SIMULATIONS OF A 6-DOF PROBE ENTRY IN NEPTUNE ATMOSPHERE

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ABSTRACT

In the present work a probe entering Neptune's atmosphere is considered from its trajectory and attitude point of view. Emphasis is on the attitude stability analysis for identifying possible problems or performance goals. Relatively simple models are used such as the Neptune-GRAM model for describing the atmosphere, a Galileo-like probe with heuristically prescribed mass and moments of inertia variations, and fluid dynamic models for determining the aerodynamic coefficients. Assessment of the sensitivity of the problem parameters is obtained by the use of Monte Carlo simulations. Probe trajectories are numerically determined with ENTRAP, a 6 degrees of freedom (DoF) multi-purpose computational tool for entry and descent trajectory simulations that can take into account many kind of perturbations.

1. INTRODUCTION

Prediction of the trajectory and attitude of probes during the entry and descent in planetary atmospheres is an important task as the success of a mission can depend on the correct assessment of the real conditions that probes will encounter. Trajectory and attitude prediction have to rely on assumed knowledge of the problem and deal with the uncertainties of the models describing the relevant physical phenomena such as the conditions and properties of the planet's atmosphere. On the other hand, numerical algorithms must be reliable and fast, and it is highly desirable that they can be easily adapted to other proposed problems.

Consistency and reliability of numerical predictions can arise from diverse prediction tools with eventually different approaches arriving to similar results. The use of different tools and algorithms can also be useful for developing purposes of faster and/or improved ways of solving these kind of problems. ENTRAP — ENtry TRajectories in Atmospheres of Planets, is an autonomous tool that is being developed by our group for precise prediction of orbits and entry trajectories in any planet, capable of taking into account all kind of parameters and applicable to all kind of situations with any assumptions [1, 2]. Presently, it has been extended to 6 DoF, also allowing attitude analysis.

In this paper we use the novel 6 DoF capabilities of ENTRAP to study the descent of a Galileo like probe in the atmosphere of Neptune. Validation of results is achieved by performing a comparison with Mars Pathfinder predictions and results [3, 4]. Calculations are performed using relatively simple models with some reasonably accurate results.

2. SIMULATION OF ENTRY IN NEPTUNE ATMOSPHERE

2.1. Simulation Outline

We simulate both the trajectory and attitude dynamics of a probe entering Neptune atmosphere. As a general framework concept we used the Neptune Polar Orbiter with Probes [5] and data from the Neptune Aerocapture Reference Mission [6]. The probe configuration for a Neptune exploration mission should be similar to the Galileo probe that we use as a model. The code makes use of Runge-Kutta integration methods for trajectory as well as for attitude determination. Attitude is determined by computing the set of Euler angles defined as consecutive rotations ϕ about the X inertial axis, θ about the new y' axis and ψ about the body z axis. XYZ is the inertial frame and xyz the body frame with z the symmetry

axis of the probe. Details about the atmosphere model, the aerodynamic coefficients and initial conditions used in the simulations can be found in the following Sections. Monte Carlo simulations were also performed for assessing the influence of some parameters variation in the trajectory.

2.2. Atmosphere Model

We use the NeptuneGRAM atmosphere model [7], developed based on Voyager and other data, for determining the atmospheric density. The prescribed envelop of minimum-average-maximum density profile with altitude includes the effects of the data uncertainties, the expected latitudinal variations and the expected seasonal and time-of-day variations.

NeptuneGRAM is more complex than exponential models, but it is much more complete and precise. The parameter $\mathrm{Fminmax}$ is used to define the range of density profiles. The nominal profile is represented by $\mathrm{Fminmax} = 0$, the minimum by $\mathrm{Fminmax} = -1$ and the maximum by $\mathrm{Fminmax} = +1$. In this model the zero altitude level corresponds to the 1 bar. Latitudinal variation of density is determined by its effect in the value of $\mathrm{Fminmax}$. For the particular arrival season of the reference concept [6] we have $\mathrm{Fminmax} = 0.44 \times \cos(4.0 \times \mathrm{latitude}) + \mathrm{fbias}$ where $-0.56 < \mathrm{fbias} < 0.56$; this parameter is later randomized in the Monte Carlo simulations with a uniform distribution, since the most probable value is not known.

The temperature profile, important for determining the flow regime and Mach number, was derived from Voyager Ultraviolet Spectrometer (UVS) solar and from Radio Science Subsystem (RSS) Earth occultations. Details can be found in [8].

2.3. Flow Regimes and Aerodynamic Coefficients

The Knudsen number Kn determines if the fluid should be considered as a collection of particles or as a continuum; Kn is determined based on the freestream mean free path formula [9]; it was evaluated assuming a pure atmosphere of H_2 with constant effective diameter of the gas particles during the entry. We used the cone base radius as characteristic dimension since Galileo probe is a blunt-nosed cone probe and the cone base area is often used to define the force and moments coefficients. In Neptune atmosphere these assumptions imply free molecular regime ($Kn > 10$) above 300 km to 400 km of altitude, depending on the value considered for the density (minimum to maximum in NeptuneGRAM), and continuum regime ($Kn < 0.01$) below around 100 km of altitude.

Numerically simple techniques were used for simplicity and speed of computation, avoiding CFD analysis, for determining the aerodynamic coefficients. They were calculated for the Galileo probe geometry using the modified Newton method in the continuum regime and the diffusive reflection model with Maxwellian velocity distribution in the free molecular regime; an interpolation between both methods depending on $\log Kn$ was used in the transition regime. The modified Newton method is not precise at low Mach numbers so the simulations can only consider the hypersonic part of the entry. For lower speeds other methods should be used. Because of that, the stop condition considered for the simulations was Mach number lower than 4. On the other hand these methods do not take into account the effects of the sonic line transition, which is also a limitation (see discussion later in the paper).

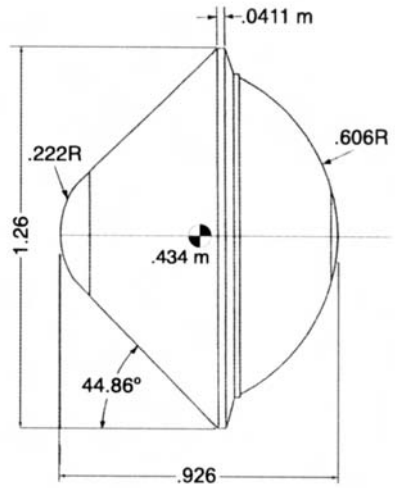

Figure 1. Galileo probe geometry [10] used in the Neptune entry simulations.

2.4. Probe and Initial Conditions

As already mentioned, a Galileo like probe was used in the simulations i.e. a probe with the mass (335 kg) and geometry (Fig. 1) of the Galileo probe. Initial position and velocity were chosen in accordance with a mission with aerocapture [6]. We considered the probe that is

Table 1. Initial conditions considered for a Galileo like probe entering Neptune atmosphere.

Entry characteristic		Neptune entry probe
Geodetic altitude	[km]	1000
Inertial velocity	[km/s]	29
Flight path angle	[deg]	-15.35
Latitude	[deg]	20
Angle of attack	[deg]	3.571
Roll rate (spin)	[rad/s]	0.25

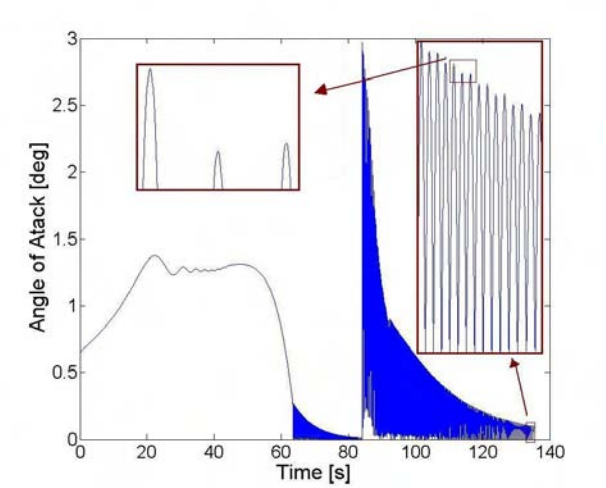

Figure 2. Angle of attack of MPF in a 6 DoF simulation using a heuristic variation of C_m taking into account the sonic line transition effect. Results agree qualitatively with literature. The zoom boxes show that there are no numerical problems but only lack of resolution due to high frequency oscillations.

released from the orbiter when still in a hyperbolic orbit (direct entry). Initial attitude was chosen for having a small angle of attack as expected. The probe slowly rotates about its symmetry axis for stability. Initial conditions can be found in Table 1.

3. TESTING AND VALIDATING: COMPARING WITH MARS PATHFINDER

Since the attitude code was new it was necessary to test both the code and the algorithms used in a real situation beyond simple standard test cases. Mars Pathfinder (MPF) was used to test and validate the results of the attitude module. Data from MPF is available from CFD analysis as well as from flight data that confirmed the numerical prediction [3, 4].

Comparison with MPF data show that the methods for determining the aerodynamic coefficients are limited when comparing with CFD analysis (which presents good agreement with flight data). In particular, the methods used (Newton method plus diffusive reflection model) do not predict the angle of attack instability. This instability is caused by the subsonic zone after the bow shock formed in front of the probe during the entry and it is designated by sonic line transition effect [3]. In order to compare the results we superimposed to the value of the coefficient C_M, determined by the methods, a heuristic variation depending on Mach number (a simple sine function).

Results of the evolution of the angle of attack with time with the heuristic C_m variation included are shown in Fig. 2. They qualitatively agree with literature showing

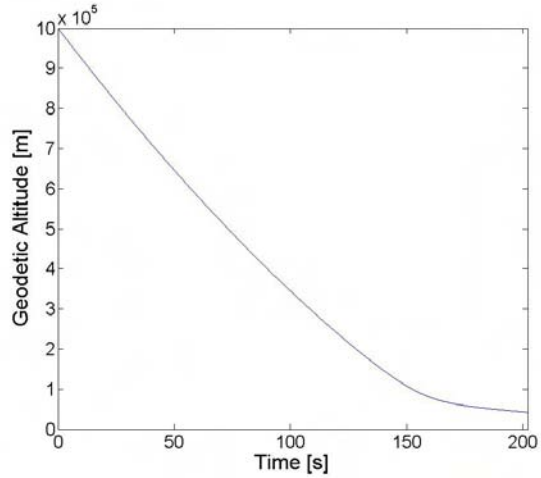

Figure 3. Altitude as function of time of a probe entering Neptune atmosphere in the hypersonic region of its trajectory (nominal case).

that if the sonic line transition effect is taken into account a simple calculation (not CFD) can deliver approximate results. Note that the shadow in Fig. 2 is not due to any kind of numerical instability but a question of scale, as shown by the zoom boxes.

4. RESULTS

Results from simulations are presented below. Calculations were performed for a nominal trajectory obtained from the stated initial conditions. From this nominal case some parameters were varied and Monte Carlo simulations were obtained and dispersion in latitude (Section 4.3).

4.1. Trajectory

Fig. 3 presents geodetic altitude as function of time for the nominal trajectory (Table 1). At about 150 s the variation of altitude starts to decrease since at that time the speed already decreased considerably (Fig. 4). Note that these simulations only consider the hypersonic region of the entry path since it was imposed that they stop running at Mach 4 due to the limits of validity of the methods that evaluate the aerodynamic coefficients (see Section 2.3). Because of that, simulations stop at about 40 km above zero altitude reference level (1 bar pressure level). The entry will continue for much longer time (up to 4 hours [5]).

Maximum load factor occurs at about an altitude of 80 km, slightly after the beginning of the continuum regime, and peeks at about 100 Earth g's.

A three dimensional view of the hypersonic part of the entry trajectory is presented in Fig. 6.

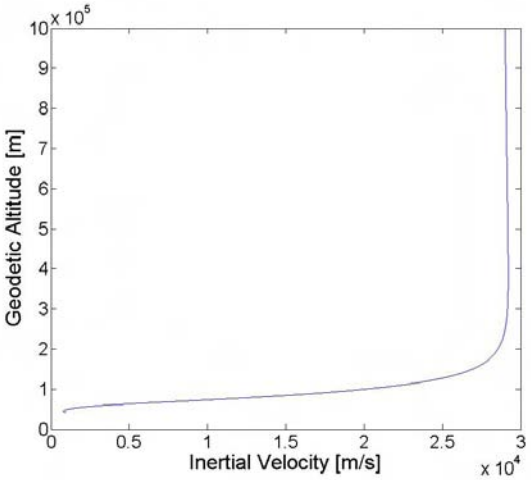

Figure 4. Altitude as function of velocity for the nominal case.

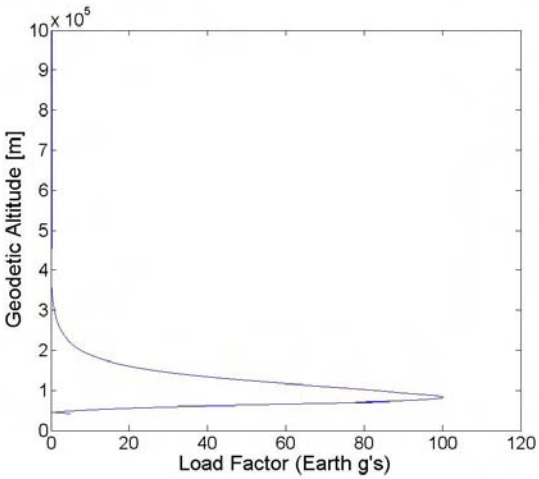

Figure 5. Altitude as function of the load factor measured in units of Earth g's for the nominal case.

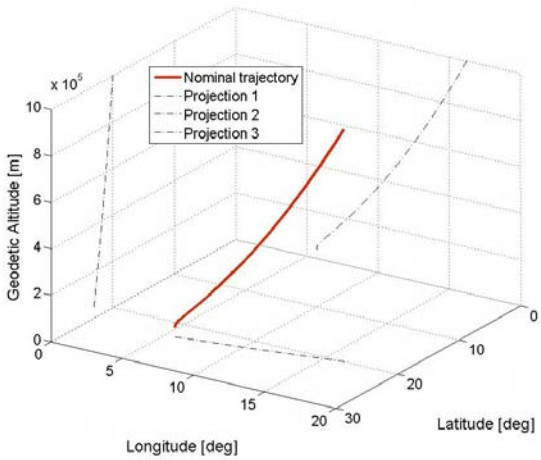

Figure 6. Three dimensional view of the trajectory for the nominal case.

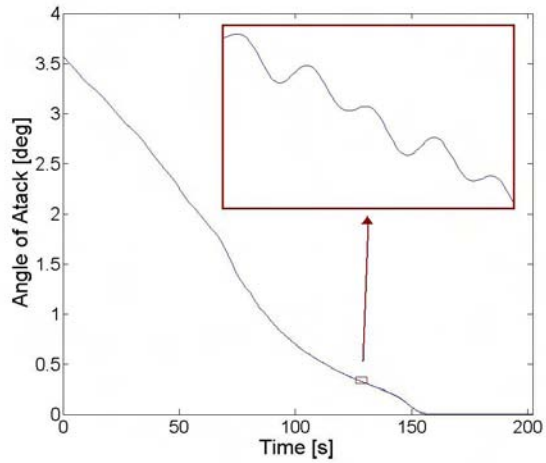

Figure 7. Angle of attack versus time during the entry for the nominal case. The zoom box show the small scale variations.

4.2. Attitude

Fig. 7 shows the variation of the angle of attack with time. The initial angle of attack was arbitrarily set for a sufficiently high value trying to detect any potencial stability problem (other than the sonic line transition effect, not detected by the algorithms used to calculate the aerodynamic coefficients as already discussed). The probe attitude stabilizes towards zero angle of attack during the hypersonic part of the entry with some small scale variations, as seen in the zoom box, without any instabilities. At this time no attempt to simulate the sonic line transition effect is made (see Section 5).

4.3. Monte Carlo Simulations

For assessing the variability of results with some parameters we performed Monte Carlo simulations. The parameters that were subject to variations can be found in Table 2.

Preliminary results for 400 Monte Carlo simulations suggest that there is no substancial difference between the 3 DoF and the 6 DoF cases, at least in this approximation where attitude stability stands. Horizontal dispersion (Fig. 8) at stop instants (at Mach 4 speed) vary between $5.00° - 6.38°$ longitude and $22.65° - 23.40°$ latitude. Uncertainty in longitude is larger because the velocity has a greater longitudinal component. The maximum load factor (Fig. 9) varies considerably (between 77 and 120 Earth g's) and clearly decreases when it occurs at higher altitudes.

Table 2. Parameters with their nominal values and associated uncertainties for running the Monte Carlo simulations.

		Nominal	$\pm 3\sigma$ or min/max	Distribution
Geodetic altitude	[km]	1000	–	–
Geodetic latitude	[deg]	20	± 0.5108	normal
Longitude	[deg]	16.2	–	–
Inertial entry speed	[km/s]	29	± 1	normal
Inertial flight path angle	[deg]	-15.35	± 0.5108	normal
Orbit inclination	[deg]	153.55	± 0.5108	normal
Fbias[a]		0	-0.56 to 0.56	uniform

[a]Parameter defining variability of the atmosphere in NeptuneGRAM; see Section 2.2.

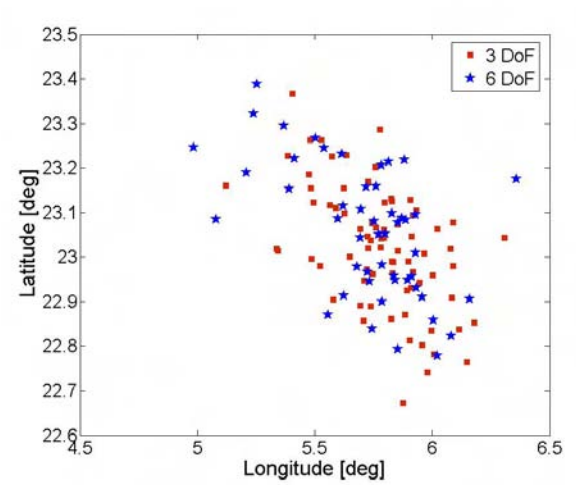

Figure 8. Horizontal dispersion for the 3 DoF and 6 DoF Monte Carlo simulations at stopping condition (Mach 4 reached). The altitude is approximately 40 km above the reference zero altitude.

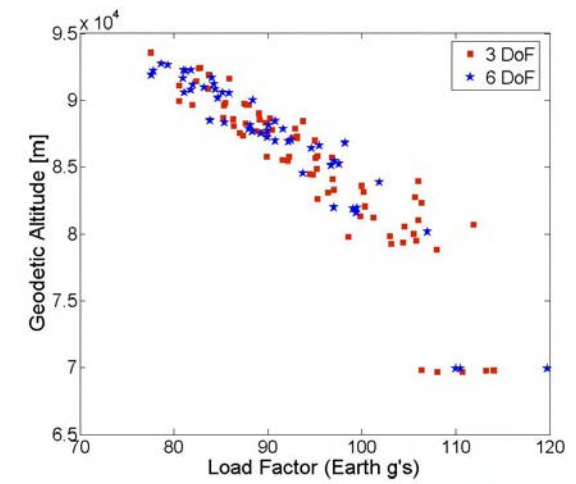

Figure 9. Altitude at maximum load factor versus maximum load factor for the 3 DoF and 6 DoF Monte Carlo simulations.

5. CONCLUDING REMARKS AND FURTHER WORK

The 6 DoF extension of ENTRAP allowed to reproduce approximately the MPF results. Although the methods used for determining the aerodynamic coefficients are simpler and faster than CFD analysis, they are restricted to the hypersonic regime and fail to predict possible attitude instabilities due to the sonic line transition effect.

The number of Monte Carlo simulations performed are small, hence just preliminary results are presented. Results suggest that there is no considerable difference between 3 DoF and 6 DoF simulations. However, since possible attitude instabilities due to the sonic line transition effect could be present, this conclusion will have to be confirmed.

The sonic line transition effect was not taken into account, not even with a heuristic formula, in the simulations for Neptune. One possible way of improving the results without using CFD analysis would be trying to obtain a way of including the sonic line transition effect. Attitude stability is a matter of crucial importance and can not be an open question.

It is also necessary to extend the calculations to the supersonic and subsonic regimes. The goal was to achieve (acceptable) approximate results with simple calculations but this task can be unattainable and its feasibility is still to be proved.

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