Estimating atmospheric density profiles using orbit determination with a focus on JUICE and Cassini

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Abstract

Orbit determination allows us to determine a spacecraft's position, velocity, and dynamical model parameters that directly affect a spacecraft's trajectory, such as gravity field coefficients, which relate to the interior structure of a planetary body, and tidal forces. In addition, when a spacecraft experiences substantial drag in the presence of an exosphere/atmosphere, the density profile may be estimated. This work presents an analysis of two cases where atmospheric drag has effects on the orbit and gravity measurements in planetary missions: Cassini, the mission to Saturn's system which ended with a plunge into the planet in 2017, and JUICE, the future mission to Jupiter's icy moons which will include an insertion into a circular, polar orbit around Ganymede.
For Saturn, we have estimated a vertical atmospheric density profile which we have compared with in-situ measurements taken by Cassini's INMS (Ion and Neutral Mass Spectrometer). For Ganymede, we find that the exosphere may be dense enough to affect JUICE's trajectory around the moon.

Keywords: orbit determination, radio-tracking, atmospheric density, exosphere, JUICE, Cassini

Introduction

The Cassini-Huygens mission was a joint project between NASA, ESA, and ASI (the Italian Space Agency) that was launched in 1997 to study the Saturn System and spent almost two decades in space. The final mission phase focused on the planet and its rings and ended with a deliberate plunge into Saturn on 15 September, 2017.
JUICE is an ongoing mission to study Jupiter's icy satellites that will launch in 2022 and arrive in the Jovian system in 2029. The mission will end with a 3-month tour of Ganymede at an orbit of approximately 500 km to investigate the moon's surface, its magnetic field and exosphere among other scientific objectives.
The atmosphere or exosphere of a planet or moon can be studied both from a distance or in-situ. Several methods exist to carry out these studies including: solar and stellar occultations, mass spectrometers, using thruster torque, and orbit determination. The objective of this work is to use the methods of orbit determination to estimate the density profile of Saturn's upper atmosphere during Cassini's plunge and to estimate Ganymede's exospheric density and determine if the presence of the exosphere influences the estimation of Ganymede's gravity field

Saturn

Saturn's upper atmosphere consists mainly of molecular hydrogen (H_2) but also helium (He) and traces of hydrocarbons such as methane (CH_4) and ethane (C_2H_6). Prior to Cassini, information known about Saturn's upper atmosphere was provided by the Voyager missions' Ultraviolet Spectrometer solar and stellar occultations. Vervack and Moses (2015) re-analysed 6 occultations and produced temperature and density profiles for Saturn's upper atmosphere after some of the original occultation analysis results varied within the scientific community.

Following the Cassini mission, we now have density data measured by other methods and instruments such as the INMS, the estimates from the navigation and AACS solutions, and occultations at the time of the proximal orbits but mostly throughout the plunge, when the lowest atmospheric altitude was reached by Cassini.

Ganymede

Ganymede, being the largest moon in the Solar System and the only moon known to have its own magnetic field, is an important target for a planetary exploration. It is generally agreed that the moon is fully differentiated with a metallic iron core, a spherical mantle and a thick shell made mostly of water ice. Ganymede has a spatially inhomogeneous H_2O and O_2 exosphere owed to a complex interaction between the icy surface of the moon, its intrinsic magnetic field and Jupiter's magnetosphere. Three processes are responsible for the formation of the exosphere (see Figure 1): ion sputtering, radiolysis and sublimation (Plainaki, *et al.*, 2015).

Figure 1. Diagram of the exospheric production processes on Ganymede

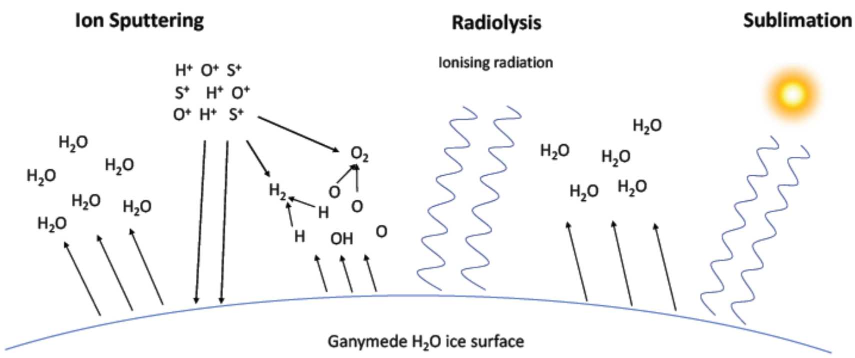

Fig 1. ***Ion sputtering:*** *magnetospheric ions bombard the surface and sputter H_2O into the exosphere (left).* ***Radiolysis:*** *ionising radiation dissociates the water ice into different molecules which recombine and are, in turn, sputtered into the exosphere.* ***Sublimation:*** *on the dayside, water is sublimated into the exosphere (Plainaki, et al. (2015).*

Atmospheric density

The equation that describes a multi-layered atmospheric density profile in hydrostatic equilibrium is given by:

$$\rho_i = \rho_{i-1} e^{\frac{z_{i-1} - z_i}{H_{i-1}}} \quad (1)$$

where ρ is the atmospheric density, z is the altitude and H is the atmospheric scale height and each layer denoted by the index i.

As previously mentioned, orbit determination (OD) can be used to infer any variable that directly affects the spacecraft's trajectory including atmospheric drag and therefore atmospheric density. Equation 2 gives for formula for the force due to atmospheric drag:

$$\boldsymbol{F}_{\boldsymbol{drag}} = -\frac{1}{2} \rho C_d A {v_{rel}}^2 \hat{\boldsymbol{v}}_{rel} \quad (2)$$

where ρ is the atmospheric density, $\hat{\boldsymbol{v}}_{rel}$ is the velocity relative to the atmosphere, A is the area of the spacecraft (well known from its geometrical model) normal to the flow, and C_d is the drag coefficient (a dimensionless number taken to be 2.1, which has been widely accepted for the case of the plunge, but no ground test has been done to measure it).

Methodology

Orbit determination

The motion of the spacecraft is subject to perturbations by several forces (both gravitational and non-gravitational) which can be estimated with the OD process, if sufficiently accurate models of these forces exist and can be implemented. We accounted for all the forces able to produce an acceleration large enough to perturb the spacecraft motion to a level that can be probed by the radioscience instrumentation. Such forces include the gravity of planets and their natural satellites, solar radiation pressure, possible thermal thrust from Radioisotope Thermoelectric Generator, and atmospheric density, which is the focus of this work.

Cassini estimation process

Firstly, an exponential, 4-layer model (model 1, per equation 1) was fitted to the INMS data and implemented in the OD process. Using this model showed that there was no sensitivity to the upper layer density and scale height. As the lower and denser atmosphere has more significant dynamical effects, it was subdivided into smaller, shallower layers (see figure 2b). Three other models were used (only models 1 and 2 are shown here); model 1 has the least number of layers and fits the smoothed INMS profile with the divisions corresponding to points where the scale height starts to change significantly. Each successive model has more layers, with model 4 having the most (9 layers). It is worth noting that no change was made to the scale height when subdividing the layers. For example, by looking at the two profiles in Figure 2, the scale height at 2000km is 160km, regardless of the number of layers. The different scale heights are, of course, estimated in the OD process. Table 1 shows the estimation parameters for Cassini which only change depending on the atmospheric model being used, i.e., the more layers, the more scale heights to be estimated but the spacecraft state, the gravity field coefficients and base density are always estimated. The estimation was also run using Doppler data averaged over different compression times: 1s, 5s, and 10s, to increase the sensitivity to finer structures in the atmosphere.

Table 1: Cassini estimation parameters

Model	Atmospheric parameters	Other parameters
1	Base density ρ_0, 4 scale heights	State position and velocity (Saturn's gravity field has been constrained to the Grand Finale Orbits solution)
2	Base density ρ_0, 7 scale heights	
3	Base density ρ_0, 8 scale heights	
4	Base density ρ_0, 9 scale heights	

Table 1: Atmospheric estimation parameters depending on model used and global parameters

JUICE simulation method

Two cases have been considered for JUICE: one in which the simulation of the observables and the estimation both account for the exosphere and another in which the simulation accounts for the exosphere but the estimation does not. From here on, a comparison is made between the two.

As previously mentioned, the primary components of Ganymede's exosphere are H_2O and O_2. For this work, the H_2O model was provided by Plainaki, *et al.* (2015) in the form of a 3D data-array which was interpolated to find the density value at the location corresponding to the spacecraft position. In contrast, the O_2 exosphere is described by an analytical model which is a function of 6 free parameters, the altitude above the surface (R), and the subsolar

Figure 2: Atmospheric models used for Cassini with subdivisions of the sensitive layer

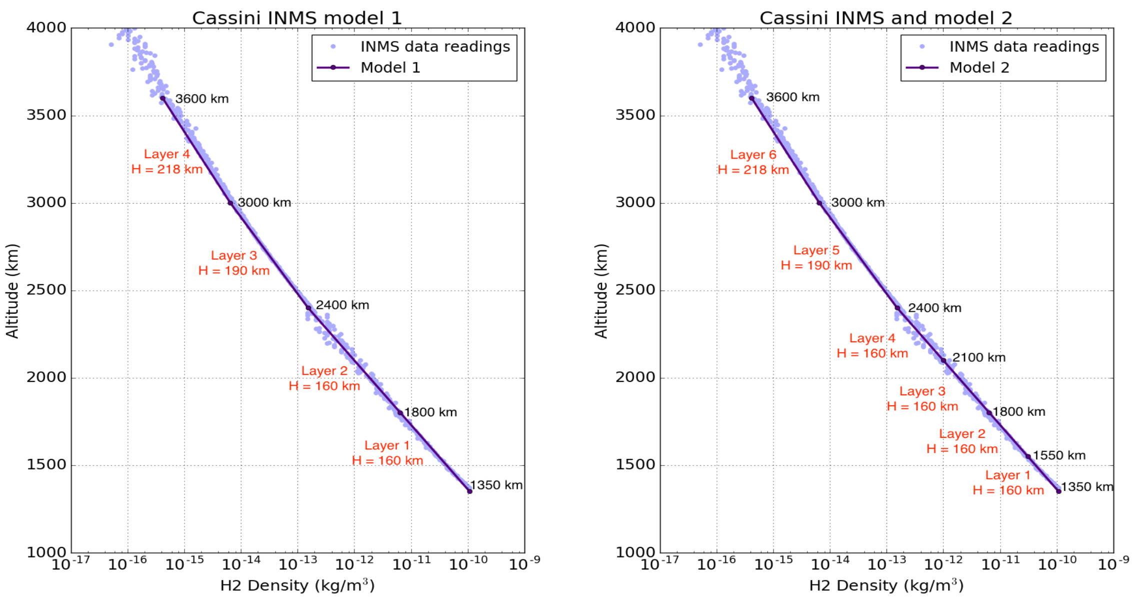

Fig 2. (Left) 4-layer exponential atmospheric profile fitted to the original INMS data with the different layers based on scale height changes. (Right) A similar model with further subdivisions in the lower layer. Models 3 and 4 have lower layers with more subdivisions.

angle (α). Since JUICE will orbit Ganymede at an altitude of about 500 km, we can make R a constant to simplify the equation. Equation 3 describes the O_2 model where k_1 and k_2 relate to the parameters of the Milillo, *et al.* (2016) model and are included as estimation parameters:

$$log_{10}\rho\left(R,\,\alpha\right) = k_1 + k_2\cos(\alpha) \tag{3}$$

where

$$k_1 = p5\, e^{-(p4)(R-1)} - \frac{(R-1)}{p1} + p2 \qquad k_2 = p6\, e^{-(p4)(R-1)} + p3$$

JUICE will orbit Ganymede for approximately 3 months, so the trajectory has been split into 35, 3-day arcs. This means that some estimation parameters are unique to each arc (local) whereas some (global) are applicable to all arcs (see Table 2).

Table 2: JUICE estimation parameters

Case No.	Exosphere included?	Local parameters estimated	Global parameters estimated
1	No	Cassini's position and velocity	Ganymede's 50x50 gravity field
2	Yes	Cassini's position and velocity	Ganymede's 50x50 gravity field, exospheric parameters: k_1, k_2, H_2O scale factor

Table 2. Local and global estimation parameters for each case number for JUICE simulations

Results

Estimates from Cassini Data

The estimation profiles from each model and data compression time are plotted alongside the original INMS data in Figure 3. In every profile, the base density is higher than that of INMS and there is no sensitivity above approximately 2300 km. The associated RMS values are 0.3, 0.1, and 0.07 mm/s for the 1s, 5s, and 10s data, respectively.

Figure 3. Estimated atmospheric profiles of Saturn's upper atmosphere

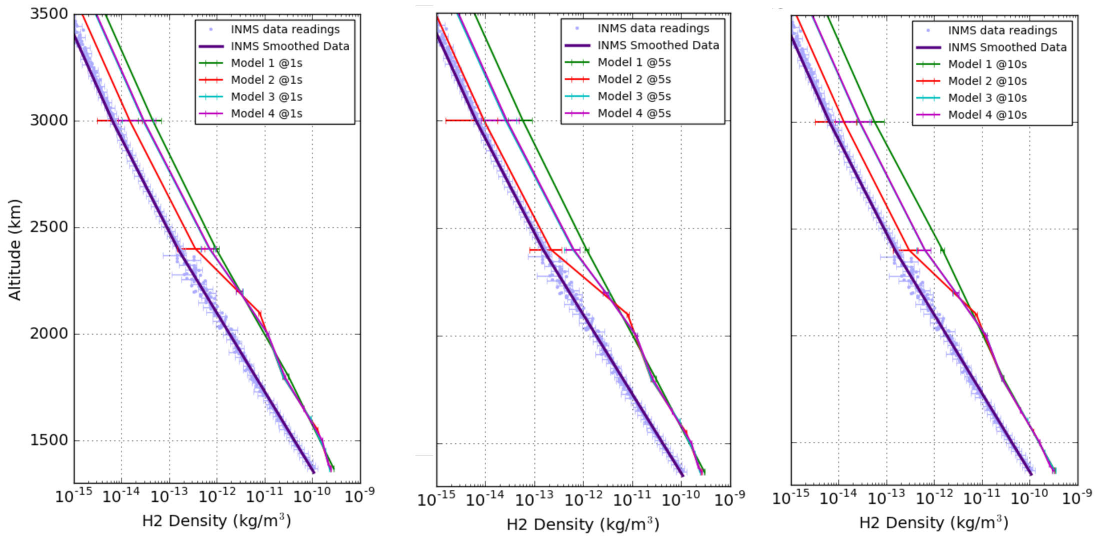

Fig 3. Estimated atmospheric profiles for each model using 1s (left), 5s (middle) and 10s (right) averaged data. The original INMS profile (from H. Waite and the INMS team) is also included for comparison (with error bars) and the lack of sensitivity in the higher altitudes can easily be seen.

Simulation results for JUICE

Figure 4 plots the drag acceleration experienced by JUICE along a few orbits around Ganymede. The order of magnitude is 10^{-14} km/s^2, with a peak-to-peak variation of a factor of two, depending on the subsolar longitude. Figure 5 shows the primary results from the simulations for JUICE's tour of Ganymede. The panels on the left show the residuals which, in an ideal case, resemble white noise. If we simulate and estimate while accounting for the exosphere (bottom left panel), the residuals flatten but if we omit the exosphere from the simulation, signatures are present in the residuals, demonstrating that the density of the exosphere is large enough to produce a signal that cannot be flattened. As well as the residuals, the uncertainty in the gravity field estimation has been plotted for both cases, showing a slight but negligible increase in the uncertainty when the exosphere is accounted for, due to the increase in the number of estimation parameters (k_1 and k_2).

Conclusions

The work presented here shows that we can use radio-tracking data and knowledge of the spacecraft dynamical model to determine the effect of atmospheric drag and reconstruct an atmospheric density profile (in the case of real data) or predict the effect that an atmosphere or exosphere will have on a future trajectory if we implement sufficient force models. The analysis of the Cassini data has shown that, to account for the perturbation on the spacecraft during the plunge, the base density ρ_0 must be 2-3 times larger than that measured by INMS which is not surprising to the INMS team. This discrepancy is still under investigation but it is possible that an uncorrected instrumental effect caused the INMS to underestimate the densities during the plunge (Yelle, *et al*, 2018). Regarding JUICE, the analysis shows that Ganymede's exosphere produces a Doppler signal that can be detected by the very accurate radio tracking system and should be accounted for in the OD process by appropriate modelling. Although it is difficult to model all forces that JUICE will experience, such as radiation forces, these can be disentangled from a signal owed to the atmosphere since the timescale of these effects is different.

Figure 4. Acceleration due to drag on JUICE

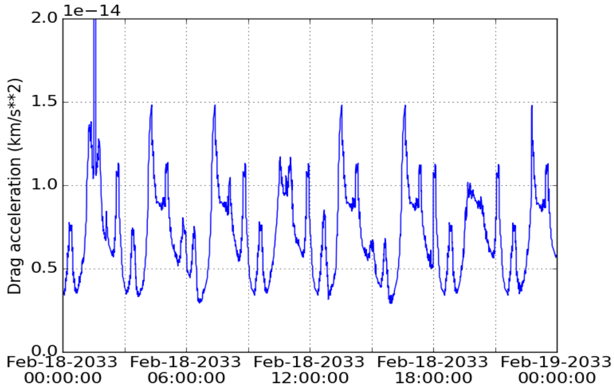

Fig 4. Plot of the drag acceleration on JUICE along its orbit due to Ganymede's exosphere based on Plainaki et al (2015).

Figure 5. Residuals and gravity field estimation uncertainty from JUICE simulation

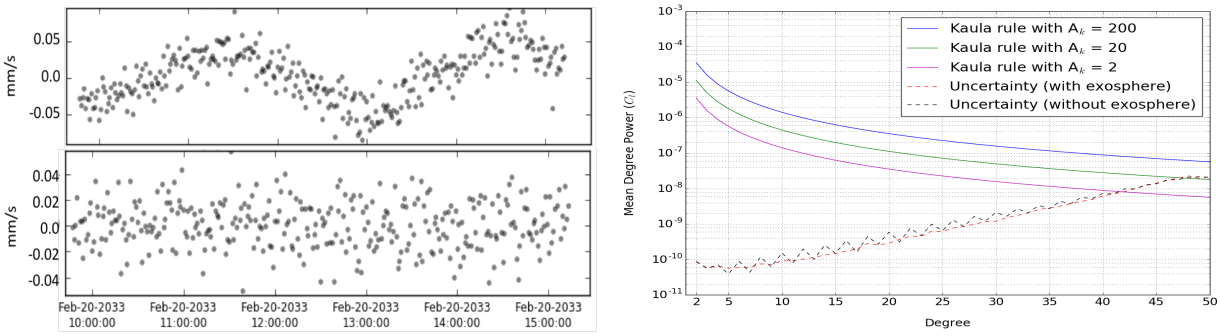

Fig 5. (a) Residuals for the case without accounting for exosphere in estimation (top) and accounting for exosphere (bottom). (b) Gravity field coefficients based on different Kaula rules (Kaula, 1963) and estimation uncertainties.

Acknowledgements

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