

The Huygens Mission to Explore the Saturnian Moon Titan

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ABSTRACT: Exploration of the enigmatic atmosphere of Saturn's largest moon Titan was the objective of the HUYGENS descent probe, when it successfully landed at 14. January 2005 on the surface of Titan. The system design aspects of this mission and technical approaches are summarized in this contribution. In particular the evolution of the descent control system is outlined. Planned data are compared to measured performance data in Titan's atmosphere.

INTRODUCTION

Titan's unexpectedly dense atmosphere did not allow any glance to its surface, when the Voyager 1 spacecraft passed in a distance of just 4394 km in November 1980. Analyses of the atmospheric composition revealed large quantities of carbon based chemicals, including in particular methane. This placed a return to Titan with high priority on space exploration programs. Finally the NASA/ESA mission Cassini / Huygens^{1,2,5,6,12} emerged, where the CASSINI spacecraft was provided by NASA to perform remote observation of the Saturnian system over years, while the European Space Agency ESA contributed the atmospheric entry probe HUYGENS for in-situ analyses of Titan. This entry probe had a mass of 318 kg. On 14. January 2005 HUYGENS entered Titan's atmosphere, provided the planned scientific measurements and successfully landed on the surface. This paper reviews this challenging mission, its technical realization and the achieved results.

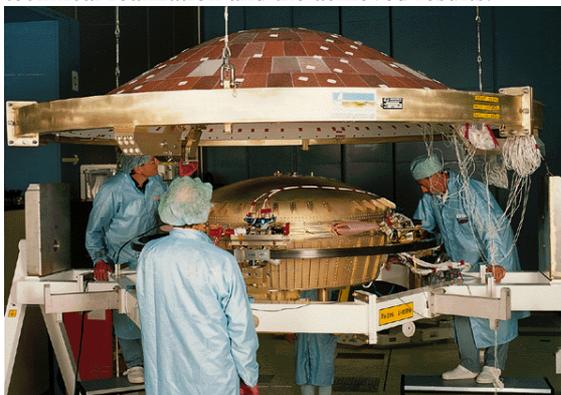


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Figure 1: Integration of the Huygens Probe

THE HUYGENS MISSION

An energy-efficient trajectory with fly-bys at Venus (twice), Earth and Jupiter transferred the spacecraft after the launch on 15 October 1997 to an arrival in the Saturnian system on 1. July 2004⁸. After injection into an orbit around Saturn in the subsequent 4 years flybys at Titan change the trajectory for an appropriate tour of the Saturnian system¹³.

On the way by simulation tests an anomaly in telecommunication link between HUYGENS and CASSINI was detected. Therefore a mission redesign was performed in order to reduce the Doppler effect⁹. While at the originally planned Probe release at the first close Titan flyby, a maximum relative velocity between the two spacecraft of 5.7 km/s was predicted, in the finally realized scenario during the third close Titan flyby the Orbiter approaches Titan at a larger displacement of 60000 km towards the Probe path.

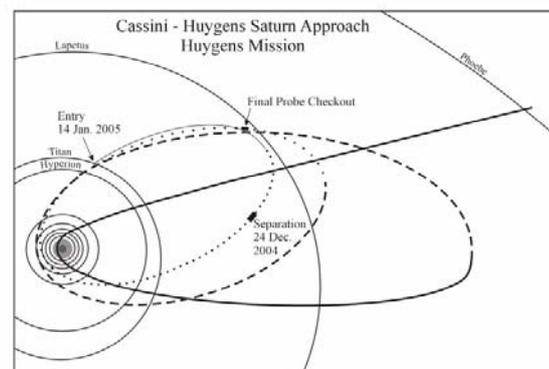


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Figure 2: The CASSINI / HUYGENS trajectory before Titan entry

Thus the relative velocity was reduced to 3.8 km/s, enabling the telecommunication system to deal with the related Doppler effect. After two close fly-bys at Titan, allowing further characterisation of its properties, the HUYGENS probe was released from CASSINI towards Titan on 25. December 2004. The probe coasted spin-stabilized towards Titan in passive state, having only the 3 times redundant alarm clocks running in order to power up the system before entry.

There is a signal propagation delay of 67 minutes due to the distance towards Earth. Thus only a data link from HUGENS towards CASSINI, acting as relay station to transfer the data, was implemented. Thus the probe had to act autonomously after separation from the orbiter. As uncertainties in atmospheric properties (atmospheric density profile, atmospheric dynamics) have a feedback on the descent trajectory, several options to adapt the descent profile had been analyzed. It was planned to land on the surface of 2.5 hours after entry. Thus surface measurements can be transferred, before the CASSINI orbiter moves over the horizon and the link is lost.

THE HUYGENS SPACECRAFT DESIGN

The HUYGENS entry probe with a total mass of 318 kg carries 6 experiments^{1,2,5} to characterize the Titan atmosphere and surface:

- Atmospheric structure instrument,
- Gas chromatograph / mass spectrometer,
- Aerosol collector and pyroliser,
- Descent imager / spectral radiometer,
- Doppler wind experiment,
- Surface science package.

The core body consists of an aluminium shell (cf. Fig.1). The conic front shield, with a diameter of 2.7 m and a mass of 79 kg, protects the probe interior during hot entry phase. By a sequence of three parachutes^{7,11}, the transfer through the atmosphere is realized:

- a pilot chute with diameter of 2.59 m, which extracts the main parachute,
- a main parachute with a diameter of 8.3 m, which provides sufficient staytime for sampling in the upper atmospheric layers,
- a stabilizing parachute with a diameter of 3.03 m to accelerate descent, in order to arrive in time at the surface.

Power was provided by 5 Lithium Sulfur Dioxide batteries. During the transfer from Earth to Saturn all power was provided from the orbiter. At the begin of December battery depassivation was performed, after separation from the orbiter just the alarm clocks were powered during the coast towards Titan, starting powering up the subsystems about 4,3 hours before the entry into Titans atmosphere.

The on-board data handling's main task is to control the timing of the descent as well as of the payload activities.

The Probe Data Relay subsystem provides a one-way link to transfer the measurement data towards the CASSINI orbiter, acting as relay station before finally transmitting them to Earth. As tumbling motion of the probe body underneath the parachute due to wind was expected, the telemetry was send in a redundant way at a delay of 6 seconds by two S-band transmitters towards the orbiter. A problem with the ultrastable oscillator in the receiver onboard the orbiter caused the loss of data from one transmission channel.

THE DESCENT CONTROL SYSTEM EVOLUTION

When the HUYGENS probe development activities started in 1986, the information base about Titan was rather poor, but improved continuously. While in the beginning more complex adaptive systems were designed to compensate the lack of knowledge, the improved atmospheric models coming up enabled simpler control criteria later.

Approach by Expert System Technologies

Real time expert system techniques were considered as efficient means to deal with the atmospheric uncertainties⁴. This work addressed optimization of the scientific return by adapting the mission parameters in the Scientific Management, as well as failure diagnosis and recovery by the spacecraft bus in the Engineering Management. Thus in the Scientific Management the timing of activities affecting the

- descent profile (parachute deployment, exchange of parachutes, heat shield separation),
- instrument operation modes to operate according to measured environment the appropriate instruments in order not to waste energy and data storage capacity,
- energy consumption (based on measured energy consumption priorities on how to best invest the remaining power are set)

is analyzed.

Goal	Subgoal	Major Tasks
Maximisation of scientific gain	Optimisation of - descent profile - operation modes - energy consumption - data transmission	Determination of position and velocity Adaptive descent control Updates of data base according to measurements Predictions of - remaining resources (energy, data link) - probe's trajectory - link geometry Payload operations

Table 1: Structure of Scientific Management upper layers

An expert system based on facts (estimated values updated by measurements as soon as they become available), models (of Titan, orbiter and probe trajectories, of atmospheric density profiles updated to most recent facts) and rules (procedures to adapt

the knowledge base to draw conclusions, algorithms) was implemented and initially tested by hardware in the loop simulations.

Despite good test results, the software complexity was considered too risky and the storage requirement of 400 kB in radiation hard components was at those days a problem.

Adaptive Descent Control

The adaptive control approach¹⁰ is based on improving process models and related controls by continuous identification from measurements of characteristic parameters of the atmospheric model and of the spacecraft properties. From that, the descent profile predictions are updated and subsequently appropriate control actions are initiated. The atmospheric density model is approximated by an exponential function with respect to altitude h

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

based on the model parameters c_1 , c_2 to be derived from measurements. In order to predict the forces determining the descent, the deceleration due to drag a_D is modelled by

$$a_D = -0.5 c_D \rho(h) A v^2 / m$$

with the Probe's properties drag coefficient c_D , effective cross section area A , mass m and velocity v .

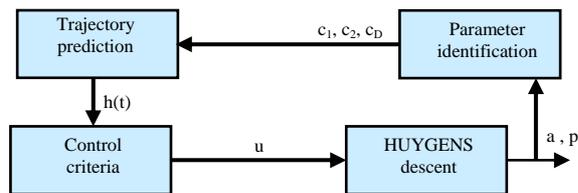


Figure 3: Schematic of the adaptive descent control system

As c_D might have changed during the long interplanetary transfer under extreme conditions, it might deviate from the values measured during wind channel tests before launch. Thus the parameters c_1 , c_2 , c_D are derived from continuous accelerometer and pressure measurements. At altitudes below 45 km the height above surface can be determined directly by the radar altimeter. Crucial actions to influence the descent profile concerned the timing of

- deployment of the pilot parachute,
- jettison of heat shield,
- exchange from large to small parachute.

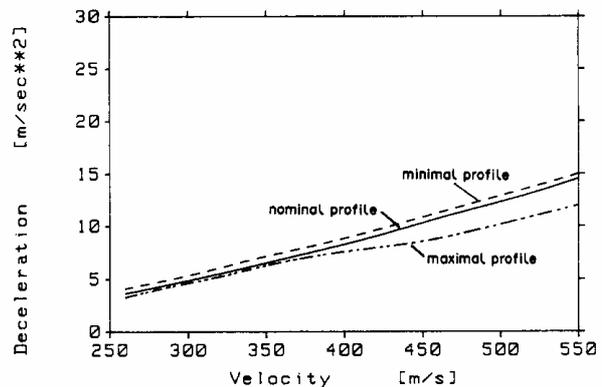
Thus within a reasonable environment parameter range, it was possible to adapt the descent duration according to mission needs.

Finally Realized Landing Sequence

Finally the Huygens mission had as only adaptive element the timing of the parachute deployment, inherited from the adaptive control approach. All other activities were based on fixed timer sequences. During the 7.5 years of transfer by new observations and re-analyses of Voyager data, the earlier Lelouch-

Hunten atmospheric model was replaced by the improved Yelle-model in 2000. Due to the trajectory redesign related to the radio anomaly, there were two close flybys at Titan, which were also used to collect further data on Titan's atmosphere enabling to update the atmospheric models and to adapt the descent timing sequence consequently.

The observation data of 2004 also indicated that earlier uncertain topographical height variations were less than 150 m and therefore would have no significant impact on descent duration. Thus deployment of the pilot parachute was initiated at the detection of an acceleration threshold of 10 m/s², correlated to a velocity of about Mach 1.5 (400 m/s).



ENTRY FOR LELLOUCH/HUNTEN

Figure 4: The velocity / acceleration profile, displaying the stability of the timing criterion for the main parachute deployment (at a velocity of 400 m/s) with respect to different atmospheric density profiles.

This pilot chute inflates 27 m behind the Probe body and directly removes the protective after cover in order to deploy the main parachute. At which altitude this would occur within an expected range between 180 km – 150 km remained uncertain. The heat shield was to be jettisoned 30 s later, while the exchange from the large to the smaller chute has been scheduled 900 s after parachute deployment. Then 2.5 hours after begin of the entry phase the Huygens Probe was planned to land on the surface of Titan.

DESCENT MISSION PERFORMANCE

On 14. January 2005 it became obvious that the Probe targeting was achieved with high precision, leading to an entry angle of 65.02°, compared to the planned 65°±3°. During entry a deceleration in the range 10 g – 20 g was expected, while a maximum of 122 m/s² was measured by the atmospheric structure instrument. At an altitude of about 150 km the main parachute had been deployed, followed by the inflation of the third smaller parachute at a height of about 115 km.

In the atmosphere a Methane content of 2 – 3 % was measured. Frequent temperature variations in the upper atmospheric layers were detected related to inversion layers. Clouds obscured the images much longer than expected and allowed to see surface feature only below an altitude of 30 km.

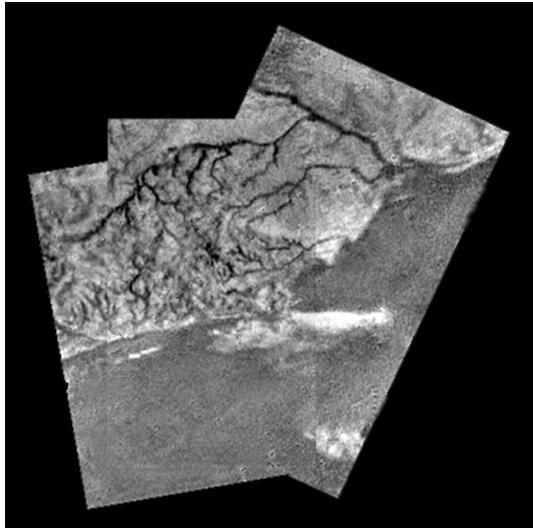


image courtesy of ESA/NASA/
University of Arizona

Figure 5: The surface of Titan from an altitude of 16.2 km

147 minutes after start of the entry (with respect to the reference altitude of 1270 km) landing at a velocity of 5 m/s and an deceleration of 15 g occurred. Measurements of the surface science package indicate a thin surface crust rich in organic molecules with softer layers underneath. The surface is a mixture of water/hydrocarbon ice with residuals of hydrocarbons causing the dark colours. At the surface a temperature of 93.65 ± 0.25 K and a pressure of 1467 ± 15 hPa was measured. After surface impact the gas chromatograph detected a significant increase in Methane, interpreted as evaporated liquids caused by the surface impact and the heat dissipation of the Probe into this cold environment.

CONCLUSIONS

Huygens offered interesting technology challenges at the implementation of the first European entry probe for the exotic atmosphere of Titan. From Phase-A-analyses to completed mission more than 17 years passed by. In that period the models of the Titan atmosphere improved, enabling much simpler structures of related descent control schemes. As the hardware selection was fixed early, the software offered the options to adapt to the increasing knowledge. After 7.5 years at extreme space conditions the Huygens Probe performed perfectly and provided data the scientists are analyzing to better understand the enigmatic atmosphere of Titan.



image courtesy of ESA/NASA/
University of Arizona

Figure 6: Titan's surface at the landing area

Acknowledgements

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<http://www.esa.int/SPECIALS/Cassini-Huygens> and <http://saturn.jpl.nasa.gov/>

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