Probing Ice Giants' Gravity Fields and Atmospheres through Radio Tracking from Earth

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1. The Context: Ice Giants Exploration

Several mission concepts were proposed in the last few years for the in-situ exploration of the Ice Giants, both by NASA and ESA. In most cases, an orbiter was dedicated to the study of the giant planet(s) and its largest moons. In previous studies, an initial high inclination orbital phase with a very low pericenter distance (as for Juno and Cassini proximal orbits) was foreseen, to enable a **detailed mapping of the planet gravity field**. In addition, the orbiting mission scenario usually required multiple close flybys of the **Ice Giants' major satellites** to determine their gravity fields, search for satellite atmospheres, sound the interiors, and image their surfaces at high resolution.

Moreover, while the spacecraft would be probing the planetary system(s) it would be occulted by the planet atmosphere as seen from the Earth. Such a configuration offers a unique opportunity to study remotely the **physical properties of the occulting atmosphere** (probing both its neutral and charged components) using radio links as the spacecraft is being occulted. Indeed, non-null refractivity causes the radio signal to depart from the path which would be expected in vacuum. Additionally, atmospheric occultations also affect the phase velocity of the radio waves. Both changes modify the wave frequency and conversely, from the time variation of the Doppler measurements, the refractivity profile can be retrieved.

2. Proposed radioscience subsystem

The estimation of **gravity fields** from orbit requires precise spacecraft trajectory reconstruction. Radio tracking carried out using an on-board transponder allows to form **ranging and Doppler** (range-rate) measurements. While the first are typically needed to constrain the orbit of the planetary body, the latter can be used to determine the relative spacecraft velocity in the planet reference frame estimating, at the same time, a number of dynamical parameters of scientific interest, including the coefficients of the gravity harmonics. The gravity field is then modeled by using a series expansion to approximate the gravitational potential. An on-board transponder capable of coherent 2-way tracking at multiple frequencies (typically X- and Ka-band) can yield range-rate measurements with an accuracy as high as 3 μm/s @ 1000s integration time [1], [2].

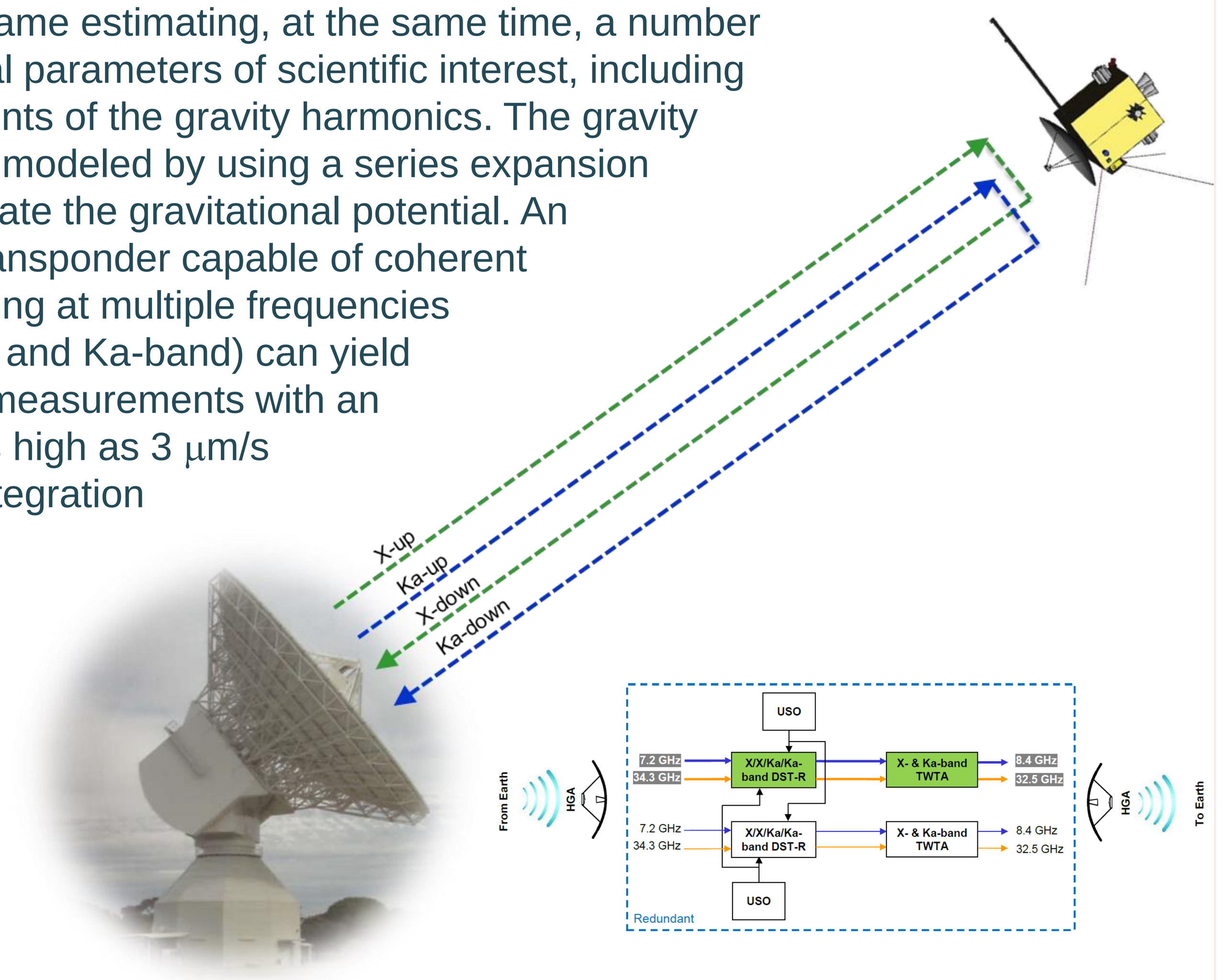

Figure 1: Schematic representation of the tracking configuration required for precision gravity science through the multi-frequency link technique [1],[2]. The green components are "active" in the *gravity science mode*. The S/C concept is borrowed from the Uranus Pathfinder proposal, submitted in response to ESA's 2014 Call for M-class Mission Proposals [3].

The determination of the vertical profiles of density, pressure, and temperature in the **planet's neutral atmosphere** could be obtained by measuring the Doppler shifts in the received frequency of a **monochromatic radio frequency signal** travelling between the spacecraft and the Earth, as it passes through the planet's atmosphere. This allows the retrieval of refractivity as a function of altitude. Using two different frequencies enables also the estimation of the total electron content in the **ionosphere**. Because of the large distances at play, radio occultations with the Ice Giants are better carried out as "up-link" experiments, where the transmitter is at the Earth Deep Space Antenna, and the receiver is on-board the S/C. This configuration allows maximizing the signal-to-noise ratio, as the transmitted power can be as large as 20kW. A successfully test was carried out with the New Horizons mission [4] and the same concept is also being proposed for the Trident ([5], [6]) mission concept to fly-by Triton and the Neptune system, a proposal managed by JPL in the context of the NASA Discovery 2019 call.

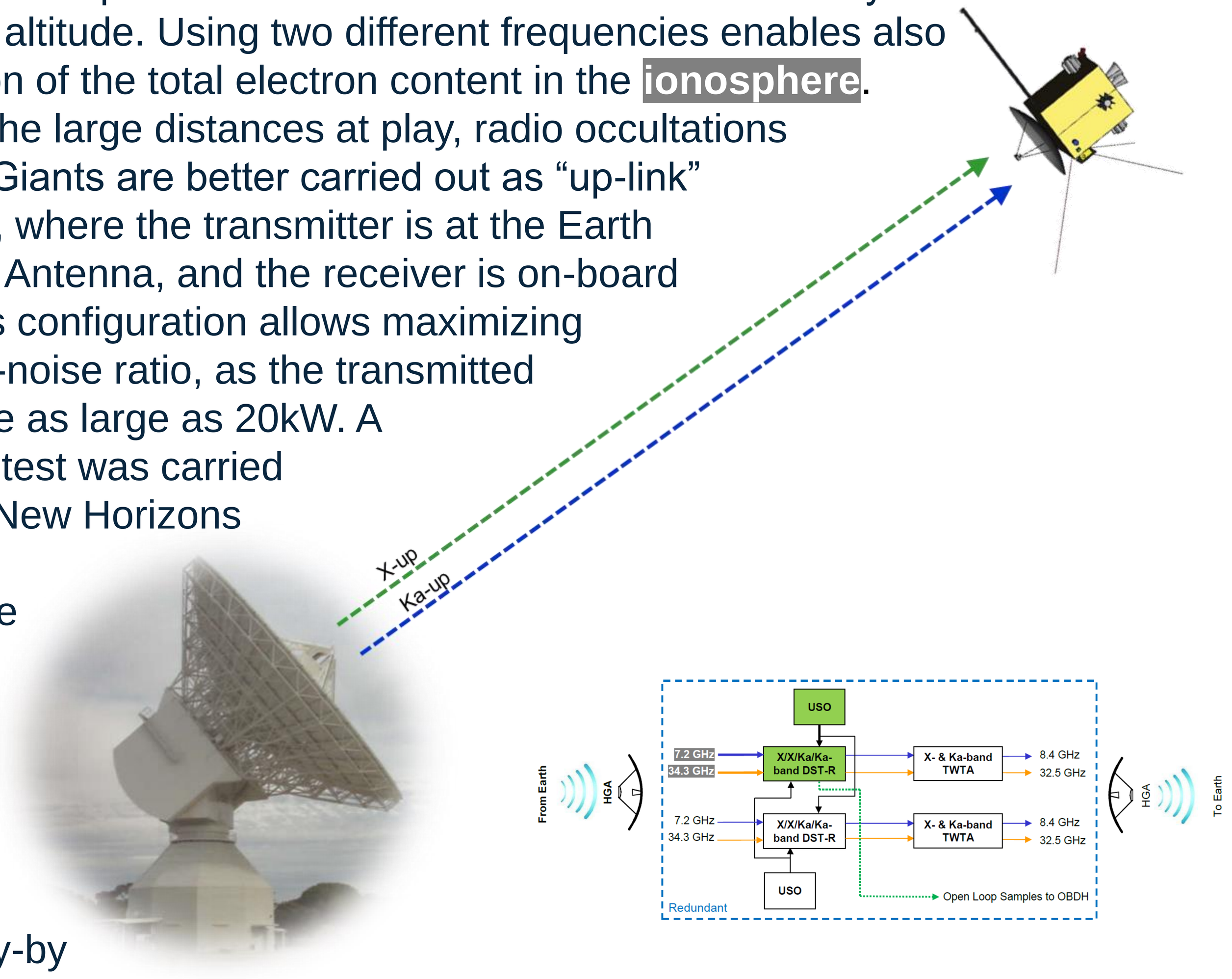

Figure 2: Schematic representation of the tracking configuration required for atmospheric profiling using the "uplink" 1-way radio occultation technique. The green components are "active" in the *atmospheric science mode*. The SNR is maximised by making use of the large available TX power at the Earth Deep Space Antenna.

3. Gravity Science

We selected Uranus as a case study, to analyze the expected performance of a gravity science experiment using the instrumentation configuration shown in Section 2. We used JPL's code MONTE (Mission Analysis, Operations, and Navigation Toolkit Environment) to run numerical simulations of the spacecraft orbit determination, based upon a realistic dynamical model of the bodies and the spacecraft.

Assumptions:

- 10 gravity "fly-bys" at Uranus pericentre;
- Fly-by geometry: from NASA's Ice Giant Decadal Study, but for C/A altitude:
  - C/A at 1.3 Ru for rings constraint at semi-latus rectum p>2Ru;
  - 2 different geometries analyzed: 1h occultation at pericenter (*worst case*), and the same geometry without occultation (*best case*)

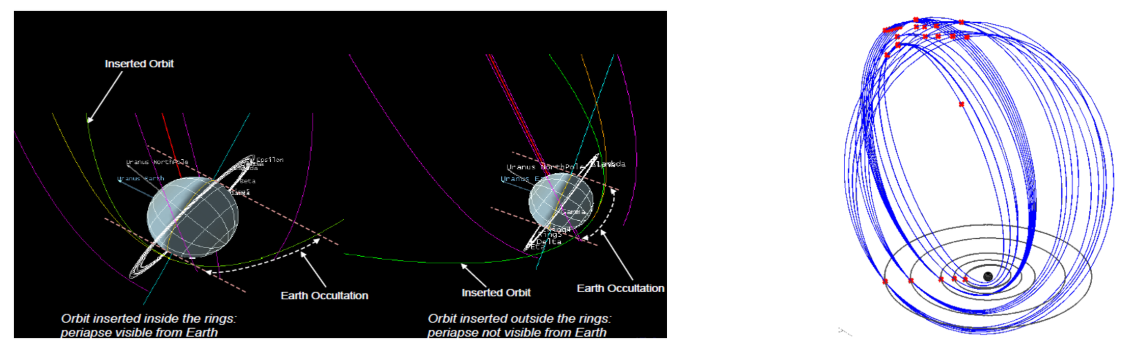

Figure 3: Possible orbital geometry of an Uranus exploration mission, from NASA Ice Giant Decadal Study [7]

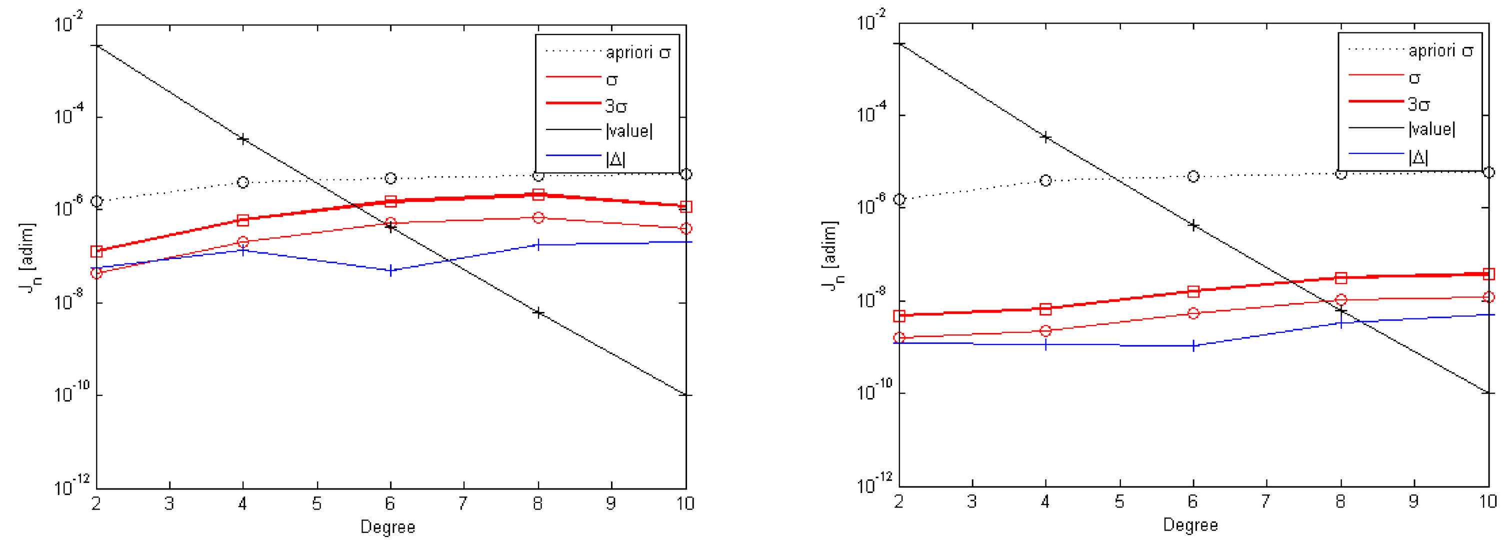

Figure 4: Results of our numerical simulations for the retrieval of Uranus gravity field. In the worst case scenario (*left panel*) we can observe up to the degree 5. In the best case scenario (*right panel*) the gravity field is observable up to degree 7.

4. Atmospheric Science

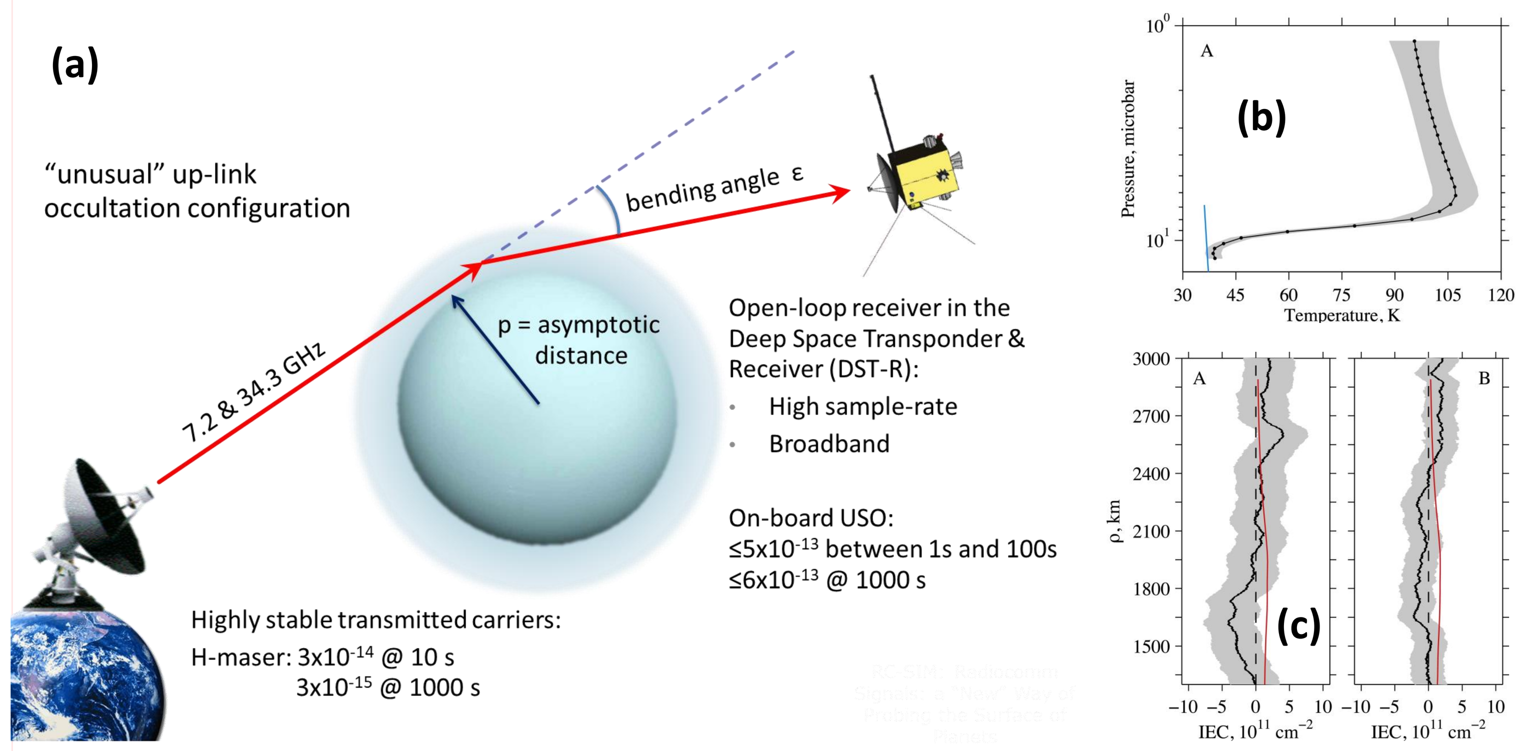

Figure 5: (a) Sketch of the basic concept of the uplink radio occultation technique with typical performance of the on-ground and on-board reference oscillators. **(b)** Profile of temperature versus pressure retrieved from REX measurements on New Horizons [8], during the entry phase at Pluto. **(c)** Profile of the integrated electron content (IEC) over Pluto's radial range where an ionosphere is expected to be present, retrieved from REX measurements on New Horizons [9], during the (A) entry and (B) exit phase at Pluto.

The Deep Space Antenna transmits highly stable carriers at two different frequencies (X- and Ka-band). The radio link is perturbed in phase and amplitude by the occulting atmosphere and ionosphere. The S/C ob-board receiver measures two observables quantities:

- Frequency shift: caused by refraction only
- Signal attenuation: caused by refractive defocusing and absorption

Much of the value of occultation profiles lies in their high vertical resolution, typically better than 1 km. This performance is enabled, even for very distant probes, by uplink radio occultations carried out both at X (~7.2 GHz) and Ka-band (~34.3 GHz), to disentangle the effect of charged particles (planetary ionospheres and plasmas) on radio signals from the one of neutral atmospheres.

5. Future Work

Additional numerical simulations of the gravity science experiment will be carried out, as mission concepts will mature in the next years. The availability of new tools and methods to deal with atmospheric occultations of oblate planets [10] will allow to accurately assess the achievable performance.

Acknowledgements

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