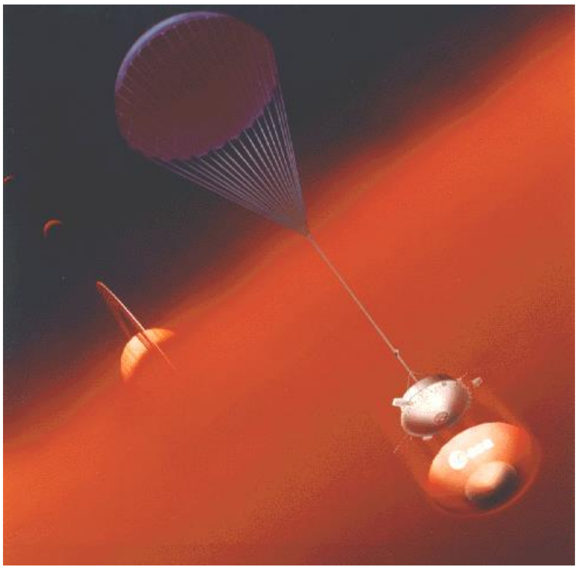
Huygens Flight Performance Validation



Executive Summary

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by

Vorticity Ltd

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Vorticity Limited
Hampden House, Monument Business Park,
Chalgrove, Oxfordshire, OX44 7RW, UK
Phone: +44 (0) 1865 893210
Fax: +44 (0) 1865 987230
Email: john.underwood@vorticity-systems.com

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SUMMARY

The Huygens mission was the first, and currently the only, successful ESA mission to land a probe on another planet or moon. It was the most distant planetary landing to date by any space agency and will remain so for the foreseeable future.

An industrial team comprising Vorticity Ltd, Fluid Gravity Engineering and the Von Karman Institute has carried out a study to examine aspects of the Huygens probe performance which were not as expected and to compile the lessons learned from the mission.

The current work has helped to explain some of the anomalies identified during the mission which allows future missions to benefit from the results of Huygens.

This document summarises the findings of the programme.

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REVISION RECORD

Issue	Date	Pages	Sections affected	Brief Description of change
01	2015-08-20	31	All	First issue
02	2015-11-06	16	All	Changed footers

This document contains 6 introductory pages and 10 pages of core text.

AUTHORISATION

	Name	Position	Signature
Prepared	Vorticity Team		
Edited	J.C. Underwood	Principal Engineer	John Underwood 2015.11.06 11:33:28 Z
Checked	Dr J.S. Lingard	Technical Director	
Released	Dr J.S. Lingard	Technical Director	

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1 INTRODUCTION

1.1 Purpose and Scope

The Huygens mission was the first, and currently the only, successful ESA mission to land a probe on another planet or moon. It was the most distant planetary landing to date by any space agency and will remain so for the foreseeable future.

An industrial team comprising Vorticity Ltd, Fluid Gravity Engineering and the Von Karman Institute has carried out a study to examine aspects of the Huygens probe performance which were not as expected and to compile the lessons learned from the mission.

This document summarises the findings of the programme.

1.2 Applicable Documents

AD	Title	Reference	Issue	Date
AD-01	No applicable document	None		

1.3 Acronyms and Abbreviations

CFD Computational Fluid Dynamics

CAD Computer Aided Design

DISR Descent Imaging Spectral Radiometer

FSI Fluid-Structure Interaction

SM2 Special Model 2

VKI Von Karman Institute

2 STUDY RESULTS

2.1 Introduction

Planetary probes are no ordinary spacecraft. In many respects the Huygens mission was unique in the ESA programme, also unique for the European industry and for the science community that provided the scientific payload. The Huygens probe was the first, and remains the only, successful ESA planetary atmosphere probe / lander.

The Huygens Probe was the ESA-element of the Joint NASA-ESA-ASI Cassini-Huygens Mission. ESA awarded the Phase-B/C/D/E contract to Aerospatiale, Cannes, in 1990. Huygens was developed in 1991-1997 and launched on board Cassini in 1997

The performance was close to expectations, or even in some cases, better than expected.

The Huygens probe reached Titan on 14th January 2005. The probe decelerated from the entry velocity of 6.03 km/s to the parachute deployment airspeed of 386 m/s whereupon the first of the three parachutes was deployed at Mach 1.49. The parachute system controlled the removal of the protective aeroshell and the subsequent descent of the probe through the Titan atmosphere.

The probe impacted the surface of the moon after a descent of 2 hours and 32 minutes and continued to operate for several hours.

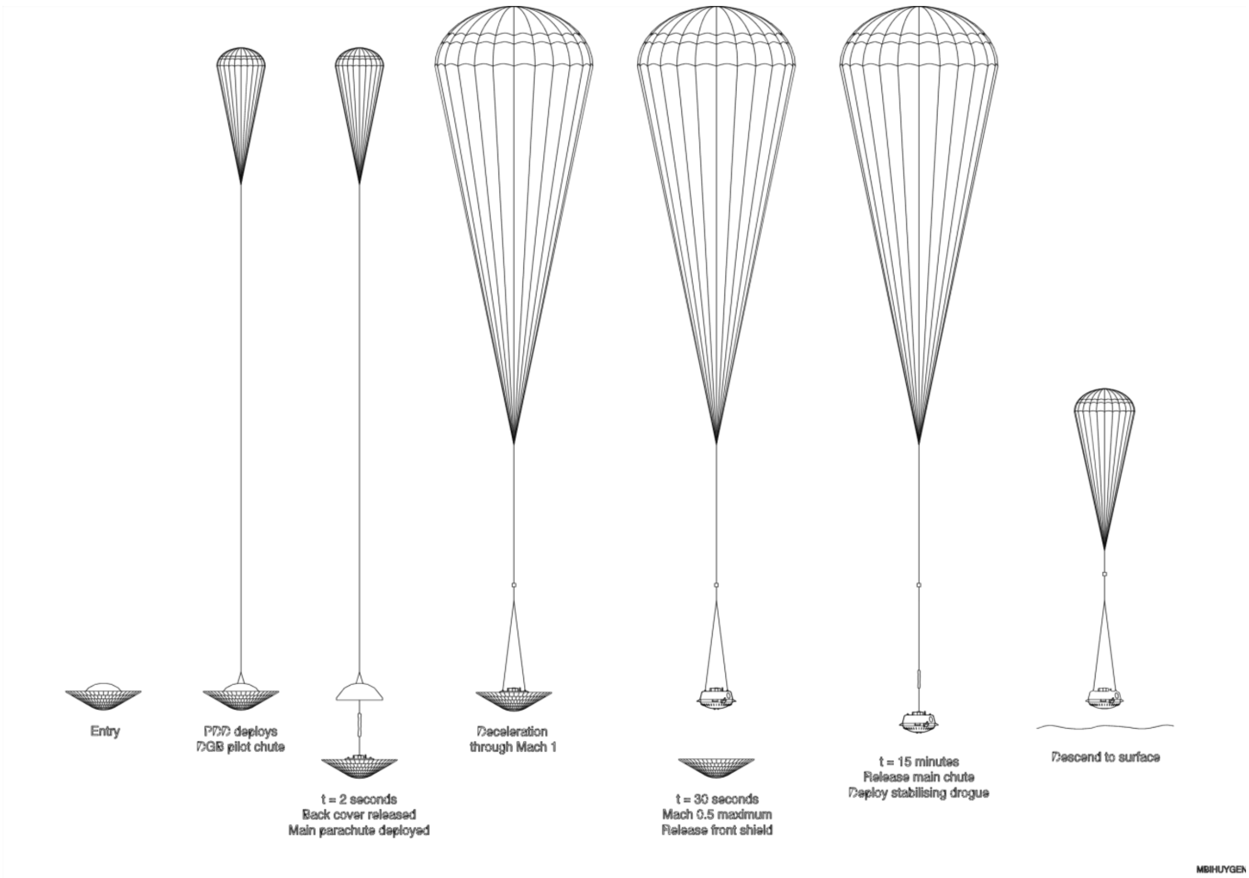

Figure 1: Huygens Descent Control Sub-System Sequence

2.2 Entry Dynamics and Aerothermodynamics

3D computations were conducted over a range of angles of attack and Mach numbers to update the Huygens aerodynamic coefficients. This included an updated atmosphere composition model. A performance aerodynamic database was generated using the latest estimate of the molecular composition of Titan's atmosphere which demonstrated atmosphere composition effects to be significant.

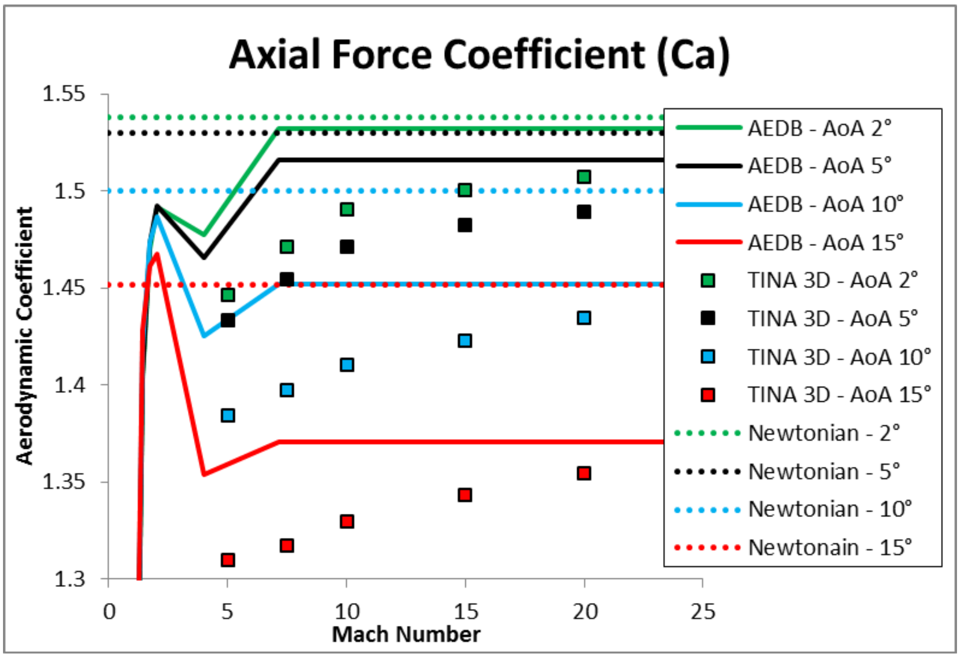

Figure 2: Comparison of updated, flight and Newtonian coefficients

A model of the AQ60 thermal protection material has been generated from ESA test data and used with a newly generated performance aerothermal database to estimate the mass loss of the Huygens thermal protection system during entry which was found to be less than 0.25% of the total probe mass.

2.3 Parachute Performance

A parachute aerodynamic database was constructed using the results of wind tunnel tests carried out during and since the Huygens development and the latest advances in the knowledge of parachute performance. The results indicated a slightly higher drag coefficient than predicted during the development programme.

Three CFD/FSI simulations of the probe / parachute system were performed at different points in the trajectory to investigate the observed probe stability. These simulated the entry module under the pilot chute and the descent module under the stabilising drogue both at high altitude, where the flight probe was observed to oscillate, and at low altitude, where it was stable.

The predicted oscillation of the probe under the stabilising drogue matched the flight values well, in terms both of amplitude and frequency.

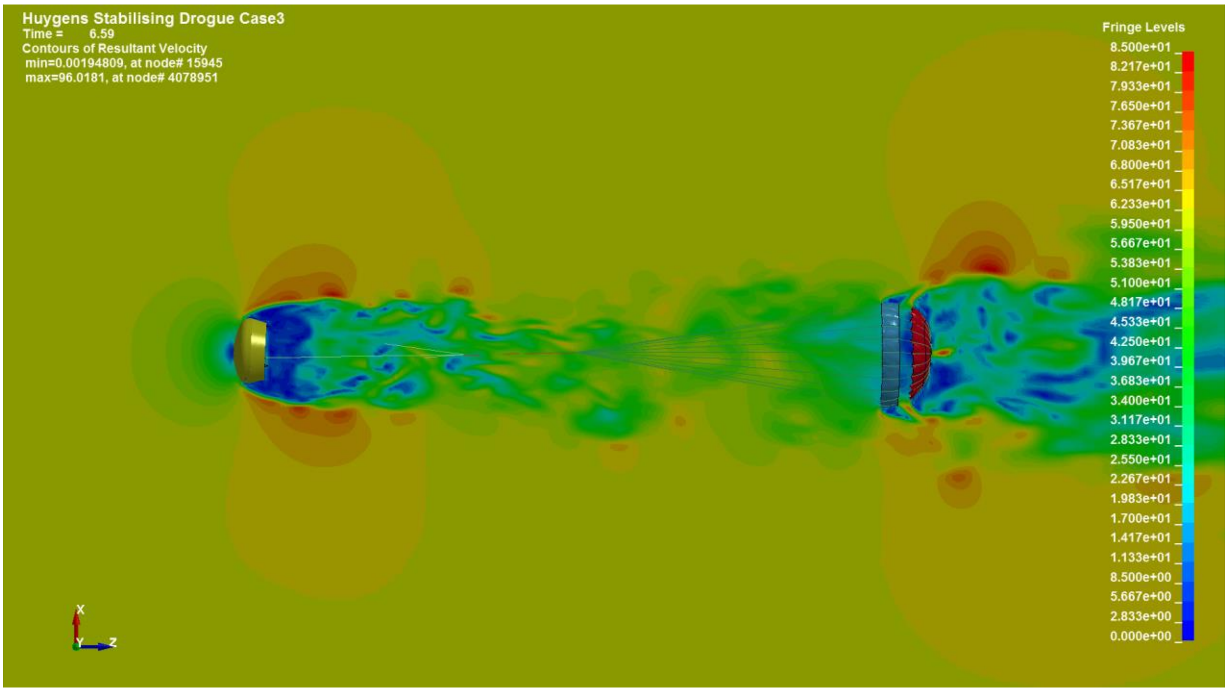

Figure 3: CFD / FSI similation - Probe / Stabilising drogue at high altitude

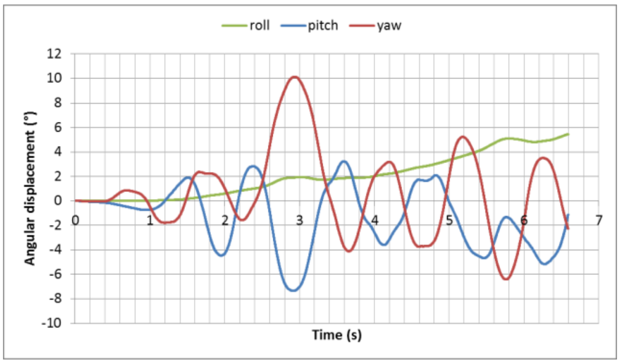

Figure 4: High altitude oscillation

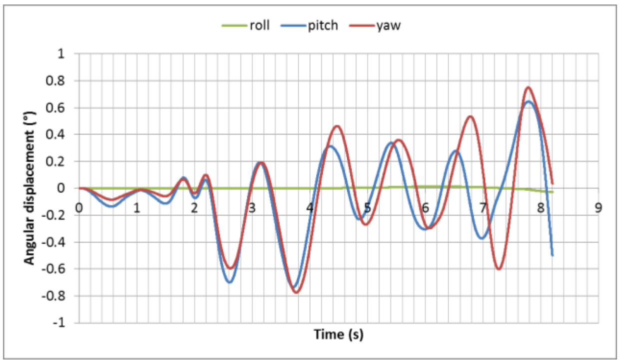

Figure 5: Low altitude oscillation

2.4 Probe Spin During Descent

The Huygens probe was intended to spin during descent in order to allow the side-looking on-board camera (DISR) to create a mosaic of images. The spin was accomplished by means of spin vanes on the forward face of the descent module. Analysis of the flight data indicated that the probe spun the wrong way during descent. Subsequent re-analysis of the development SM2 test confirmed that this model also exhibited reverse spin.

The spin phenomenon was examined using both wind tunnel tests of the SM2 probe and CFD analysis of the same configuration.

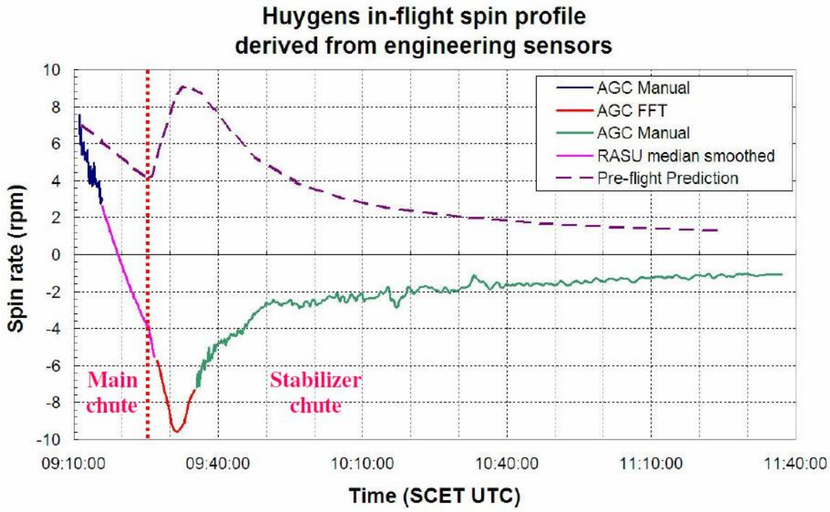

Figure 6: Huygens in-flight spin profile derived from engineering sensors

The SM2 model was mounted with its spin axis in a horizontal position on an air bearing which produced very low friction, allowing the probe to rotate under the very low torques

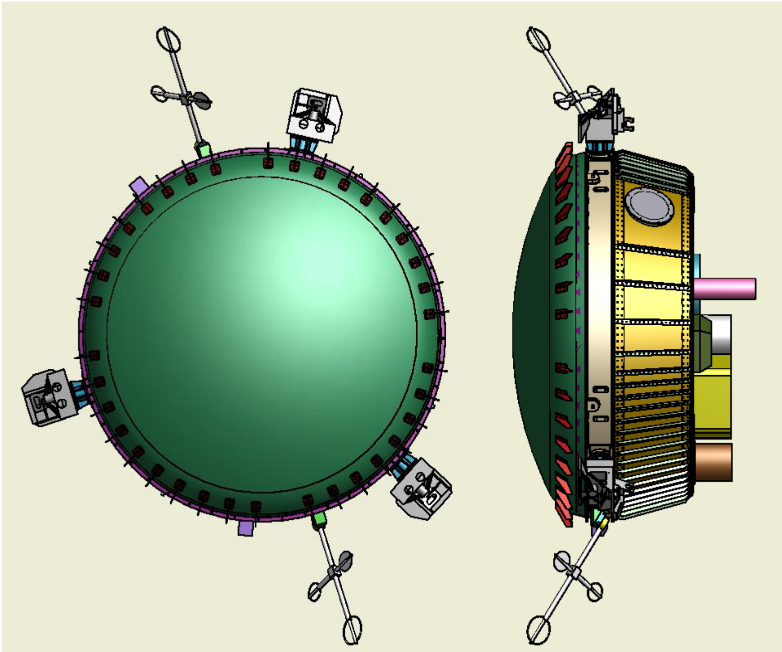

Figure 7 : Reference model with booms open

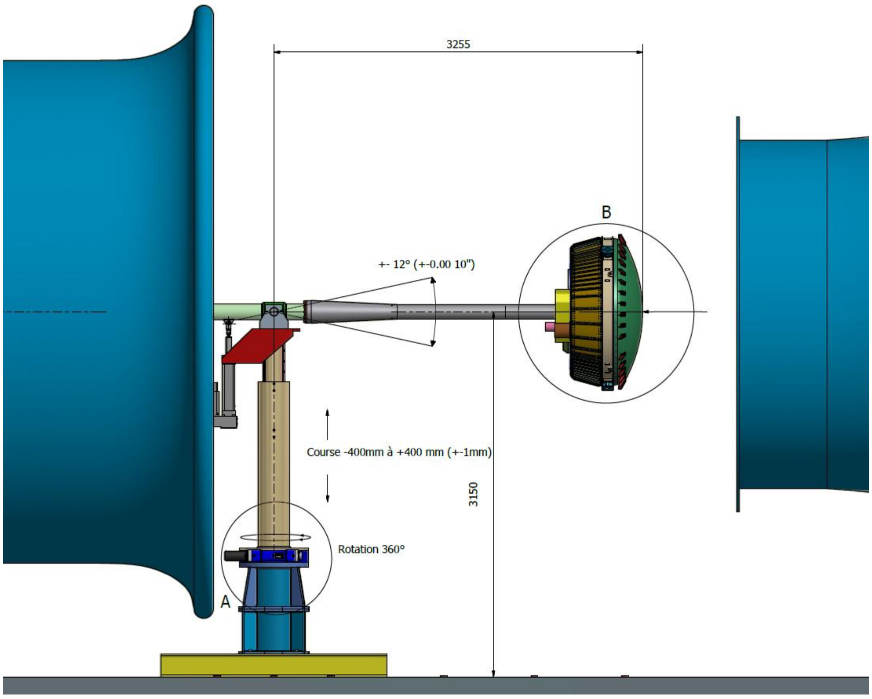

Figure 8 : Installation of the model in the wind tunnel

A number of wind tunnel tests were performed with different probe configurations: booms deployed or not, changes of centre of gravity position and removal of various components. The results indicated that the direction and speed of spin were very sensitive to the detailed configuration of the probe.

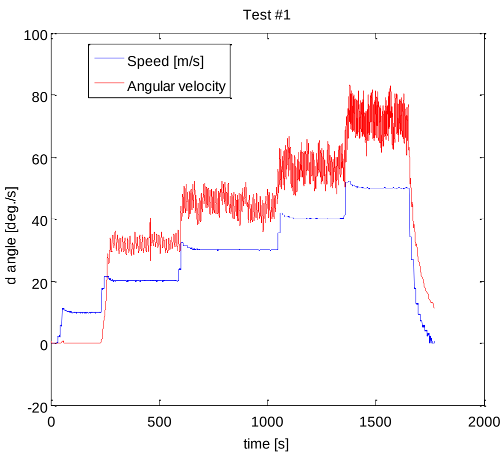

Figure 9: Test 1 angular rate

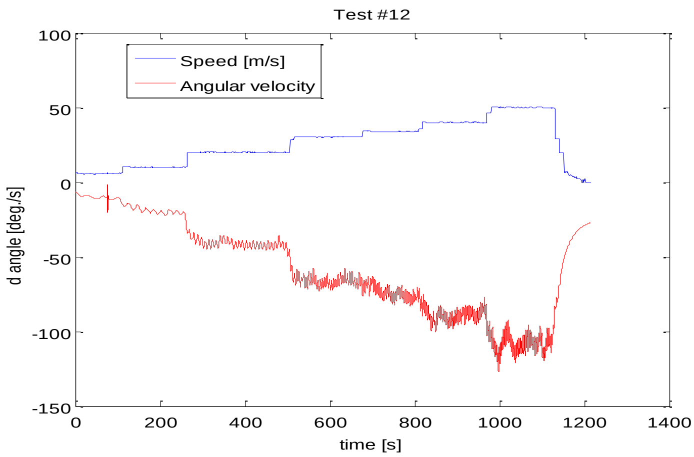

Figure 10: Test 12 angular rate

A CAD model of the probe was constructed and a CFD analysis was performed to examine the flow around the probe and to attempt to confirm the wind tunnel results. The analysis was performed under conditions both matched to the wind tunnel tests and subsequently matched to the flight on Titan. The probe model was constrained to spin at a constant rate in order to replicate the correct fluid flow. Several rates were tested in order to determine the stable rate (that at which there is no net torque from the aerodynamics).

The simulations were found to match the experimental results well.

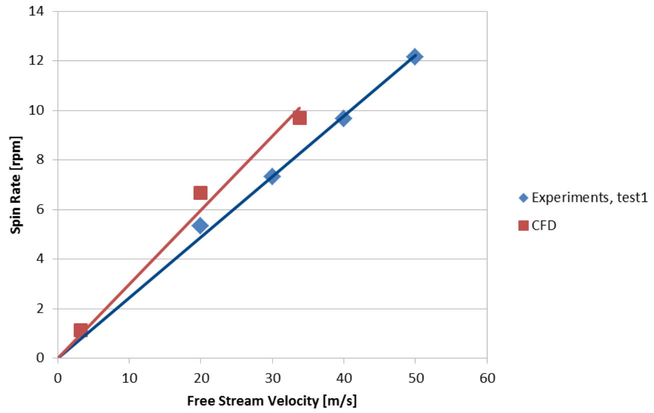

Figure 11: Comparison of CFD and Experimental Results (Base Configuration)

2.5 Overall Assessment of the Probe in Flight

The results of the preceding investigations were used to reconstruct the entire probe trajectory from entry to landing.

Firstly, the atmosphere profile was revisited. The initial post-flight atmosphere was reconstructed using the design-level aerodynamic databases and instrument data. Since the aerodynamic databases have been updated, the original model was no longer valid. Furthermore, there was a discrepancy in the initial model where the measured altitudes during final descent were not coherent with the reconstructed atmosphere which had to be resolved. A new atmosphere was constructed which was coherent with the new aerodynamic databases and all science and housekeeping measurements on the flight probe.

The updated probe and parachute aerodynamics derived previously were implemented in a six degree of freedom, multi-body simulation. An empirical model of the spin vane aerodynamics was constructed using the original Aerospatiale wind tunnel results, the observed flight and SM2 behaviour and the VKI wind tunnel results.

The predicted descent time using the new model was within 8 seconds of the mission descent time with close agreement with measured accelerations and, in the operational range of the radar altimeter, rate of descent.

The spin rate predicted by the model was close to that observed in the mission; however, the rate of change of spin rate under the main parachute was somewhat underestimated. This could be the subject of further work.

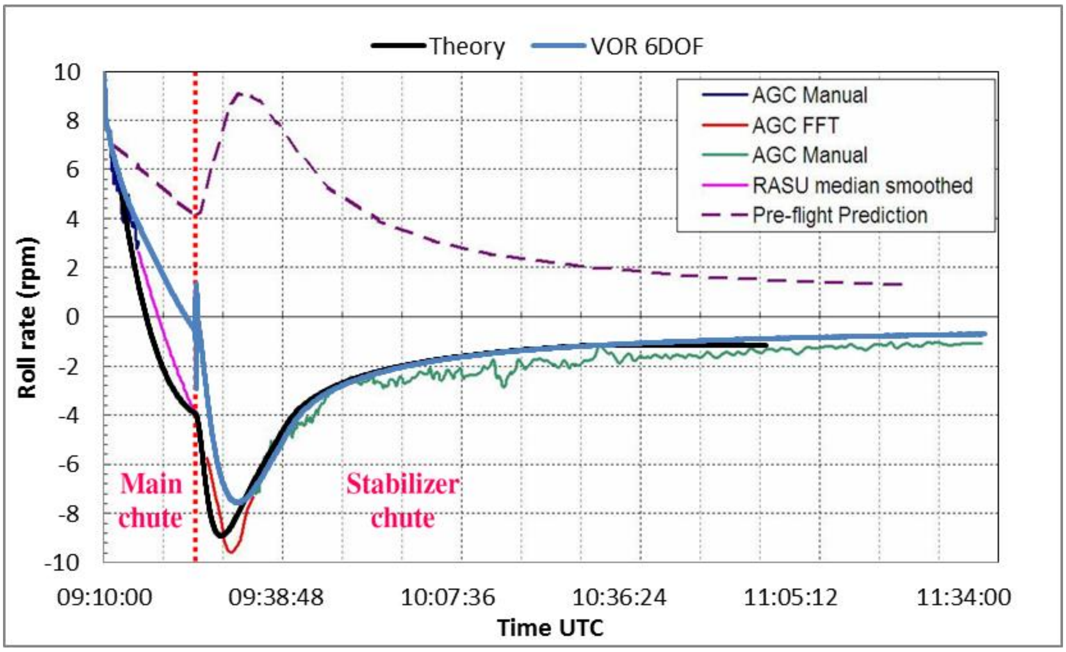

Figure 12: Huygens spin rate during its descent in Titan's atmosphere

The radial accelerations during descent, which are generated both by the probe spin and oscillations under the parachute, were extracted from the simulation results. The oscillations in the model were found to be less severe in the reconstruction than those predicted by the FSI analysis which closely replicated flight. This is probably due to the rigid body, equilibrium aerodynamics assumptions implicit in the 6 dof simulation. The results were shown to be sensitive to the damping coefficient of the parachute.

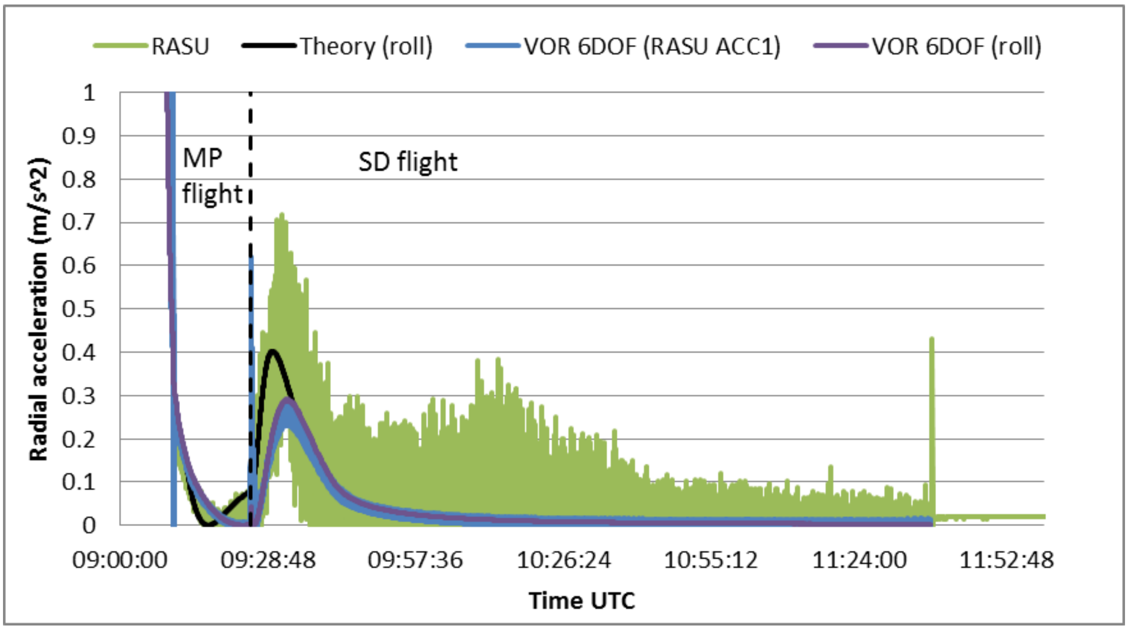

Figure 13: Radial accelerations at the location of the "RASU ACC1" accelerometer

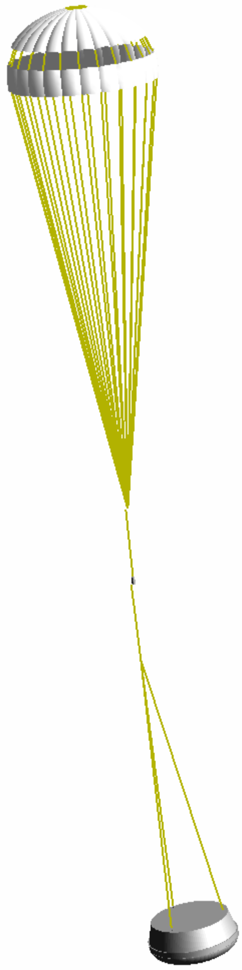

Figure 14: Huygens stabilising drogue oscillations - $C_{mq} = -0.085$

2.6 Lessons Learned

The lessons learned are not limited to aspects of the mission where problems were discovered. Successes, both technical and programmatic are equally important since these may be adopted as best practice for future missions rather than adopting new, potentially inferior approaches.

The topics discussed in this document were identified by means of a brainstorming session including personnel directly involved with the Huygens development mission and were informed by the development, flight and subsequent analysis of the data. The team's experience of working on other programmes, both ESA and non-ESA, allowed contrasts to be drawn between the Huygens programme, other agency programmes and programmes with other end customers.

The lessons learned were categorised into groups for ease of presentation. These included technical, development and verification approach, testing, organisational and post-flight analysis lessons.

Key findings were the success of the margin and spares policies which provided sufficient margin to redesign the mission profile where necessary and to extend test programmes where necessary to investigate unexpected results. The delays in performing the post-flight analysis and lack of collaboration between the science and engineering teams immediately following the mission were identified as aspects which could be improved in future missions.

2.7 Overall Conclusions

The Huygens mission was a great scientific and engineering success. It was the first, and remains the only, European probe to land on another planet or moon successfully.

The current work has helped to explain some of the anomalies identified during the mission which allows future missions to benefit from the results of Huygens.

The aerodynamic and aerothermal databases for the probe have been revisited and updated using knowledge gained during the two decades since their construction. The new databases take into account real gas effects and the constitution of the atmosphere; in particular, methane chemistry. A performance level database has been generated which is intended to predict the actual performance of the probe rather than the original design level database which was intended to predict worst case performance. The results of this activity have been used to update the reconstructed entry atmosphere.

The performance of the parachutes and stability of the probe under parachutes was addressed using a review of all subsequent testing of this parachute type on other programmes and by CFD/FSI simulations of the system. The parachute drag was found to be slightly greater than predicted at the time of the mission design and the CFD/FSI simulations predicted the motion of the probe under the stabilising drogue accurately.

The probe spin profile during descent has been addressed by both wind tunnel tests and CFD simulations. The results indicate that the probe spin characteristics are very sensitive to the configuration of all items mounted on the periphery of the descent module: spin vanes, SEPS mechanisms, radar altimeters and HASI booms. Although the spin vanes appear to produce the desired spin rate in the nominal configuration, any small geometric deviations can affect the spin significantly. It was concluded that the spin vanes have insufficient authority to control the spin robustly.

The overall trajectory was reassessed using the updated probe and parachute aerodynamics and the results of the probe spin analysis. An updated atmosphere profile was produced which is coherent with all measured experiment data, revised aerodynamics, the probe housekeeping data and the radar altimeter readings. The stability of the probe was matched well.

Lessons learned from the design, development, operation and post-mission analysis of the Huygens mission were documented. These lessons relate both to aspects of the mission which were effective and should be replicated on future missions and aspects which could be improved on future missions. The lessons are particularly applicable for future probe or lander missions such as ExoMars.