# IN-FLIGHT PERFORMANCE OF THE HASI SERVO ACCELEROMETER AND IMPLICATIONS FOR RESULTS AT TITAN

**J.C. Zarnecki (1), F. Ferri (1,2), B. Hathi (1), M.R. Leese (1), A.J. Ball (1), G. Colombatti (2), M. Fulchignoni (3),**

*(1)PSSRI, The Open University, Walton Hall, Milton Keynes, MK7 6AA, United Kingdom*
*J.C.Zarnecki@open.ac.uk*
*F.Ferri@open.ac.uk*
*B.Hathi@open.ac.uk*
*M.R.Leese@open.ac.uk*
*A.J.Ball@open.ac.uk*
*(2)CISAS "G.Colombo", Università di Padova, Via Venezia 1, 35131 Padova, Italy*
*francesca.ferri@unipd.it*
*hasi@dim.unipd.it*
*(3)Université Paris 7, LESIA, Observatoire de Paris-Meudon, 5 place Jules Janssen, 92190 Meudon, France*
*marcello.fulchignoni@obspm.fr*

## ABSTRACT

The *Huygens* Atmospheric Structure Instrument (HASI) includes a high sensitivity servo accelerometer to sense deceleration in the direction of the probe trajectory as it enters Titan's atmosphere in January 2005. These data will be used to determine the atmospheric density profile in the upper reaches of the atmosphere where it is least well constrained. Results are presented of the performance of this subsystem during the in-flight checkouts performed to date. In particular, the noise performance is assessed. This is especially important as it limits the resolution, and therefore performance, of the sensor at the very top of Titan's atmosphere. Implications for the results expected at Titan are presented.

## 1. INTRODUCTION

The *Cassini/Huygens* mission, currently *en route* to the Saturnian system, will devote particular attention to Titan, Saturn's largest moon. In January 2005 the *Huygens* probe will descend through the thick atmosphere of this satellite down to its surface. Measurements will be performed during the entry, descent and landing phases in order to characterize the atmosphere and surface of Titan. In particular, vertical profiles of atmospheric density, pressure and temperature will be derived using accelerometric and direct pressure and temperature measurements.

Here we discuss the expected performance of the HASI accelerometer (ACC) Servo subsystem at Titan on the basis of the results obtained during the in-flight checkouts performed to date during the cruise phase. The actual performance of the HASI ACC Servo is compared with that of similar instrumentation flown on probes and landers of other missions.

## 2. OUTLINE DESCRIPTION OF HASI

The *Huygens* Atmospheric Structure Instrument (HASI) [1] is one of the six experiments on board the *Huygens* probe, which will descend onto Titan in January 2005. HASI consists of a suite of sensors to characterize physical properties of Titan's atmosphere and surface. Measurements will be performed by pressure, temperature, acceleration and electrical properties sensors, starting from the entry phase (at an altitude level >1270 km) throughout the descent through Titan's atmosphere down to the surface.

HASI derives its heritage from instruments flown on previous planetary entry probes, such as those of *Venera 8-14* [2, 3], *Mars 6* [4, 5], *Viking Landers 1 & 2* [6], *Pioneer Venus* [7], *Mars Pathfinder* [8, 9] and *Galileo* [10].

The HASI accelerometer subsystem (ACC) consists of a one-axis highly sensitive accelerometer (Servo) and three piezoresistive accelerometers aligned to the principal axes of the *Huygens* probe. The Servo is mounted as close as possible to the *Huygens* probe's centre of mass, in order to sense acceleration along the probe's descent axis (X axis). Two AD590 temperature sensors are in thermal contact with the accelerometers and their measurements are used to compensate for the accelerometers' temperature dependence.

*Proc. Int. Workshop 'Planetary Probe Atmospheric Entry and Descent Trajectory Analysis and Science', Lisbon, Portugal, 6-9 October 2003 (ESA SP-544, February 2004)*

## 3. HASI-ACC SERVO ACCELEROMETER

The sensor, a commercially procured Sundstrand QA2000-030, is a linear, force-balance, closed-loop servo accelerometer. It utilises a pendulous or seismic mass, suspended by a quartz flexure, which essentially only allows movement in one axis. An applied acceleration in this axis produces a displacement, which is detected by a capacitative sensor. A current is then applied to a coil that is fixed to the seismic mass, in order to bring the mass back to its reference position. The current is sensed (by passing it through a resistor and measuring the potential difference) and is a direct measure of the applied acceleration. The seismic mass system and its associated front-end electronics are housed in a hermetically sealed canister containing 1 atmosphere of 90% $N_2$ / 10% He. This gas filling is necessary to act as a damping medium for the seismic mass—its absence would result in unstable operation. A full technical description is given in [11].

During the high speed entry phase of the mission, a very wide range of accelerations will be experienced from the limiting resolution (around 0.3 μg) to a maximum approaching 20 g. In order to be able to handle this wide dynamic range, the HASI-ACC Servo accelerometer employs two separate amplifiers; in addition, each of these two channels has two different switchable gain settings (high & low), giving a total of four different modes of operation. The main characteristics of these modes of operation are given in Table 1. The sensor is sampled within HASI at 400 Hz but only every $4^{th}$ point is recorded, (i.e. 100 Hz) due to bandwidth limitations. Further on-board summing of 32 values by HASI then gives an effective sampling frequency during the entry phase of 3.125 Hz.

Table 1. HASI-ACC Servo operational modes*

| *Mode* | *Range* | | *Resolution* | |
|---|---|---|---|---|
| | ***High Gain*** | ***Low Gain*** | ***High Gain*** | ***Low Gain*** |
| *High resolution* | ±2 mg | ±20 mg | 0.3 μg | 3 μg |
| *Low resolution* | ±1.85 g | ±18.5 g | 0.3 mg | 3 mg |

*Gain ranges are nominal. Actual ranges will differ slightly due to zero offset.

The 1-bit resolution on raw data (i.e. sampled at 100 Hz) is ~0.005 V (12 bit resolution over ±10 V sensor output range). The sums of 32 measurements obtained at 3.125 Hz are organized in unique time-stamped telemetry packets. Each sum is a 16-bit word. This processing results in a resolution of ~0.002 V, equivalent to 0.3 or 3 μg in scientific units (depending on which gain is selected).

## 4. *HUYGENS* IN-FLIGHT CHECKOUTS

The ACC Servo has been subjected to a test sequence during each of the regular Flight Checkouts (FCO) of the actual *Huygens* probe, under nominally 'zero-g' conditions. These FCOs have been performed approximately every 6 months since launch, to test the probe and its subsystems during simulated entry, descent and surface proximity phases. Table 2 lists those already performed at the time of writing. For the Servo, the checkout procedure is initiated at the start of the checkout entry sequence by starting to sample the sensor's acceleration and temperature voltage output signals. The acceleration sampling mode is started in high resolution, low gain mode (i.e. ±20 mg range). After one sample the very low measured value causes the experiment to switch automatically to high resolution, high gain mode (i.e. ±2 mg range) for the rest of the checkout entry phase of approximately 15 min duration. For the subsequent checkout descent phase, the sampling is forced by software into low resolution, high gain mode (i.e. ±1.85 g range). Thus three of the Servo's four operational modes are tested.

Table 2. Flight Checkouts of *Huygens*.

| **In Flight CheckOut No.** | **Date** | **Heliocentric Distance [AU]** |
|---|---|---|
| 1 | 23/10/1997 | 1.0 |
| 2 | 27/03/1998 | 0.7 |
| 3 | 27/12/1998 | 1.6 |
| 4 | 15/09/1999 | 1.3 |
| 5 | 03/02/2000 | 2.9 |
| 6 | 28/07/2000 | 4.1 |
| 7 | 22/03/2001 | 5.5 |
| 8 | 20/09/2001 | 6.4 |
| 9 | 17/04/2002 | 7.2 |
| 10 | 16/09/2002 | 7.7 |
| 11 | 30/04/2003 | 8.2 |
| 12 | 18/09/2003 | 8.6 |

For the Servo, in-flight checkouts provide an opportunity to monitor the accelerometer's offset in a nominally zero-g environment and to characterise the sensor's noise performance.

## 5. HASI-ACC SERVO CHECKOUT DATA

Fig. 1 shows the HASI-ACC Servo accelerometer output as a function of time for a typical checkout (FCO#10) during entry phase when the sensor is set in high resolution, high gain mode.

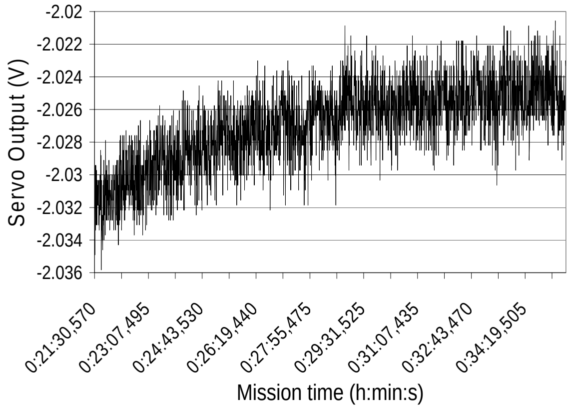


Fig.1. In-flight Checkout ACC Servo data (3.125 Hz sampling) during entry phase (FCO#10).

The gradual change in the output may at first sight seem surprising, since the acceleration environment is essentially zero and unchanging during the checkout. However, as with almost all sensors, the HASI-ACC Servo accelerometer has a temperature dependence. As the checkout progresses, the temperature of the sensor slowly increases due to heat generated within the sensor package and elsewhere within *Huygens*. The temperature within the HASI-ACC Servo accelerometer is monitored regularly but at a lower rate than the sensor (1.5625 Hz vs. 3.125 Hz). We have used simple linear interpolation to determine a temperature at each time that the sensor is sampled—this seems justified as the temperature is changing only slowly. Fig. 2 shows the same data as Fig. 1, but plotted vs. temperature (in engineering units) rather than time, and as a mean of 7 points, a timescale short enough for the temperature to be effectively constant.

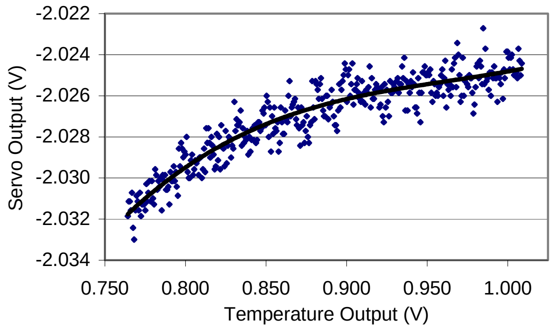


Fig. 2. FCO#10 ACC Servo output vs. temperature (in engineering units), with a polynomial fit.

A third-order polynomial fit is shown. A clear trend is visible as well as scatter or noise about this trend. This noise is a measure of the intrinsic stability of the sensor and thus of its ability to measure fine variations in acceleration and thus atmospheric density. We have subtracted the fitted polynomial trend from the data points and then computed the standard deviation of the resultant residuals. In the case of checkout #10 (Fig. 2), this amounts to 0.0016 V which, using the nominal pre-launch calibration, is equivalent to 0.3 μg. We have applied this technique to all checkouts performed to date and the results are shown in Table 3.

Table 3. ACC Servo noise figures.

| **In Flight CheckOut No.** | **Noise (1 σ) [V]** | **[μg]** |
|---|---|---|
| 1 | 0.0014 | 0.3 |
| 2 | 0.0015 | 0.3 |
| 3 | 0.0015 | 0.3 |
| 4 | 0.0016 | 0.3 |
| 5 | 0.0015 | 0.3 |
| 6 | 0.0070 | 1.4 |
| 7 | 0.0071 | 1.4 |
| 8 | 0.0016 | 0.3 |
| 9 | 0.0016 | 0.3 |
| 10 | 0.0016 | 0.3 |
| 11 | 0.0013* | 0.2 |
| 12 | 0.0016 | 0.3 |

**estimated on an incomplete data subset since the first telemetry packet containing temperature measurements was missing in this checkout.*

During the cruise phase, the long-term stability in the zero offset can be measured at each checkout. Fig. 3 shows the ACC Servo data (in high resolution and high gain mode, and as the mean of 128 values of every 8th point of the 100 Hz data, i.e. ~0.1 Hz) plotted vs. temperature (in engineering units) for checkouts 1-12. The sensor drifted by 3 μg over the course of the first 5-month cruise period (i.e. from checkout #1 to checkout #2). From the second checkout until now, the offset in zero g has varied within a range of 4 μg. We attribute the shift following checkout #1 to initial stabilisation of the sensor in the first few months after launch, although this effect is still under investigation.

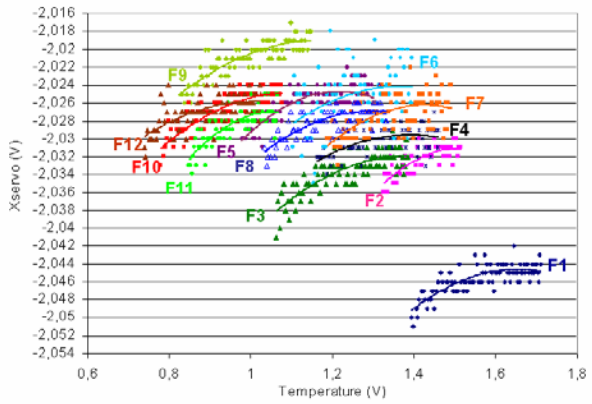


Fig. 3. ACC Servo output vs. temperature (in engineering units) for all the in-flight checkouts (F1-12) performed to date, plus third-order polynomial fits.

## 6. COMPARISON WITH PERFORMANCE OF PREVIOUS AND FUTURE PLANETARY ENTRY ACCELEROMETERS

A comparison of the various uncertainties (noise, resolution, offset, etc.) in the acceleration measured by the HASI-ACC Servo in high resolution, high gain mode with entry accelerometers on other missions is given in Table 4. Note that for different sensors not all sources of uncertainty are quoted, and in some cases the uncertainties are predicted rather than measured. Therefore direct comparisons should be performed with caution.

Table 4. Comparison of HASI-ACC Servo uncertainty in highest sensitivity range with that of accelerometers on other missions.

| **Mission(s)** | **Uncertainty in highest sensitivity range [μg]** |
|---|---|
| *Venera 8* | $3 \times 10^6$ [12] |
| *Mars 6* | 250000 [4, 5] |
| *Venera 9,10* | $3 \times 10^6$ [13] |
| *Venera 11,12* | $3 \times 10^6$ [14] |
| *Venera 13,14* | ~$1.56 \times 10^6$ (1 bit resolution) [3] |
| *Viking Lander 1,2* | ±6.1 [15] |
| *Pioneer Venus* (Large, Day, Night & North Probes) | Most sensitive channels (100 μg & 10 mg) failed [7] |
| *Galileo* Probe | 4000 [10] |
| *Mars 96* Small Stations | <1000 [16] |
| *Mars Pathfinder* | ~4 (noise) [17] |
| *Deep Space 2 Mars Microprobes (Scott & Amundsen)* | 38000 (1 bit resolution) [18] |
| *Beagle 2* | 61 (1 bit resolution) [19] |
| *Mars Exploration Rovers (Spirit & Opportunity)* | 35 (noise) [20] |
| *Huygens* HASI-ACC Servo | Noise: 0.3<br>resolution: 0.3<br>offset: ≤4 |

It can be seen here that the *Huygens* HASI-ACC Servo accelerometer is one of the most sensitive and stable launched to date.

## 7. IMPLICATIONS FOR PERFORMANCE AT TITAN: ENTRY MEASUREMENTS

HASI ACC will be the first instrument to be operative, measuring the deceleration of the *Huygens* probe as a function of time. The entry experiment will begin at an altitude determined by the accelerometer sensitivity, which is 0.3 μg in the most sensitive range. Given the expected velocity and flight path angle, mass and frontal area of the probe, the threshold atmospheric density measurement is estimated to be ~$1.75 \times 10^{-12}$ kg m$^{-3}$, which is expected to occur at an altitude of ~1430 km.

The ACC sampling will start 2 min before nominal entry, at an altitude of ~1900 km. The first data will be used to establish the sensor's offset and reading at 0 g at the time of entry (to be compared with the data from the last in-flight checkout, performed some weeks prior to entry).

The vertical resolution is determined by the sampling rate, probe descent velocity and flight path angle, and is ~1.8 km above 570 km. It improves as the descent speed decreases, reaching ~90 m at parachute deployment (i.e. nominally 162 km).

The density is derived from

$$\rho = -\frac{2ma}{C_D A V^2}, \qquad (1)$$

where $m$ and $A$ are the mass and frontal area of the probe, $a$ the measured deceleration, $C_D$ the drag coefficient and $V$ the velocity of the probe relative to the atmosphere in the direction of the descent trajectory. In Table 5 the expected values and the associated uncertainties of the parameters in Eq. 1 are reported.

Table 5. Uncertainty contributions to atmospheric density determination.

| **Parameter** | | **Value** | **Uncertainty [%]** |
|---|---|---|---|
| *m* | Probe mass | Measured (318.32 kg) and estimate of ablation | ~1% |
| *A* | Probe frontal area | Measured (22.795 $m^2$) and estimate of ablation | 0.1% |
| *V* | Velocity relative to atmosphere | To be derived from time integration of acceleration | ~2% |
| $C_D$ | Drag coefficient | From *Huygens* aerodynamical database | 5% |
| - *a* | Probe deceleration | To be measured | ~5.5% @1200 km ~1.6% @1100 km |

The mass and the frontal area of the *Huygens* probe were measured prior to launch. The uncertainties reported relate mainly to the estimation of the effect of ablation on the heat shield. The probe velocity will be derived from the time integration of the aerodynamic deceleration along the flight path sensed by the probe. The drag coefficient $C_D$ for the *Huygens* probe has been determined for the expected ballistic range to an accuracy of the order of 5%.

The accuracy on the probe deceleration measurements is of the order of 5.5% at 1200 km altitude and will improve rapidly, to less than 2% at 1100 km. Therefore the uncertainty on the atmospheric density determination is due mainly to the poor knowledge of the aerodynamic parameters rather than the accuracy of the acceleration measurements.

## 8. CONCLUSIONS

Flight checkout data and analysis of the zero-g offset, temperature dependence and noise characteristics demonstrate that the *Huygens* HASI-ACC Servo accelerometer is one of the most sensitive and stable launched to date, promising to deliver excellent performance during entry into Titan's atmosphere. The uncertainty on the derived atmospheric density will not be dominated by the uncertainty on acceleration measurements, except of course for the initial period following first detection of the deceleration. Reducing the uncertainty in the probe's drag characteristics would improve the atmospheric density profile results throughout the entry phase.

## 9. ACKNOWLEDGEMENTS

HASI-ACC is funded by the UK's Particle Physics and Astronomy Research Council (PPARC), whose contribution is acknowledged. The authors also wish to acknowledge the critical contribution of H. S. Jolly to the design and development of this subsystem.

## 10. REFERENCES

1. Fulchignoni, M., et al. The Characterisation of Titan's Atmospheric Physical Properties by the Huygens Atmospheric Structure Instrument (HASI). *Space Sci. Rev.* **104**(1), 395-431, 2002.
2. Avduevskiy, V. S., et al. Structure and Parameters of the Venus Atmosphere According to Venera Probe Data. In: Hunten, D. M., Colin, L., Donahue, T. M. and Moroz, V. I. (Eds), *Venus*. University of Arizona Press, Tucson, pp. 280-298, 1983a.
3. Avduevskii, V. S., et al. Characteristics of the Stratosphere of Venus from Measurements of the Overloads during the Braking of the Venera 13 and Venera 14 *Spacecraft. Kosmich. Issled.* **21**(2), 205-210, 1983 (in Russian). Translation in: *Cosmic* Res. **21**(2), 149-154, 1983b.
4. Avduevskii, V. S., et al. Martian Atmosphere in the Vicinity of the Landing Site of the Descent Vehicle Mars-6 (Preliminary Results). *Kosmich. Issled.* **13**(1), 21-32, 1975 (in Russian). Translation in: *Cosmic Res.* **13**(1), 18-27, 1975.
5. Kerzhanovich, V. V., Mars 6: Improved Analysis of the Descent Module Measurements. *Icarus* **30**(1), 1-25, 1977.
6. Seiff, A. and D. B., Kirk Structure of the Atmosphere of Mars in Summer at Mid-Latitudes. *J. Geophys. Res.* **82**, 4363-4378, 1977.
7. Seiff, A., et al. Measurements of Thermal Structure and Thermal Contrast in the Atmosphere of Venus and Related Dynamical Observations: Results from the Four Pioneer Venus Probes. *J. Geophys. Res.* **85**, 7903-7933, 1980.
8. Magalhães, J. A., et al. Results of the Mars Pathfinder Atmospheric Structure Investigation. *J. Geophys. Res.* **104**(E4), 8943-8955, 1999.
9. Schofield, J. T., et al. The Mars Pathfinder Atmospheric Structure Investigation/Meteorology (ASI/MET) Experiment, Science, 278, 1752-1758, 1997.
10. Seiff, A. et al. Thermal Structure of Jupiter's Atmosphere Near the Edge of a 5-µm Hot Spot in the North Equatorial Belt. *J. Geophys. Res.* **103**(E10), 22857-22889, 1998.
11. Cardy, W., Q-Flex Accelerometer, Construction and Principle of Operation. *Technical Note* **TN-103**, Sundstrand Data Control Inc, 1984.

12. Cheremukhina, Z. P., et al., Estimate of Temperature of Venus' Stratosphere from Data on Deceleration Forces Acting on the Venera 8 Probe. *Kosmich. Issled*. **12**(2), 264-271, 1974 (in Russian). Translation in: *Cosmic Res.* **12**(2), 238-245, 1974.
13. Avduevskii, V. S., et al. Automatic Stations Venera 9 and Venera 10 – Functioning of Descent Vehicles and Measurement of Atmospheric Parameters. *Kosmich. Issled*. **14**(5), 655-666, 1976 (in Russian). Translation in: *Cosmic Res*. **14**(5), 577-586, 1976.
14. Avduevskii, V. S., et al. Stratosphere of Venus According to the Data of the Accelerometer Measurements of the Venera-11 and Venera-12 Spacecraft. *Kosmich. Issled*. **20**(6), 913-920, 1982. Translation in *Cosmic Res*. **20**(6), 649-655, 1982.
15. NASA-TN-3770218 Entry Data Analysis for Viking Landers 1 and 2 Final Report (NASA-CR-159388) by Martin Marietta Corp. November 1976.
16. Linkin, V., et al. A Sophisticated Lander for Scientific Exploration of Mars: Scientific Objectives and Implementation of the Mars-96 Small Station *Planet. Space Sci*. **46**(6/7), 717-737, 1998.
17. Seiff, A., et al. The Atmosphere Structure and Meteorological Instrument on the Mars Pathfinder lander. *J. Geophys. Res*. **102**(E2), 4045-4056, 1997.
18. Smrekar, S., et al. Deep Space 2: The Mars Microprobe Mission. *J. Geophys. Res.* **104**(E11), 27,013-27,030, 1999.
19. Towner, M., Private communication.
20. Mars Exploration Rover Mission Participating Scientist Programme A.O. Proposal Information Package http://merpip.jpl.nasa.gov