Presentation

HUYGENS DCSS PERFORMANCE RECONSTRUCTION

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ABSTRACT

The Huygens DCSS was designed to remove the protective aeroshell from the Huygens probe and control its descent through the atmosphere of Titan over the following 2.5 hours.

It was clear, even before the first housekeeping data were received via Cassini, that the DCSS sequence had operated correctly and that the descent time was within the specified range. Subsequent analysis of the housekeeping and experiment data has allowed the performance of the system to be quantified.

This paper describes the design and operation of the Huygens descent control subsystem and its performance compared with that predicted before the mission. The accuracy of the parachute model used for performance prediction is also assessed.

Lessons learned during the development and requalification programs and from analysis of the flight data are presented and improvements for future missions suggested.

1. INTRODUCTION

The Huygens Descent Control Sub-System (DCSS) was designed to allow the Huygens probe to perform its task of measuring the properties of the Titan atmosphere in-situ.

The probe arrived at the edge of the atmosphere at a velocity of 6.0 km/s on 14th January 2005, having been released by the Cassini orbiter 20 days earlier. As it passed through the upper atmosphere it decelerated to Mach 1.5, cocooned within its 2.7 m diameter protective aeroshell.

The task of the DCSS was to remove the protective aeroshell and control the descent profile of the probe through the atmosphere; too short a descent would have reduced the science return while too long a descent would have risked missing out on data from the moon's surface. During the descent the DCSS was required to maintain the probe in a stable attitude to allow the science experiments to perform their tasks and not to interfere with the probe spin, which was designed to be controlled by spin vanes on the probe.

In order to accomplish its mission, the DCSS required three parachutes: a pilot chute to remove the rear portion of the aeroshell, a main parachute to allow the front portion of the aeroshell to fall away and a stabilising drogue to modulate the overall descent time. It also incorporated a pyrotechnic mortar to deploy the pilot chute, a container to house the main parachute and stabilising drogue, a release mechanism for the main parachute and two low friction swivels to prevent spin coupling between the parachutes and probe [1].

2. HISTORY

The Huygens DCSS was developed during the early 1990's for the Huygens launch in October 1997. At the time it was being developed the only information on the Titan atmosphere came from the NASA Voyager missions and stellar occultation measurements: there was therefore a high level of uncertainty about its properties. Margins were built into the system as a consequence.

During the development a great deal of testing was performed on the DCSS, from wind tunnel tests [2] through low altitude drop tests [3] to a full system drop test [4, 5,]. A great deal was learned about the parachutes baselined for the mission and modifications were made to the design as a consequence.

During the seven years between launch and arrival, improvements in the scientific knowledge of Titan and issues discovered with other elements of the Huygens probe, necessitated a redesign of the baseline mission so that the final mission was quite different to that originally envisaged. A re-assessment of the DCSS performance [6] was carried out during 2003 which demonstrated that, due to the margins included during development, the DCSS was robust to the new entry conditions.

3. SEQUENCE

The DCSS was initiated at Mach 1.49 when the pilot chute was deployed by the pyrotechnic mortar (PDD) (Fig. 1a). The 2.59 m diameter, Disk-Gap-Band (DGB) pilot chute deployed 27 m behind the probe in approximately 1 second and inflated (Fig. 1b). Two and a half seconds after the PDD firing, the rear aeroshell of the probe was released (Fig. 1c), thus allowing the pilot chute to remove the aeroshell and deploy the 8.3 m DGB main parachute, which was connected to the rear aeroshell by a lanyard.

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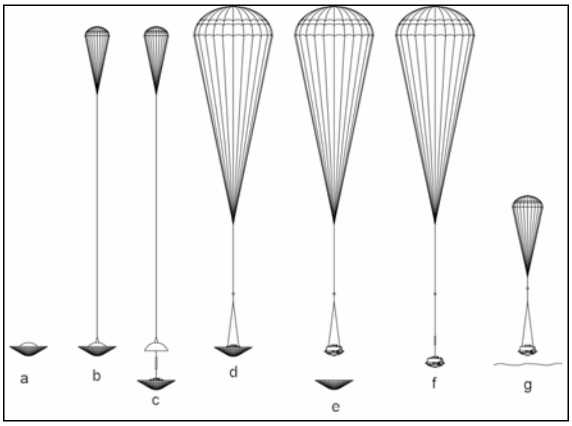

Fig. 1. The Huygens DCSS sequence

Thirty two and a half seconds after the PDD firing, the front shield was released from the probe (Fig. 1e) and fell way below it, thus allowing the science data collection to begin.

The main parachute was sized to ensure the robust separation of the probe from the front shield. This requirement caused it to be too large to complete the descent within the allocated 2.5 hours. It was thus necessary to release the main parachute 15 minutes into the descent sequence and deploy a 3.03 m stabilising drogue (Fig. 1g) which controlled the remaining 2¼ hours of the descent.

One hour and seven minutes after the opening of the main parachute, the carrier signal from Huygens was received by radio telescopes on Earth, demonstrating that the critical deployment sequence had completed successfully, although it was a further 5 hours before telemetry data were relayed to Earth via the Cassini orbiter.

4. RECONSTRUCTION

The performance of the DCSS has been reconstructed using the engineering housekeeping data from the probe along with the predicted probe entry point into the atmosphere and acceleration data from the HASI experiment.

The reconstruction uses the atmosphere profile derived during the Ta Titan flyby in 2004 since results from the experiments are not available at this time. Furthermore, great care must be taken when using experiment data to reconstruct the probe descent profile: if assumptions have been made about the parachute system in analysing the data, the data may not be used to derive the performance of the parachute system.

The entry state vector used for the reconstruction was provided by JPL following the mission and is reproduced in table 1:

Table 1. Entry position

Time (UTC, SET)	2005-01-14 09:05:52.253
Latitude (deg)	8.5014 S
Longitude (deg)	174.467 E
Altitude (m)	1,270,011
Velocity (m/s – rotating)	6,038.333
Flight path angle (deg – rotating)	-65.3998
Azimuth (deg)	-99.76

Comparing the results of the simulation and flight data from the housekeeping accelerometer (CASU) and the HASI accelerometer indicates a 3.2 second offset (Fig 2); well within the entry state vector uncertainty. The corrected arrival time is 09:05:49.053.

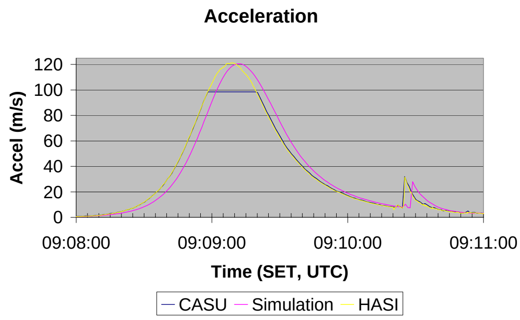

Fig. 2. Entry profile

Using the corrected arrival time and the Ta atmosphere, the mission timeline may be derived. After PDD fire, which is determined by readings from the housekeeping accelerometers, the timings for the release events were defined by means of a fixed timeline in the probe on-board software.

Table 2. Predicted timeline

Event	**Time UTC**	**Height km**	**Accel m/s²**
Entry	09:05:49.1	1270	0.0
PDD Fire (T0)	09:10:20.3	156.3	8.0
Back cover release	09:10:22.8	155.5	10.0
Front shield release	09:10:52.8	150.6	3.1
Main para release	09:25:20	110.3	1.3
40 km	10:00:42		
30 km	10:15:03		
20 km	10:34:12		
10 km	10:58:54		
Landing	11:29:40		

The predicted conditions for each of the events above is given in Table 3.

There is no way of verifying the altitudes at which the release events took place. However, the latter part of the descent may be verified using readings from the radar altimeters mounted on the probe. The radar altimeters readings were designed to work at altitudes of up to 20 km. In fact one returned data from above 45 km and the other from just under 40 km above the surface. The comparison between the altimeter readings and predicted timeline is shown in table 4.

Table 3. Conditions at each event

Event	Mach	q	Velocity
		Pa	m/s
Entry		0	6038
PDD Fire (T0)	1.49	317	386
Back cover release	1.41	289	365
Front shield release	0.40	27	104
Main para release	0.14	10	34.8
40 km	0.079	62	13.5
30 km	0.058	62	10.0
20 km	0.043	63	7.6
10 km	0.032	63	6.0
Landing	0.025	64	4.9

Table 4. Radar Altimeter comparison

Altitude	Simulation	RadAlt A	RadAlt B
40 km	10:00:42		10:08:02
30 km	10:15:03	10:24:48	10:24:48
20 km	10:34:12	10:44:58	10:44:48
10 km	10:58:54	11:09:17	11:09:05
Landing	11:29:40	11:38:12	11:38:13

It should be noted that the reading from RadAlt B is very noisy at 40 km so there could be an error of up to a minute. Furthermore, the reading cannot be relied on given the range is beyond the qualified range.

The results clearly indicate the descent took longer than expected. The possible reasons for this are discussed later.

5. KEY EVENTS

5.1 PDD Firing and Pilot Chute Deployment

The predicted (and measured) acceleration at PDD firing was 8.0 m/s². Since the acceleration is proportional principally to dynamic pressure, the conditions at PDD firing must be close to those predicted: dynamic pressure of 317 Pa and Mach number of 1.489. Under these conditions the pilot chute deployment is predicted to take 0.95 seconds and the inflation about 0.06 seconds. The peak inflation force is expected to be 1.45 kN; well within the design value of 1.8 kN.

The inflation force is not measured directly but could be inferred from the deceleration of the probe. Since the housekeeping accelerometers are sampled at only 1 Hz, they are very unlikely to detect the inflation peak. The HASI accelerometer is sampled at a slightly higher rate of 3.125 Hz but this is still very unlikely to detect the inflation peak.

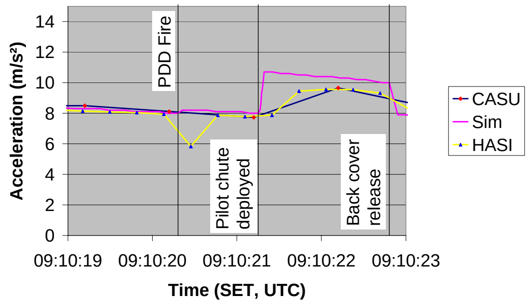

Fig. 3. Pilot Chute deployment and inflation

The measured accelerations are shown in Fig. 3. Two features are immediately evident: a reduction in acceleration measured on the HASI accelerometer just after the PDD firing and a lower than expected deceleration from the pilot chute. The first is caused by the reaction load of up to 8.5 kN from the mortar. The cause of the second is less clear.

The onset of acceleration at pilot chute inflation appears lower than expected. However, this is simply due to the sampling frequency. In fact it appears the pilot chute took slightly longer than expected to deploy. The deceleration under the pilot chute does appear to be lower than expected (equivalent to a pilot chute drag reduction of 30%) and this could be due to the very short flight time which gives the parachute insufficient time to reach an equilibrium flight in the wake of the supersonic probe. Analysis of the deployment time of the main parachute (described below) indicates the pilot chute produced its expected drag during this event.

5.2 Main Parachute Deployment and Inflation

The rear aeroshell was released 2.5 seconds after PDD initiation, thus allowing the pilot chute to pull the aeroshell away from the probe and deploy the main parachute. The dynamic pressure at the start of main parachute deployment will be close to the predicted value of 289 Pa for the reasons discussed in the previous section. At this dynamic pressure, the main parachute deployment is predicted to take 1.8 seconds assuming nominal pilot chute drag. If the pilot chute drag were reduced to the extent apparent from the deceleration prior to rear aeroshell release the deployment time would increase to 2.35 seconds. In fact the deployment took between 1.9 and 2.1 seconds, indicating that the pilot chute drag was closer to the nominal value than earlier. This could be due to the additional time from inflation for stabilisation or the increasing distance from the probe (and thus reduced probe wake effect).

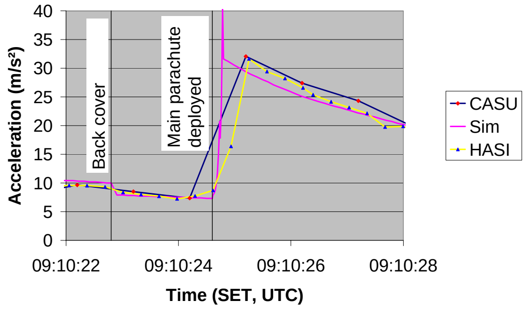

Fig. 4. Main parachute deployment and inflation

The inflation of the main parachute was predicted to take 0.22 seconds. The sampling frequencies of both the housekeeping and HASI data are insufficient to resolve this event.

5.3 Main Parachute Drag Coefficient

The measured acceleration under the main parachute is plotted in Fig. 5. Although the prediction is very close to the measured values there is a small discrepancy between 5 and 10 seconds after inflation where the measured deceleration was less than predicted. This is evident on both the HASI and housekeeping accelerometers.

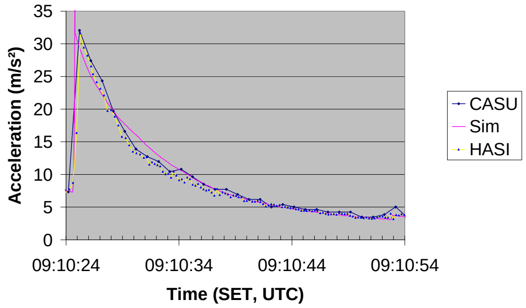

Fig. 5. Deceleration under main parachute

Since the dynamic pressure at the start of main parachute inflation is known from the T0 conditions it is possible to integrate the accelerometer data to obtain the velocity and dynamic pressure decay over the first few seconds of main parachute flight and thus derive the main parachute drag coefficient (assuming the atmospheric density changes only slightly during this period). The drag coefficient has been calculated in this way and is plotted in Fig. 6 against Mach number along with the drag coefficient from the Huygens parachute aerodynamic database.

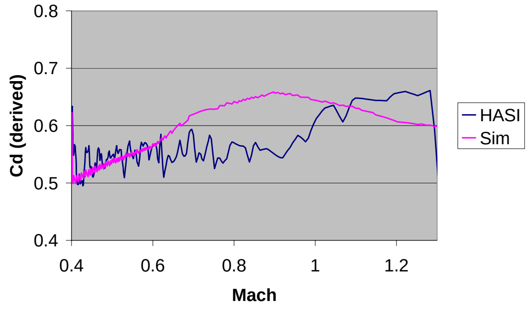

Fig. 6. Derived main parachute drag coefficient

It is evident that the predicted drag coefficient is very close to that measured at Mach numbers below 0.6 but is higher in the high subsonic regime. This is a region in which very few test data were available during development; all full-scale drop tests were performed at low Mach number in order to limit costs, only wind tunnel tests were performed at high Mach number. Since the drag coefficient of the parachute in this region is not critical to mission success further tests were not carried out.

5.4 Front Shield Release

The front shield release event, 30 seconds after PDD firing, is visible on the accelerometer data (Fig. 7); the deceleration of the probe under the parachutes increases since the decelerating mass reduces. The step in acceleration is less well defined than expected, although the acceleration before and after release suggests the probe is oscillating. The change in acceleration also appears to be greater than expected although the data is not clear. A possible cause would be a higher than expected mass of released heat shield (due to a reduced ablation) or a greater than expected increase in the parachute drag once the wake of the front shield is removed.

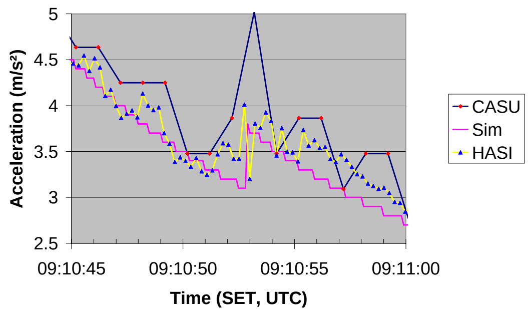

Fig. 7. Acceleration at front shield release

5.5 Stabilising Drogue Deployment

The stabilising drogue event is very clear on the accelerometer data and the acceleration over the next 90 seconds as the probe accelerates to its new terminal velocity matches very well with the predictions (Fig. 8). This indicates the system drag is close to prediction.

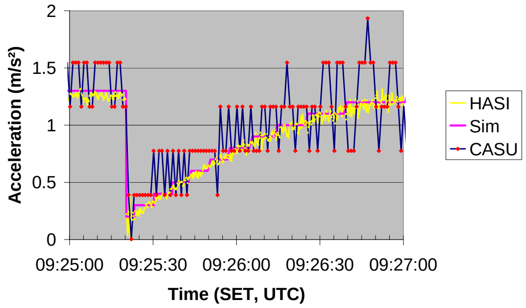

Fig. 8. Stabilising Drogue acceleration

5.6 System Drag Area

The drag area of the probe under pilot and main parachutes has been assessed during the early part of their flights while the payload was decelerating from the known initial dynamic pressure. However, once the probe has reached its steady state descent velocity it is impossible to determine a drag coefficient since velocity (measurable only in the last 40 km of descent via radar altimeter data) depends on both the parachute drag coefficient and the atmospheric density:

$$m \cdot g = \frac{1}{2}\rho V^2 C_d S$$

In order to assess the drag area of the system an atmosphere profile would have to be obtained. However, this must be derived using altitude data which does not make any assumptions about the probe drag area for obvious reasons.

The overall descent time has been compared with predictions (Table 3). It was found that the descent took nearly 10 minutes longer than the nominal simulation. However, the time difference between the simulation and mission did not increase steadily as would be expected if the parachute drag coefficient measurements were in error (Fig. 9). In fact the probe descended less quickly than expected above 15 km and then at above the predicted rate as it approached the surface. This is more likely to be due to an atmospheric effect (either density or convection) than due to a parachute effect.

A Monte-Carlo simulation was performed, varying the parachute and probe drag coefficient within their expected bounds and the atmosphere density using TitanGRAM. The results indicate that the overall descent time is 2.27σ above the nominal descent duration.

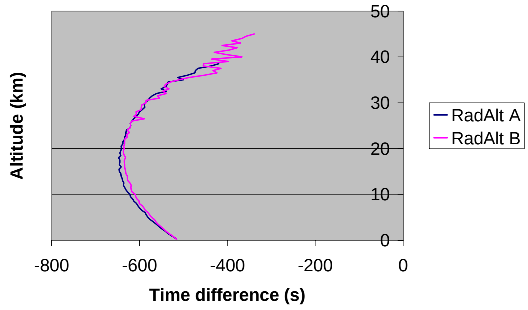

Fig. 9. Descent time differences

5.5 System Stability

Data from the housekeeping lateral accelerometers indicates the probe oscillated during the descent with a frequency of around 0.8 Hz under the main parachute and 1 Hz under the stabilising drogue. The amplitude was at a maximum during the early part of the stabilising drogue descent. The frequency of the oscillation is coherent with a rotation of the probe about its centre of gravity in simple harmonic motion under the action of the parachutes; any swinging mode under the parachutes would have a much longer time constant.

Although the mode of motion is understood, the excitation mechanism is not as yet. Possibilities include vortex shedding from the probe or the parachutes interacting with the probe wake or atmospheric turbulence.

A similar phenomenon was observed during the Huygens system drop test on Earth. However, the analysis at the time suggested this was caused by a resonance between the probe oscillation frequency and vortex shedding frequency which would not occur on Titan (due to the differences in atmosphere and gravity). It is possible, of course, that the mechanisms are different in the two cases.

6 LESSONS LEARNED

During the Huygens development a large number of parachute tests were carried out in wind tunnels and low altitude helicopter drop tests. However, the only test which was representative of the flight dynamics (velocity and dynamic pressure at opening) was the system drop test; only one test being performed due to the significant costs associated with it. This test identified dynamic phenomena with the probe / parachute system which were not fully understood at the time (§5.5).

Following the Huygens launch, high altitude tests by NASA for the MER programme on a DGB parachute similar in design to the Huygens parachutes, indicated the opening characteristics were different to those measured in the Huygens development tests. Analysis of these data in

conjunction with that obtained during the Huygens development allowed development of an improved inflation model which predicted slightly higher inflation forces for the flight parachutes.
In both cases, the importance of testing the parachutes in conditions as close as possible to flight conditions is evident. While such testing is usually expensive, the results can make the difference between a successful mission and an unexplained failure.

7 FUTURE MISSIONS

During the time since the design and launch of Huygens great advances have been made in design and analysis capabilities. Interactions between a forebody and parachute may be modelled using fluid structure interaction software on personal computers which would have been impossible on supercomputers 10 years ago. Use of such tools has the capability to optimise the design of future systems and to model their performance both in terrestrial conditions (to validate trials) and in the target environment. Computer modelling may (and should) be used to "test" conditions which can never be replicated on Earth.
Since the development of Huygens a great wealth of test data have been obtained for parachutes intended for extra-terrestrial use. It is important that these data are fully analysed and that the results are used in the design of future systems. In particular, the original test data gathered during the Huygens development could usefully be revisited to investigate the phenomena observed during the flight.

Test instrumentation has also improved significantly since the Huygens parachute tests. Parachute descent velocities were derived during the low level tests from analysis of cine data. Those on the SM2 made use of a very early version of DGPS. Use of the latest WAAS DGPS receivers or the new Galileo system will allow significant improvement in the determination of parachute performance and the use of multiple receivers even promises the possibility of determining the orientation of the parachute / payload system by the same means.

CONCLUSION

The Huygens mission was a resounding success, due to both the robust application of margins and redundancy and extensive testing of the final system. The lessons learned will be of value for future extraterrestrial missions as well as for the design of systems for use on Earth.

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REFERENCES

1. Neal, M.F. and Wellings, P.J., *Descent Control Subsystem for the Huygens Probe,* AIAA-95-1533
2. Underwood, J.C. and Sinclair, R.J. *Wind Tunnel Testing of Parachutes for the Huygens Probe*, The Aeronautical Journal, October 1997.
3. Underwood, J.C, *Development Testing of Disk-Gap-Band Parachutes for the Huygens Probe*, AIAA 95-1549
4. Jäkel, E. et al., *Drop test of the Huygens Probe from a stratospheric balloon*, Advances in Space Research 21 (1998).
5. Underwood, J.C., *A System Drop Test of the Huygens Probe*, AIAA 97-1429.
6. Underwood, J.C., Lingard, J.S. and Darley, D.G., *Revalidation of the Huygens Descent Control Sub-system*, 2nd International Planetary Probe Workshop, NASA Ames, August 2004.