing UOP tour relied on resonant orbits in order to minimize the total ΔV. However, we find that the current spatial and temporal coverage of the two moons is inadequate for the stated scientific objectives. Despite the numerous flybys, the ground tracks are confined in latitude and longitude, which only allows for the proper determination of the gravity field up to degree two for both moons. The obliquity can only be measured with a formal error at the 0.0001° level when optical data is also combined. It is not possible to measure tides and libration amplitudes because of the poor coverage of Ariel and Titania's mean anomaly with respect to Uranus.

Suggestions for the RS experiment: In order to improve the science return expected with the UOP current orbit (nominal tour), we test different RS experiment configurations to better constrain the interior structure of the Uranian moons. In particular, the effect of different flyby geometries and ground track coverage, observation strategies, frequency bands of the radio link, etc., are assessed for their ability to measure the static gravity field, tidal Love number, obliquity, and libration amplitude with the necessary accuracy. This sensitivity study could prove useful for future updates to the UOP mission design.

Conclusion: To support the future development of the UOP mission, we calculate the expected libration amplitude and obliquity of the five major moons of Uranus, completing the set of target measurements defined by [10] to constrain their interior structure. We assess which target observables can be measured precisely enough with the nominal RS experiment configuration and suggest different measurement strategies if the science goals are not met.

Acknowledgments: This work was financially supported by the French Community of Belgium within the framework of the financing of a FRIA grant.

References: [1] Cartwright, R. J. et al. (2015) Icarus, 257. [2] Tyler, G. L. et al. (1986), Science, 233. [3] Smith, B. A. et al. (1986), Science, 233. [4] National Academies of Sciences, Engineering and Medicine, (2023), The National Academies Press. [5] Simon A. et al. (2021) PMCS. [6] Durante et al. (2019), Icarus, 326. [7] Hemingway, D. et al. (2018), The University of Arizona Press. [8] Hussmann, H. et al. (2006), Icarus, 185. [9] Bierson, C. J. and Nimmo F., Icarus, 373. [10] Castillo-Rogez, J. et al. (2023), J. Geophys. Res. Planets, 128. [11] Evans, S. et al. (2018), CEAS Space Journal, 10. [12] Milani and Gronchi (2009), Cambridge University Press. doi:10.1017/CBO9781139175371. [13] Della Corte, V. et al. (2014), SPIE, 9143. [14] Owen, W. M. (2011), JPL, https://hdl.handle.net/2014/41942.

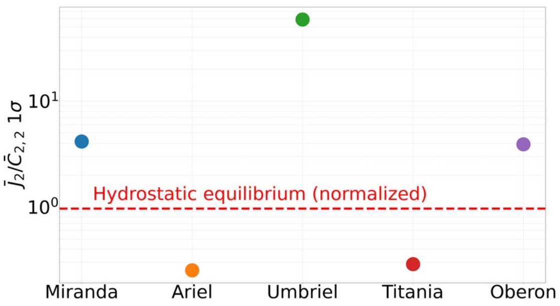

Figure 1: Ratio of the estimated J_2 and $C_{2,2}$ formal errors (1σ). If the measurement precision is below the hydrostatic equilibrium value (red dotted line) then J_2 and $C_{2,2}$, coefficients can be measured independently without the need to apply the hydrostatic constrain.

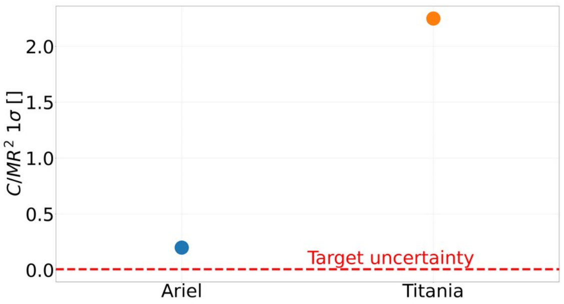

Figure 2: Inferred normalized polar of inertia formal error (1σ). Target uncertainty value from [10].