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AUTONOMY AND ON-BOARD MISSION MANAGEMENT ASPECTS FOR THE CASSINI TITAN PROBE†

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Abstract—The Cassini mission is a joint ESA/NASA mission for the exploration of the Saturnian System. It consists of two components: an Orbiter designed to tour Saturn for 4 years (developed by NASA) and an atmospheric Probe to Titan, Saturn's largest moon (developed by ESA). The Probe's objective is to explore Titan's atmospheric composition and dynamics as well as its surface properties. The Probe will be carried by the Orbiter on a 6.5 year journey from Earth to Saturn with gravity assists at Earth and Jupiter. From a Saturn-centred orbit, the Probe is targeted for a 2.75 h atmospheric descent into Titan's atmosphere. The prediction of the Probe's trajectory and mission characteristics is complicated by the uncertainties included in the available data about Titan's atmosphere. As the mission success is dependent upon critical factors like the radio relay link geometry to the Orbiter (serving as relay for data transmission towards Earth), the limited power resources and the atmospheric descent profile, there is a strong need for adaptive control measures. Due to the transmission delay towards Saturn, ground control during the Probe's atmospheric entry and descent is excluded. Thus, on-board data analysis should lead to autonomous updates of the mission operations profile. Concepts to approach these problems will be discussed.

1. INTRODUCTION

Current space missions exhibit a rapid growth in the requirements for on-board autonomy. This is the result of increases in mission complexity, intensity of mission activity and mission duration. In addition, for interplanetary spacecraft the operations are characterized by complicated ground control access, due to the large distances and the relevant solar system environment:

- large delays between signal emission and reception
- signal degradation
- periods without ground contact
- uncertainties of the particular planetary environment
- long time intervals between launch and arrival.

To handle these problems, the spacecraft design has to include some form of autonomous control capability.

An interesting example for such requirements is provided by Cassini, the NASA/ESA mission for the exploration of the Saturnian System. It includes, in particular, a Probe to investigate the atmosphere of Titan, Saturn's largest moon. In the following are discussed the requirements and the means of the Probe's autonomous control during its descent through Titan's poorly known atmosphere.

After a summary of the Titan Probe mission in Section 2, the particular uncertainties influencing the Probe's trajectory are described in Section 3. The quantitative consequences are discussed in Section 4, leading to requirements for an adaptive descent control as listed in Section 5. Section 6 discusses the means and effects for adaptive control actions, while the conclusions in Section 7 emphasize the potential use of these techniques for other missions.

2. CASSINI TITAN PROBE MISSION

The Cassini mission is aimed to further advance the exploration of the Saturnian System, initiated by Pioneer 11 and Voyager 1, 2. The mission consists of an Orbiter to observe the Saturnian System for 4 years and a Probe to Titan, Saturn's largest moon (Fig. 1). The NASA contribution to Cassini is a Mariner Mark II spacecraft to be used as Orbiter, while the ESA share consists of the Titan Probe. Titan is a target of particular interest, as it is the only moon in our solar system possessing a significant

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The research described in this paper was performed within the framework of the ESA Phase A Study for the Cassini Titan Probe. The ESA part of the Titan mission is now called "Huygens" honouring the discoverer of Titan.

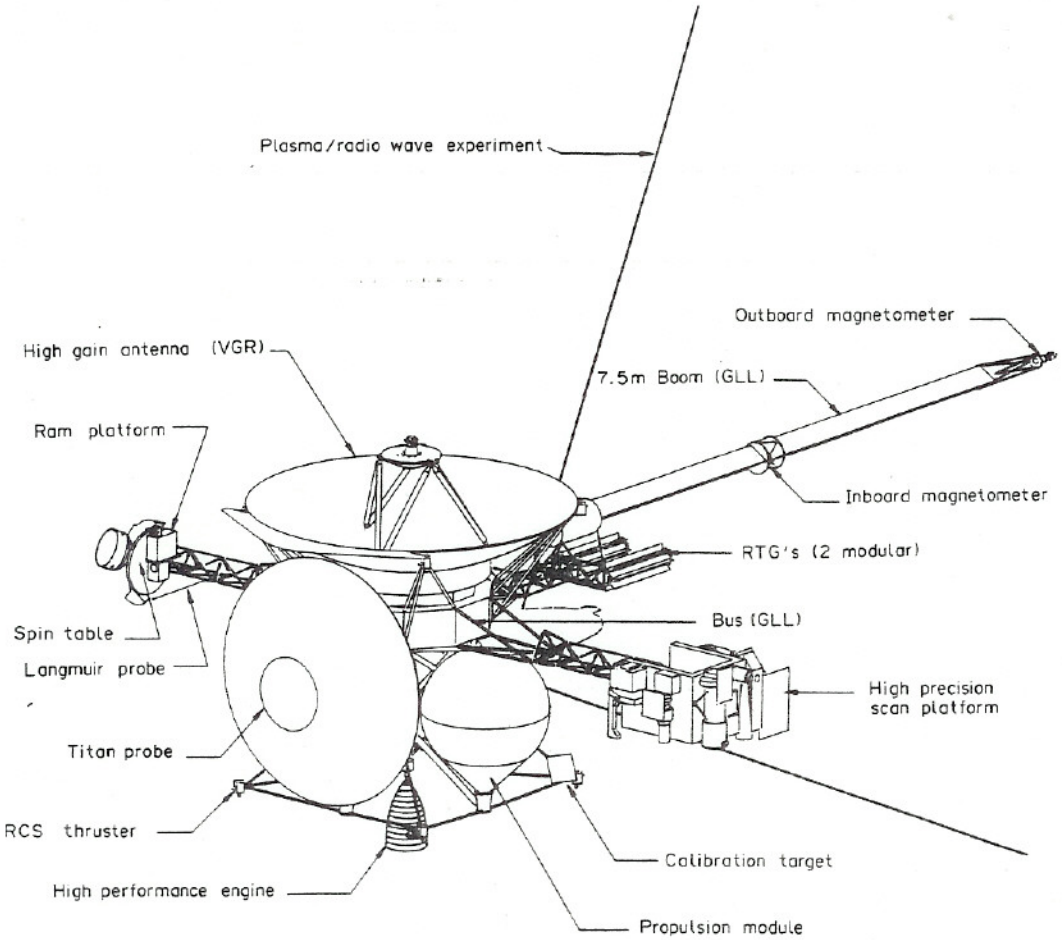

Fig. 1. The Cassini spacecraft composed of the Titan Probe (left) and a Mariner Mark II.

atmosphere. Like Earth it is composed mainly from nitrogen (approx. 90%), and even organic molecules have already been detected there. Therefore, this mission may well contribute to our understanding of processes of organic chemistry within the cosmos.

The design of the interplanetary trajectory is based upon a Titan IV launch and swing-bys at Earth and Jupiter, to bring the spacecraft (approximate injected mass: 5127 kg) into an orbit around Saturn (Fig. 2). The swing-by technique uses the given planetary environment to reduce the launch energy requirements at the cost of a longer flight time in comparison with direct trajectories (cf. [1,2]). By this type of trajectory the asteroid belt is penetrated twice, offering opportunities for asteroid observations (for the 1996 baseline trajectory, displayed in Fig. 2, it is the asteroid Maja). While this trajectory is very energy efficient (with $C_3 = 30\ \mathrm{km^2/s^2}$), the disadvantages are the extended flight time of 6.5 years and the launch window limited to starts in 1995, 1996, 1997, as favourable positions of the planets are necessary.

During the swing-by at Saturn, the spacecraft will be inserted into a highly excentric Saturn orbit with a period of 100 days (Fig. 3). Near apoapsis a pericrone raise (PCR) manoeuvre is carried out, including as a major objective the targetting for the Titan encounter. About 12 days before the Titan encounter, the Probe is aligned for its Titan aim point, spun up and separated from the Orbiter. The probe targetting requirements are as follows:

- Atmospheric entry and descent should be on the dayside of Titan.
- Atmospheric descent should occur within the latitude band (30°N, 30°S). Latitudes close to the equator ($\pm 5°$) are undesirable for the Doppler wind experiment.
- The selected entry trajectory should provide favourable conditions for the Doppler wind experiment.

In the subsequent Coast Phase the Probe approaches Titan on a ballistic trajectory, without any means for attitude control. About 2 days after separation, the Orbiter performs a deflection manoeuvre (ODM) in order to achieve an optimal Titan fly-by geometry for the following objectives:

- to act as relay for the radio relay link (RRL) of the Probe towards Earth and
- to get suitable start conditions for the subsequent 4 years of touring the Saturnian System.

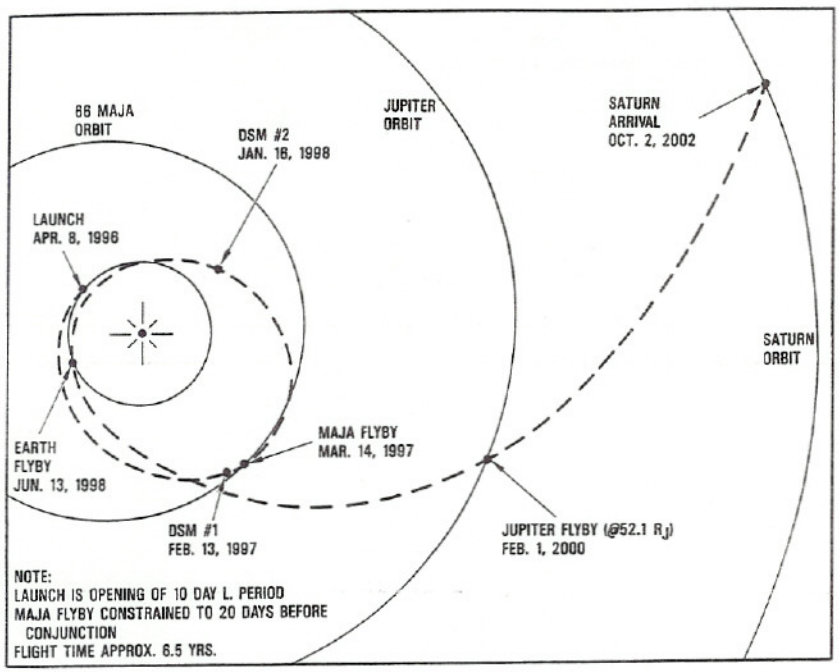

Fig. 2. Cassini 1996 baseline trajectory (courtesy of JPL).

The friction with the atmospheric particles is used during the Entry Phase to decelerate the Probe, which therefore includes a decelerator ring to enlarge its drag area (dia: 3.1 m, ballistic coefficient during entry: 16.6 kg/m^2). To maintain sufficient flexibility within the mission the Probe design is suitable for a broad spectrum of start conditions for the Entry Phase (given at a height of 1000 km):

- the entry angle ranges from $-90°$ to $-60°$
- the entry velocity could be selected between 5.8 and 7.1 km/s.

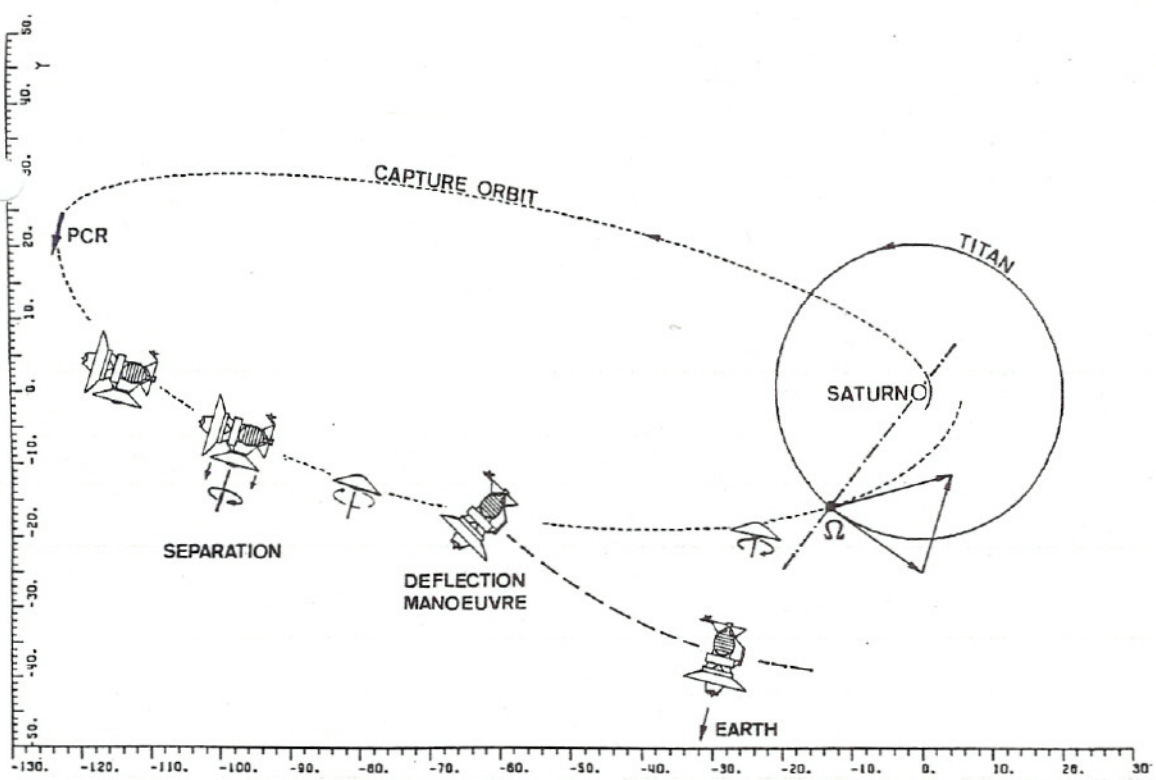

Fig. 3. Spacecraft manoeuvres from Saturn orbit insertion to Titan encounter.

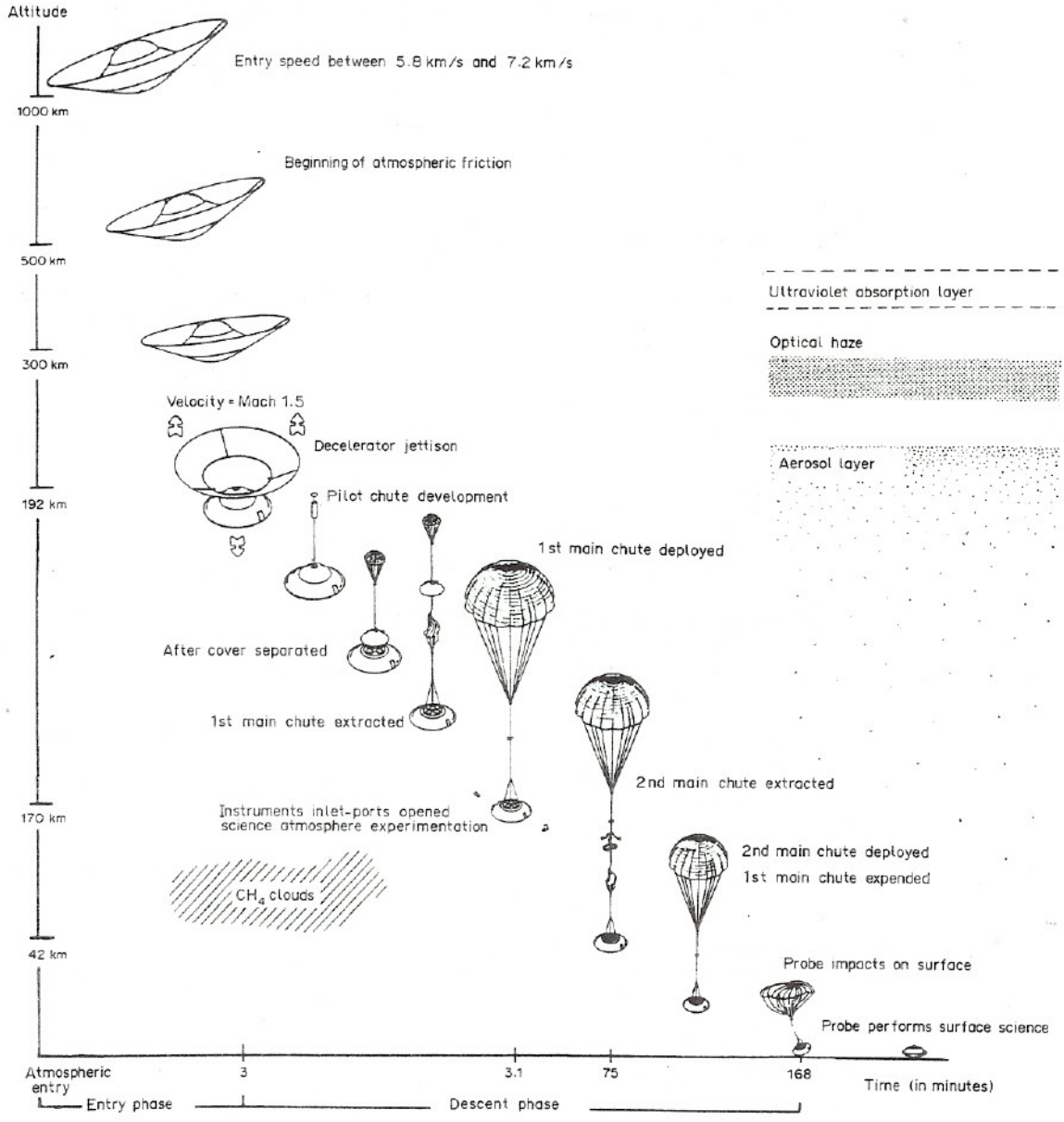

Fig. 4. The Probe's trajectory and operations in Titan's atmosphere.

Within approx. 3 min the Probe is slowed down to a velocity of Mach 1.5 (Fig. 4). Then the decelerator ring will be jettisoned (at an altitude of approx. 192 km). In consideration of a safe distance between the jettisoned decelerator and the Probe the Descent Phase starts with parachute deployment. By firing the mortar the pilot chute (dia: 1.84 m) is deployed, which subsequently pulls off the pyrotechnically released after cover and extracts the first main parachute. The pilot chute, the after cover and the deployment bag are expended. After inflation of the first main parachute (dia: 4.98 m, ballistic coefficient: 15.5 kg/m^2) the covers of the instrument ports are jettisoned, the acquisition of scientific data starts and data transmission to the Orbiter begins. Sufficient time is required in the upper layers of the atmosphere for the scientific experiments, although the nominal descent time is only 165 min. A viable concept is to deploy a second smaller parachute (dia: 2.31 m, ballistic coefficient: 46.6 kg/m^2) by use of the first main chute, which then is expended. If the Probe survives the landing impact on Titan's surface (it is unknown so far, if the surface is liquid or solid) and if the antenna is pointing in a favourable direction for the RRL, then additional surface science data may be obtained.

3. UNCERTAINTIES AFFECTING THE PROBE'S DESCENT

The aim of this section is to identify and summarize sources of uncertainty having impact upon the

Probe's trajectory. Most uncertainties derive from lack of environmental data, but some are due to engineering limitations.

3.1. Titan environment

The properties of Titan's atmosphere were intensively explored during the Voyager 1 close encounter with Titan (minimal distance: 3900 km) in 1980 and during the decade before by Earth-based observations. Although the Voyager measurements improved our knowledge about Titan tremendously, information relevant to the Probe's aerodynamic behaviour during entry and descent remains limited. It is currently not expected that there would be any major advancement of knowledge until the launch in 1996.

3.1.1. Atmospheric density. There are no temperature measurements available for the middle atmosphere (200–1270 km altitude). Therefore, a major gap in the knowledge about Titan's thermal structure and consequently in the related density profile results. The maximal decelerations of the Entry Phase will occur in this particular altitude range. Furthermore, crucial engineering design parameters such as the acceleration and the heat flux are proportional to the atmospheric density. Thus density data must be interpolated from measurements of the lower atmosphere (by i.r. and radio techniques) and the upper atmosphere (by u.v. occultation). Several models have been proposed for this purpose. The actual reference model developed by Lellouch and Hunten[3] replaces the assumption of isothermal behaviour used earlier by more realistic thermal features. In addition to the nominal density profile, this model also offers two extreme profiles, stating upper and lower bounds for the expected density by taking into account modelling uncertainties and measurement inaccuracies (Fig. 5).

The range below 200 km altitude is based upon radio occultation measurements and thus satisfies higher accuracy requirements. Due to the relatively long duration of the Descent Phase (165 min) the accumulation of deviations leads to considerable effects.

3.1.2. Atmospheric dynamics. During the Descent Phase, determined by the parachute, winds will cause a drift of the Probe leading to a displacement of the surface impact location. From the absence of a longitudinal thermal structure the existence of cyclostrophic zonal winds has been inferred from i.r. measurements[4]. It is assumed that the wind velocity decreases quite linearly from 100 m/s at a height of 200 km to 0 m/s at the surface (Fig. 6). But major seasonal variations are expected for the wind and temperatures field due to the derived atmospheric properties. Thus the inherent uncertainties are summarized by a variation of the model by a factor of two.

It is expected from analogy considerations with Venus, that the zonal winds flow from west to east,

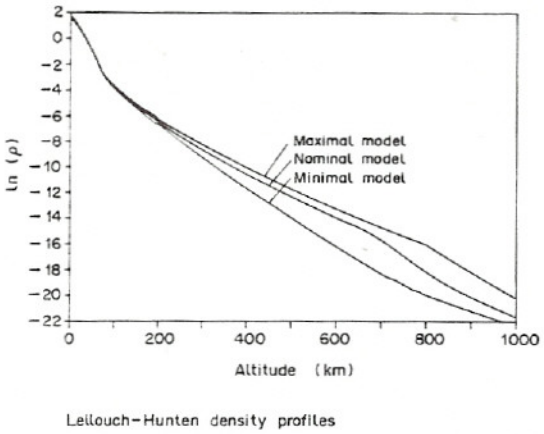

Fig. 5. The density ρ (kg/m^3) presented as a function of altitude according to the Lellouch/Hunten model[3]. In addition to the nominal profile, the two extreme profiles are also displayed.

but the measurements do not exclude the opposite direction.

So far no information about vertical wind is available. Their occurrence would exhibit major impacts upon the descent profile and in particular its duration.

3.1.3. Atmospheric precipitation. On its way to the surface the Probe has to cross haze and cloud layers. This could change the parachute characteristics due to condensation of aerosols and due to wettening by methane (CH_4) rain falls. But for the conical ribbon parachutes used, the geometric porosity does not change substantially and therefore only minor effects are expected with respect to the descent behaviour.

3.1.4. Topography. Although the two Voyager radio occultation measurements derived the same Titan radius, analogies with the relief profiles of other solid planets suggest that an uncertainty of ± 2 km should be included for the mean Titan radius. At the relatively low descent velocity before impact, this has major influences upon the total descent time.

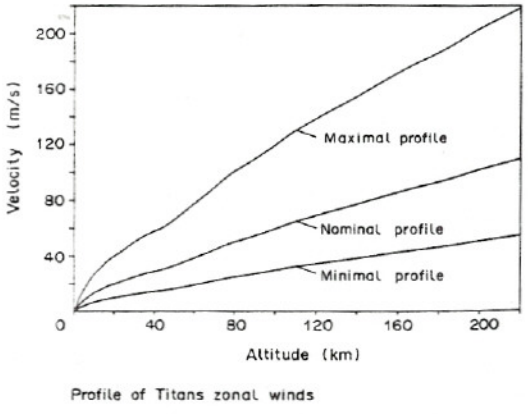

Fig. 6. The wind velocity related to altitudes as derived from the model due to Flasar *et al.*[4]. The extreme profiles are obtained by multiplying/dividing the nominal profile by the factor 2.

3.2. Engineering parameter

Inevitable sources for deviations are related to the achievable accuracy by the spacecraft's sensors, mechanisms and to real performance characteristics after the extreme conditions of the 6.5 years of interplanetary cruise.

3.2.1. Ephemeris of Titan and the spacecraft. The information needed to point the Probe accurately at separation are the spacecraft's actual position and velocity as well as a good knowledge about the Titan ephemeris. As Titan and the Cassini spacecraft orbit Saturn with different inclinations, a 3-dimensional analysis of the encounter is required. It is planned to improve information about Titan's ephemeris during the spacecraft's approach by optical measurements using the Orbiter's payload with subsequent ground processing. Improved parameters would then be used to update the spacecraft operations.

3.2.2. Separation manoeuvre. Before separation the Probe must be aligned by the Orbiter towards its Titan aim point to achieve the correct separation geometry, crucial for the separation-ΔV and the orientation of the spin axis. While the direction of the separation velocity vector is determined by the Orbiter's targetting accuracy (expected to be in the range of 3–12 mrad), the separation velocity depends upon the spin/eject device. Tests are needed to predict the properties of these mechanisms after 6.5 years storage in a deep space environment. The planned relative Probe separation velocity is in the range from 0.3 to 0.6 m/s.

3.2.3. Parachute drag coefficient. Although equally manufactured, parachutes usually exhibit some dispersion in the parachute performance, mainly in the drag coefficient c_D. In addition, wake effects have to be included in the assessment of the drag generated by the parachute in the presence of the Probe descent module as a forebody. Upper and lower bounds for this dispersion as a function of velocity could be inferred from wind tunnel tests.

3.2.4. Orbiter trajectory. The success of the Orbiter deflection manoeuvre determines the radio relay link geometry, in particular the acquired delay in Titan encounter with respect to the Probe and thus the profile for switching data transmission rates according to distance. As no radio link from the Orbiter to the Probe exists, the Probe does not receive any information about the Orbiter's actual position and has to rely upon prestored sequences according to the Orbiter's baseline trajectory. Thus, the data switching sequence has to include some margins for Orbiter trajectory dispersion.

4. IMPACTS UPON THE TRAJECTORY AND THE RADIO RELAY LINK

The aim of this section is to quantify the consequences of the environmental and engineering uncertainties for the trajectory and the related critical parameters for spacecraft design and operations.

4.1. Entry phase

During the Entry Phase the main influence of the uncertainties concerns the Probe's design requirements due to the expected acceleration forces and heat flux. In Fig. 7 the deceleration is displayed as a function of time. It includes the variation of the atmospheric density profile according to the Lellouch/Hunten (LH) model (Fig. 5) for an entry velocity $v = 7.12$ km/s (corresponding to the maximal hyperbolic approach velocity $v_\infty = 6.8$ km/s) and an entry angle $\gamma = -65.5°$. The obtained numerical results for critical design parameter are displayed in Table 1.

Due to the nonlinearity of the density profile, the maximal deceleration occurs in the minimal LH model: the velocity is higher in the upper atmospheric layers for the minimal LH model in comparison to the two other LH profiles, as these exhibit a higher density and thus create a fiercer deceleration. As the Probe enters the dense layers of the atmosphere with a much higher velocity, the forces due to friction are stronger and the maximal acceleration and heat flux is encountered for this situation. Finally, for the minimal LH model Mach 1.5 is reached most quickly and at the highest altitude.

Figure 7 includes two other extreme cases, obtained by varying in addition to the density profile the entry angle between $-55°$ and $-75°$ and the entry velocity between 5.9 and 7.12 km/s. Between the two data sets

$v = 5.9$ km/s, $\gamma = -55°$, LH model = maximal and

$v = 7.12$ km/s, $\gamma = -75°$, LH model = minimal

there are dispersions in

Peak deceleration by	168%
Peak heat flux by	143%
Altitude of Mach 1.5 by	27%
Time to reach Mach 1.5 by	48%

These numbers characterize the sensitivity of crucial Probe design requirements upon changes of entry angle and entry velocity, which could result from different release orbits or from dispersions caused by inaccuracies of the separation manoeuvre.

4.2. Descent phase

After deployment of the parachute most of the payload instruments start their measurements. In this phase the main influence of trajectory uncertainties is related to payload operations within the constraints of energy resources and to the radio relay link performance to transmit all acquired data.

The influence of winds causes a shift of the impact location of up to 700 km (dependent upon entry angle, wind velocity profile and wind direction). The variation of the wind velocity profiles in Fig. 8 is obtained by multiplying the nominal profile due to Flasar (cf. subsection 3.1.2.; Fig. 6) by the factor WINDMULT. Thus, the dispersion of the impact

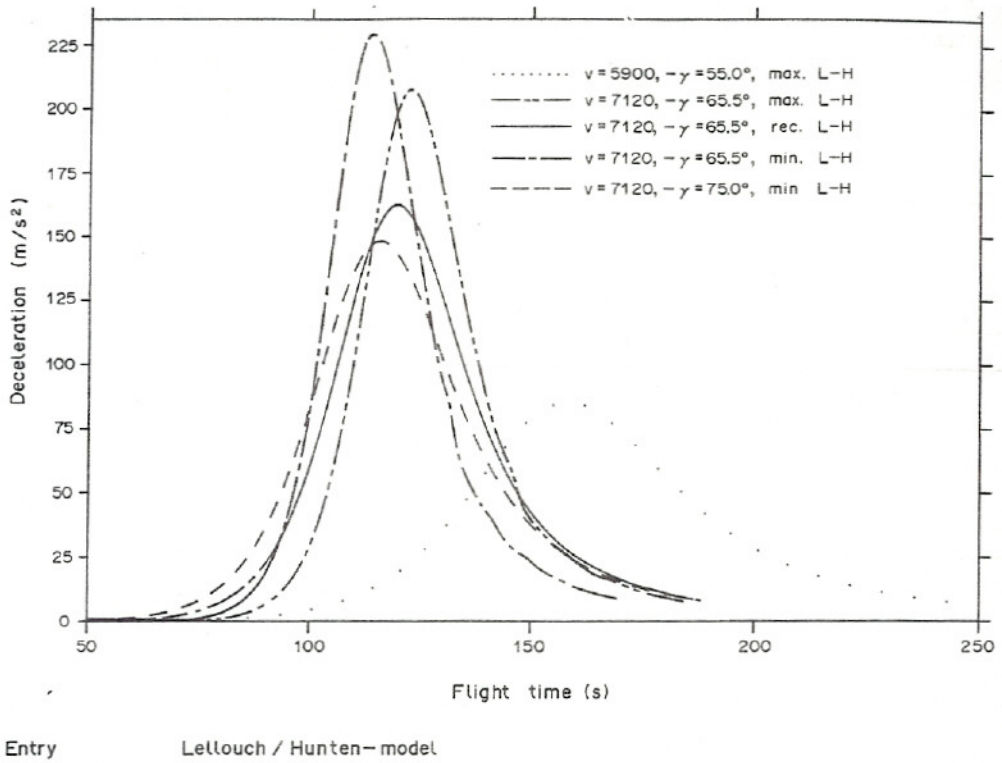

Fig. 7. Deceleration as a function of time, with the beginning of the Entry Phase (1000 km altitude) as origin. The presented profile illustrates the effects due to parameter variations with respect to entry velocity, entry angle and density profile.

Table 1. Effects upon the Probe's crucial engineering parameters caused by the variation of the density profile according to the range of the Lellouch/Hunten (LH) model

Parameter	Value at nominal LH model	Deviation for	
		Minimal LH model	Maximal LH model
Peak deceleration	162.4 m/s²	+28%	−9%
Peak heat flux	36.3 W/cm²	+15%	−4%
Heat load	1.562 kJ/cm²	−12%	+4%
Time to Mach 1.5	186.5 s	−1%	+1%
Altitude at Mach 1.5	191.2 km	−8%	+8%

location with respect to a descent without wind (WINDMULT = 0) at an entry angle of −60° is ±690 km for the extreme wind models (double wind speeds of the nominal model, corresponding to WINDMULT = ±2). While the effect of horizontal winds has no impact upon the height profile of the Probe's trajectory, the induced shift influences the radio relay link geometry and could lead to a surface impact on the night side.

The further effects influence the altitude/time profiles and in particular the total duration of the descent. The implications concern the payload operations as well as the radio relay link.

The variation of the density profiles (extending the trajectories of the preceding section to the Descent Phase) shows that dispersion in altitude at a particular time decreases with respect to mission progress (Fig. 9). The time span from atmospheric entry (1000 km attitude) to impact ranges from 162 min (minimal LH model) to 177 min (maximal LH model).

The sink velocity just before nominal impact is

5.3 m/s for the minimal LH model
4.9 m/s for the nominal LH model
4.6 m/s for the maximal LH model

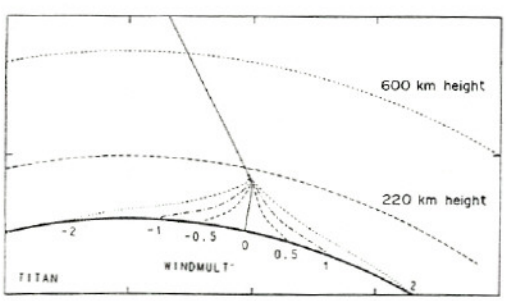

Fig. 8. The influence of horizontal winds upon the Probe's descent. These calculations are based upon an entry angle of −60° and the wind profiles from Fig. 6 (0 refers to no wind, negative numbers to winds from East to West, positive numbers to winds from West to East).

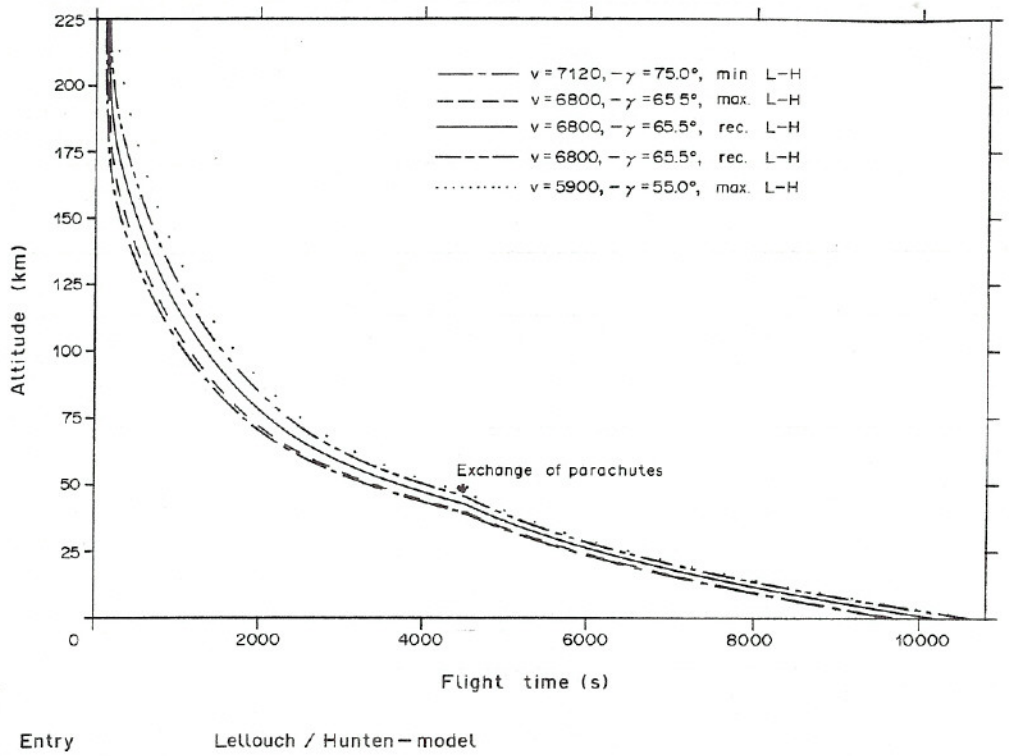

Fig. 9. The influence of parameter variations on the altitude profile of the atmospheric trajectory during the Descent Phase. The origin is the time at which Mach 1.5 is reached. The exchange of main parachutes is always initiated after 1.2 h.

This implies that the topographical uncertainty of ± 2 km leads to a maximal deviation in the descent duration by ± 7.2 min.

The dispersion of the parachute drag coefficient is assumed to be similar to former planetary missions leading here to $c_D = 0.495 \pm 0.07$. This implies for the nominal ballistic coefficient $\beta = 15.5$ kg/m^2 a deviation of $\Delta\beta = -1.7$ kg/m^2 and $+2.1$ kg/m^2 resp. This changes the descent duration (in the nominal LH model) by $+5.9$ min and -6.3 min resp.

4.3. *Radio relay link*

During the atmospheric descent, science and engineering data are transmitted to the Orbiter for relay to the Earth. The data are, however, also stored on-board the Orbiter for later replay. The RRL hardware comprises a medium-gain steerable antenna on the Orbiter and a fixed-mounted low-gain antenna on the Probe.

Table 2. Major effects influencing the Probe's descent duration. The given deviations describe the influence of just one factor to a trajectory characterized by the entry angle $\gamma = -65.5°$ and the entry velocity $v = 7.12$ km/s

Effect	Deviation
Atmospheric density	± 7.5 min
Drag coefficient	$\pm 5.9/-6.3$ min
Topography	± 7.2 min

The effective Probe antenna beamwidth is 120° including a margin of 16° allowing for $\pm 8°$ oscillations. This relatively large beamwidth has been selected to account for uncertainties in Probe location and attitude. Figure 10 illustrates the relative position between Titan, Probe and Orbiter.

Assuming a bit rate depending only on distance (512 bps at 100,000 km, 1024 bps at 73,000 km up to 16.384 at 19,200 km) the total amount of data transmitted before impact is a least 10 Mbits. This minimum performance figure takes into account uncertainties of Titan environmental models (density, atmospheric winds), uncertainties of Orbiter and Probe trajectories and a range of Orbiter fly-by conditions (fly-by altitudes 1000–15,000 km), but assumes an optimized Orbiter delay.

If the Orbiter fly-by altitude is restricted to values below 2500 km, then the minimum transferred data increases to 23 Mbits. It also allows for about 5 min post-impact transmission, provided the Probe antenna is pointing towards the Orbiter and the RRL is still functioning.

Figures 11, 12 and 13 show for a typical entry trajectory the time history of Probe aspect angle, Orbiter aspect angle, relative distance and the data transmission scenario.

An important parameter for the performance of the RRL is the delay of the Orbiter which is strongly connected to the duration of the atmospheric descent

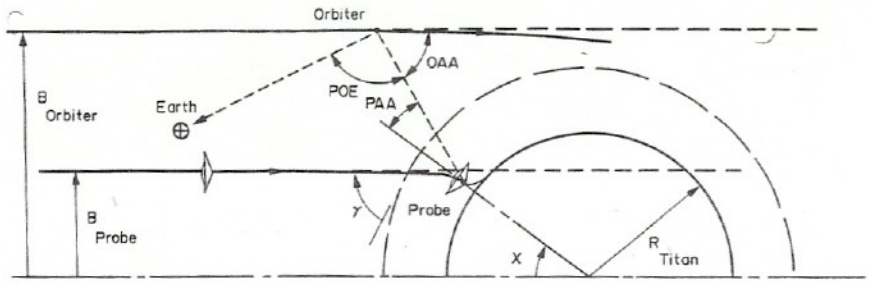

Fig. 10. The radio relay link geometry, introducing the crucial parameters Probe aspect angle (PAA), Orbiter aspect angle (OAA), angle between Probe/Orbiter/Earth (POE), and entry angle γ.

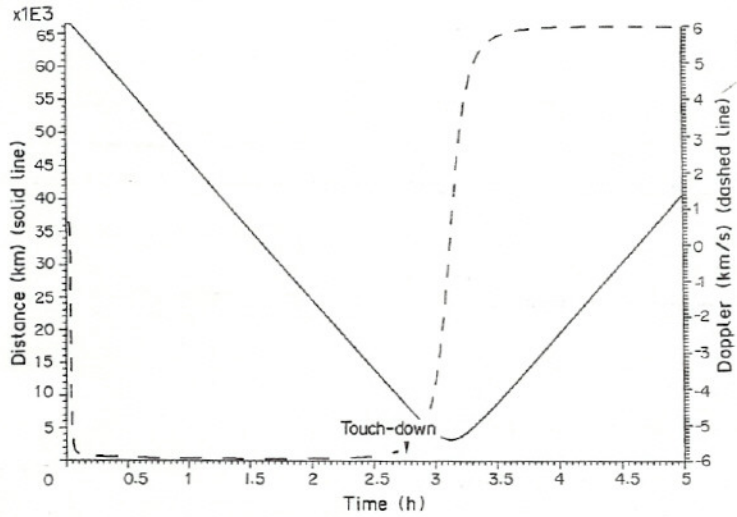

Fig. 11. Orbiter–Probe relative velocity and distance.

including uncertainties. As the period around surface impact has a high scientific priority, the delay must be selected such that even for the maximal possible descent duration the Orbiter is still in the Probe's field of view at impact. Having adjusted the Orbiter delay according to the maximal descent duration, the worst case regarding data transmission occurs in the situation of minimal descent duration.

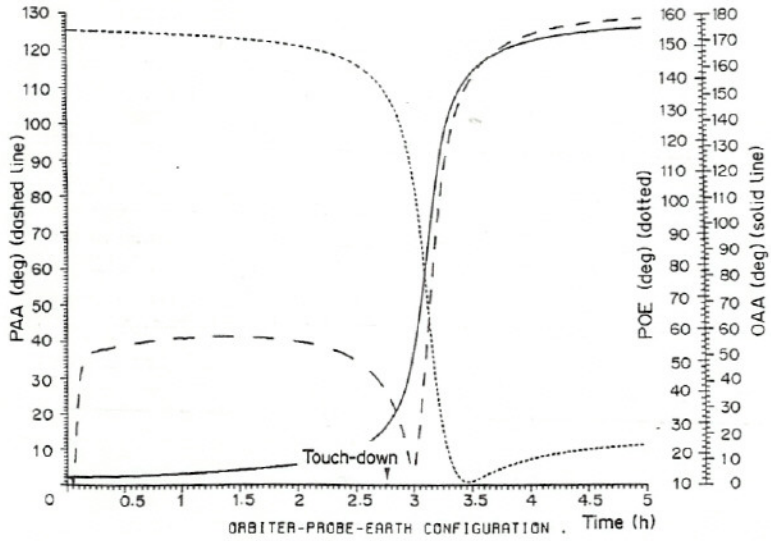

Fig. 12. Time profiles of the relevant angles for the radio relay link geometry.

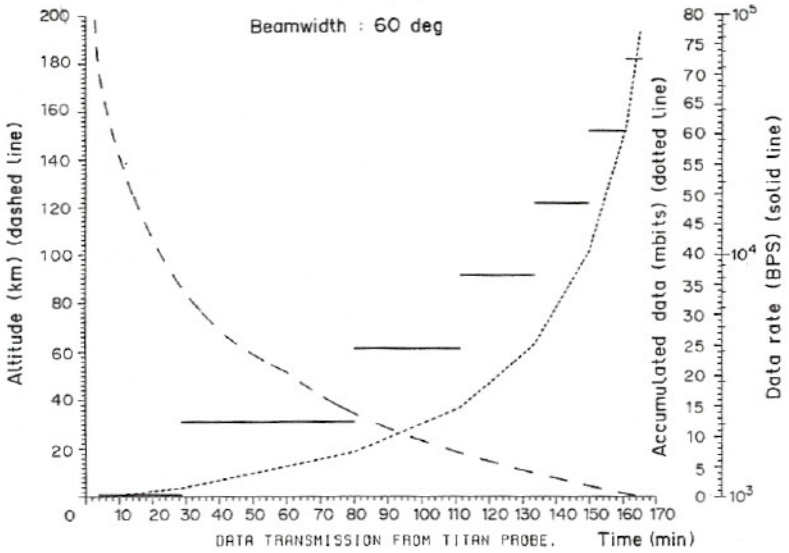

Fig. 13. Data transmission rates and accumulated transmitted data for the nominal descent trajectory.

5. AUTONOMY REQUIREMENTS

Réal time ground control of the Probe's operations in Titan's atmosphere is not feasible as the signal round trip time is about 180 min. Thus, no telecommand downlink capability to the Probe is foreseen. This implies that the Probe has to operate fully autonomously during Coast, Entry and Descent Phase. This includes in particular the adaption to the uncertainties addressed before.

During the interplanetary cruise there is a requirement for check-outs of the Probe system at half year intervals. The Orbiter's role is only to invoke this selftest and to transmit the obtained data to ground control. This implies that autonomous test procedures have to be provided, including activation sequences, monitoring and data processing for all concerned subsystems and payloads.

In the case of detected malfunctions there are control measures required for damage containment, failure localization, diagnosis and isolation. The Probe's reconfiguration capability should then enable failure correction, mainly via redundancy switching. As long as the Probe is attached to the Orbiter, these functions can still be supported by ground control access via the Orbiter, but the autonomy of this failure management is mandatory for the time after separation.

During the 12 day Coast Phase the Probe is in an almost dormant state (except the timer), until the first warmups of subsystems and payloads start 2 h before entry. As the dispersion of the expected entry time is ± 1 min, the timer would be sufficient to evoke these events.

The initiation of the decelerator jettison and the subsequent parachute deployment at Mach 1.5 needs more attention, as the related time and altitude are sensitive upon deviations in density profile, entry angle and entry velocity (Fig. 7). During entry the accelerometers are operating and their measurements are used as basis for the deployment criterion.

With the beginning of the Descent Phase almost all experiments start operations at a required minimal altitude of 170 km. For a significant exploration of the upper atmospheric layers the Aerosol Collector and Pyrolyser (ACP) experiment requires 45 min for the Aerosol sample collection between 170 and 60 km, while the gas chromatograph/mass spectrometer (GCMS) needs 20 min between 170 and 100 km. On the other hand, the total descent time should be 165 min. These conflicting requirements are satisfied by a two parachute concept. After approx. 1.2 h the first parachute is released and replaced by a second smaller one.

The timing of this event is the major control action to influence the total descent time. It is to be optimized according to some form of trajectory prediction based on a parameter identification for the atmospheric density and dynamics model as well as the Probe's actual position and velocity from *in situ* measurements.

To maximize the scientific return, the operation modes of the different experiments have to be modified according to altitude. The adaptive payload control relys upon real-time measurements of the radar altimeter with functional back-up options provided by pressure sensors and accelerometers.

As the appropriate data transmission rate towards the Orbiter is dependent upon distance, a timer based switching sequence has to be incorporated.

There might also arise a potential demand for adaptive thermal control of the Probe's interior as in extreme situations during the Descent Phase the upper (40°C) as well as the lower temperature (−20°C) limit could be approached. The Beryllium front shield is used to store heat from the Entry Phase

in order to survive the succeeding phase in the cold Titan atmosphere with temperatures down to −200°C. This determines the hot case together with the heat dissipation of the operating units at the begin of the Descent Phase, while the cooling effects of the cold environment cause a steady decrease of temperature to reach the cold case just before impact. To prevent damages by leaving the admissible temperature range, reduced (hot case) or increased (cold case) instrument operations could be planned for critical situations.

In the case of unforeseen hazards affecting the Probe's aerodynamic properties or the parachute performance the adaptive control means should contribute to receive the best return at the new constraints.

In extreme situations there are two potential scarce resources:

- energy budget.
- data transmission budget.

Shortages would require decisions within the resource management on priorities in the payload operations plan. The concept of a flexible operations plan offers in particular the potential to adapt the mission profile even during the Cruise Phase to new scientific knowledge or to new scientific objectives and priorities.

6. ADAPTIVE DESCENT CONTROL

Several areas requiring autonomous operations have been identified in Section 5, but regarding the sophistication of a particular control implementation there is always a trade-off necessary between the benefits and the related costs and risks by increased system complexity. Often it is sufficient to base the events upon timer sequences or upon simple closed loop control schemes. For the adaptive descent control more investment seems worthwhile as its aim is

- to enable an appropriate descent profile for the acquisition of the scientific data
- to achieve a suitable RRL-geometry between Probe and Orbiter.

The Probe has only information about the expected Orbiter positions from a prestored baseline trajectory. Thus, the target with respect to RRL is to reach Titan's surface at some fixed time, according to which the Orbiter delay was optimized previously.

The means available to adapt the descent trajectory are timing of

- jettison of decelerator
- deployment of pilot chute
- deployment of first main parachute
- deployment of second main parachute.

The jettison of the decelerator ring marks the end of the Entry Phase. At this stage only timer and accelerometers can provide inputs for the decision to initiate this event at the planned velocity of Mach 1.5. Possible criteria are

(a) a fixed timer value
(b) a fixed period after the measurement of peak deceleration (cf. Fig. 7)
(c) the integration of accelerometer measurements to derive velocity
(d) the usage of the direct relation between the deceleration and the velocity profile.

The preferred solution is (d), as the deceleration/velocity profile is in the relevant range relatively independent from the particular entry velocity (Fig. 14) and density model (Fig. 15). But also (c) is an interesting option, if the propagation of errors due to measurement accuracy and deviations in the initial velocity vector can be sufficiently bounded. Options (a) and (b) are kept as simpler back-up solutions.

According to the baseline, a short time after decelerator jettison the mortar is fired to deploy the pilot chute, which immediately extracts the main chute. The whole sequence from mortar firing to inflation of the first main parachute is expected to last less than 3 s. If it is needed to accelerate the descent, there is the option to delay either the deployment of the pilot chute or of the first main chute. The instrument covers, including in particular the heavy Beryllium nosecap, can only be jettisoned with a fully inflated main chute in order to prevent impacts with the Probe's main body. The payload operations requires open inlets and thus constraints arising from required minimum heights for data acquisition, limit the delay of the parachute deployment. Therefore, these options will not be detailed in this paper.

The preferred measure to adapt the descent speed is the timing for the exchange of the main chutes. In the baseline profile this event is foreseen 1.2 h after the begin of Descent Phase. If a faster descent should be required, the parachute exchange happens earlier, while a extension of the descent duration is achieved by a later exchange. The attainable descent durations by this mean range from 2.25 to 3.9 h for the recommended LH model (Fig. 16).

To initiate the event at the appropriate time, there are periodic comparisons between the reference trajectory and the actual measured altitude and time (by the radar altimeter/timer). Checks at 15 min intervals should be sufficient, but around critical phases like deployment of first parachute and around the time of parachute exchange the frequency is increased to one comparison every minute. If major deviations are detected, some trajectory prediciton should be started. After a nominal deployment (descent time: 1.2 h, altitude: 42 km) the maximal dispersion in descent time only due to the extreme density profiles of the LH model is still 8.3 min. This recommends an identification of crucial inputs for the descent trajectory like parachute drag coefficient, density model

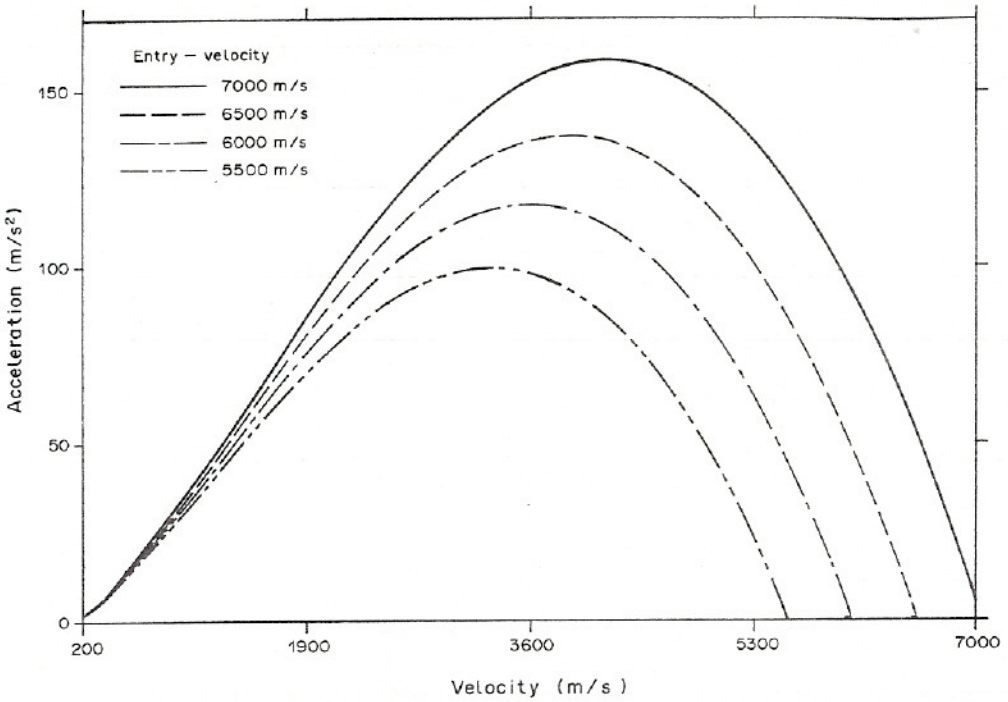

Fig. 14. The deceleration displayed as a function of velocity for different entry velocities. The related entry angle is −65.5°; for steeper entry fiercer accelerations occur, but the behaviour is similar. As the Probe's velocity steadily decreases with respect to progressing time, the related point in the diagram moves from the right to the left-hand side.

parameters from accelerometer and pressure sensor measurements. The acceleration due to drag a_D is given by

$$a_D = -\tfrac{1}{2} c_D \rho \frac{A}{m} \cdot v^2$$

with

c_D = drag coefficient
ρ = atmospheric density
A = effective cross section area
m = Probe mass
v = Probe velocity.

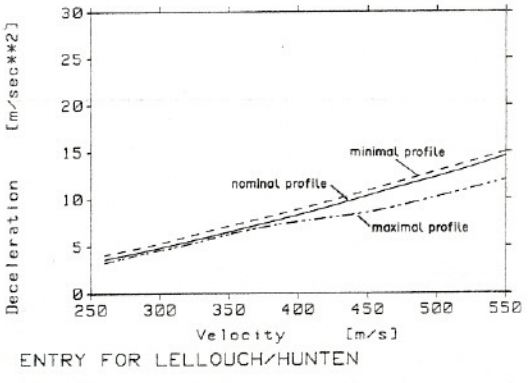

Fig. 15. The deceleration presented as a function of velocity, varied according to the three density profiles of Fig. 5 in the range near Mach 1.5.

With a sufficient degree of accuracy the density can be approximated as a function of altitude h by

$$\rho(h) = c_1 \cdot \exp(c_2 h)$$

depending upon the parameter c_1, c_2.

The constants $c_D \cdot c_1, c_2$ can be inferred from a set of actual measurements by some least squares fit.

Using these parameters as inputs, the integration of the Probe's equations of motion (including in addition to drag also gravitation and wind forces) allows a prediction of the descent trajectory and the expected descent duration. The timing of parachute exchange is adjusted in this model until the required total descent time is obtained.

This approach includes the option for an additional interesting feature: according to this predicted trajectory, together with the payload operations plan the consequences for the related energy budget profile can be derived. If an energy shortage is predicted the payload operations should be adapted. In extreme situations even an additional variation of the time for parachute exchange can be considered until the power requirements are met.

A simpler back-up alternative for timing the parachute exchange is to extrapolate the sink velocity derived from radar altimeter data via difference quotients. Together with the measured altitude the descent duration can also be inferred.

The decision to initiate the parachute exchange is always based upon the information available, thus

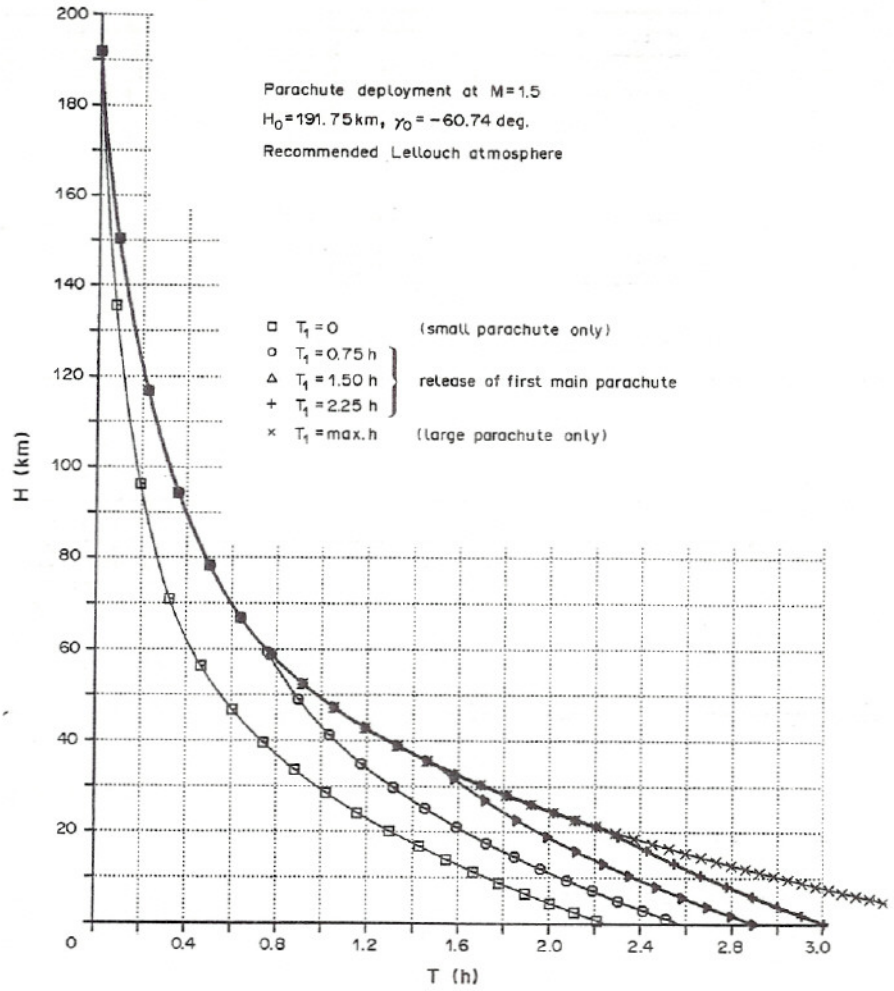

Fig. 16. Effects upon the altitude profile and descent time due to the time at which the main parachutes are exchanged. Entry conditions: $\gamma = -65.5°$; $v = 6.8$ km/s.

the future uncertainties, for example topography or (unlikely) major density profile deviations, still persist.

Nevertheless the approach developed here (Fig. 17) leads to a major reduction of uncertainties in the descent profile and offers the potential to adapt to requirements arising from updated energy budgets. There results a major reduction of the margins, which must be included in the Orbiter delay timing due to Probe descent uncertainties. Thus the available data transmission budget increases.

7. CONCLUSIONS

The aim of the presented adaptive control scheme is to reduce the uncertainties inherent in the Titan Probe mission. This implies that in near real-time from *in situ* measurements crucial parameter are autonomously identified, trajectory predictions derived and decisions drawn. The related software seems to be implementable within the available processor resources (1 redundant MAS 281 processor).

In a parallel technology study (cf. [5]) expert system techniques were studied to increase the on-board autonomy, taking the Cassini Titan Probe as an example. In this study, more complex decision rules are implemented, supported by a knowledge base. With the steady increase of computational capability this approach should offer interesting future applications in the area of on-board mission management.

Future planetary missions (to Mars, to comets and to asteroids) exhibit similar problems arising from the operations in an uncertain environment with limited ground control access. There might also arise requirements for an autonomous adaption of the mission plan.

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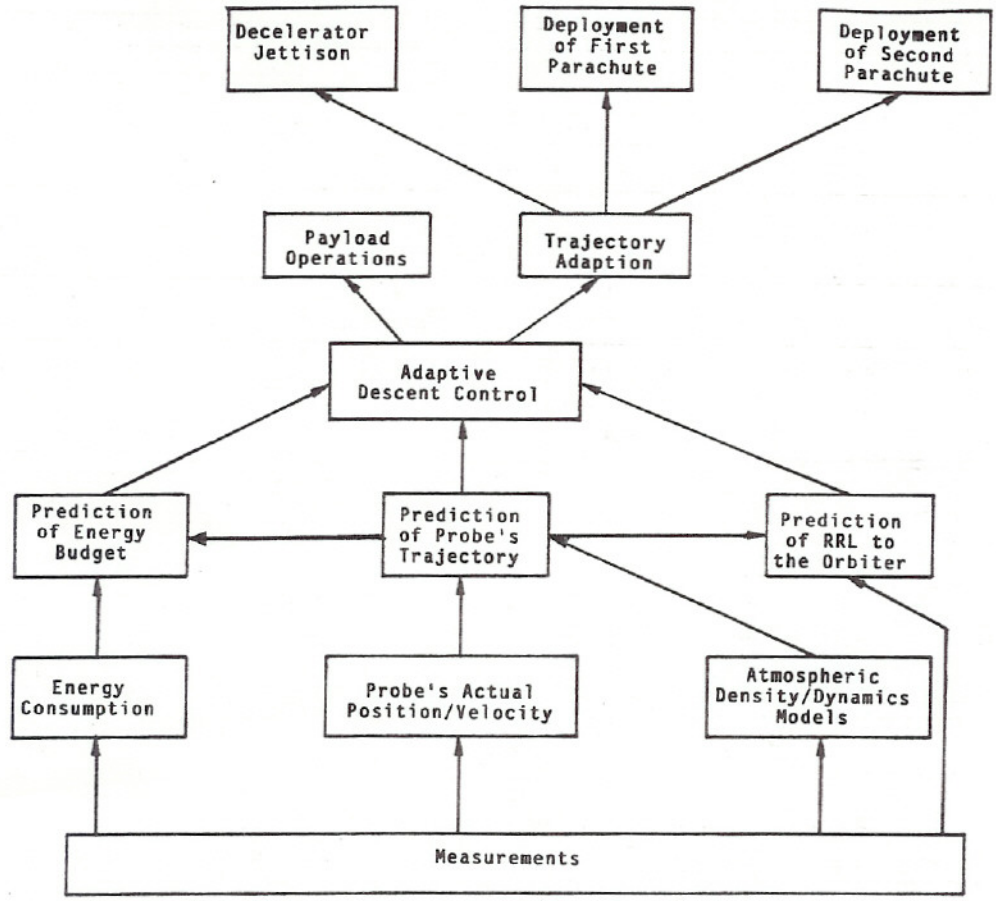

Fig. 17. The information flow for the adaptive descent control.

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