Descent Dynamics of the Huygens Probe : Signatures in SSP Measurements

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ABSTRACT

Signatures of short-term motions appear in Surface Science Package data during the Huygens Descent. We present a preliminary survey of the data, identifying some dynamical signatures that vary during descent. A significant contribution to long-term variation of signals is due to temperature variation. Short-term variations are attributable to motion of the probe, which represents the aerodynamic interaction of the probe / parachute system with the changing ambient conditions during descent.

1. INTRODUCTION

The Surface Science Package [1] on the Huygens probe comprised a suite of small sensors designed to characterise the Titan environment, primarily on the surface but also during descent. In this paper we report the results of sensors sensitive to the motion of the probe during its descent, with two goals. First is a contribution towards the multi-instrument reconstruction of the probe's descent trajectory and attitude dynamics to aid in interpretation of remote sensing from the probe (optical sensing and radar altimetry). Second, the probe's dynamics are a combination of stochastically self-excited motions (aerodynamic 'instabilities', such as vortex-shedding from probe structures or interaction of the parachute with the probe wake) and motions driven by the Titan environment. Although significant modelling effort will be required to separate these components, it is hoped that study of the SSP dynamics data may ultimately help characterize the turbulent nature of the Titan atmospheric environment, as has been done on previous missions [2].

The initial results of the SSP at Titan are summarized in [3].

2. ACCELEROMETER - INTERNAL

The ACC-I (Accelerometer-Internal) sensor on SSP is a commercial piezoelectric design. The sensor was optimized to record landings of the probe on hard surfaces (e.g. Lorenz, 1994) and is thus relatively insensitive, having a full-scale reading of 100 g. Digitized at 12 bits, this gives a resolution of 0.05 g. However, the sensor is not DC-sensitive, and only has a meaningful response to signals with frequencies above about 2 Hz.

Data from this sensor was recorded during descent, at one sample per second, until around 7200 s (mission time from T0, the start of the descent phase) when SSP entered a proximity mode which did not permit ACC-I data to be telemetered until impact detection had occurred.

The sensor performed well at measuring the 18 g impact on the Titan's surface [3], indicative of a soft, but non-liquid, surface, see also [4].

During descent, the sensor exhibited a somewhat smooth variation in its raw output voltage (figure 1), upon which fluctuations of one or two bits (DN) was superimposed. Since it is known that thermal variations can impose small stresses on the sensor, it seemed plausible that the long-term variations might correlate with the temperature changes inside the probe. The probe initially warms due to the near-constant power dissipation (~300 W) within: as descent proceeds into colder, denser air, convective cooling soon exceeds the dissipation and the internal temperature steadily falls. A temperature sensor on the SSP tilt (TIL) sensors, about 10 cm from the accelerometer has its temperature derivative plotted in figure 1: the overall shape is very similar to that of the raw ACC-I reading, suggesting that indeed the baseline ACC-I value is drifting due to temperature changes.

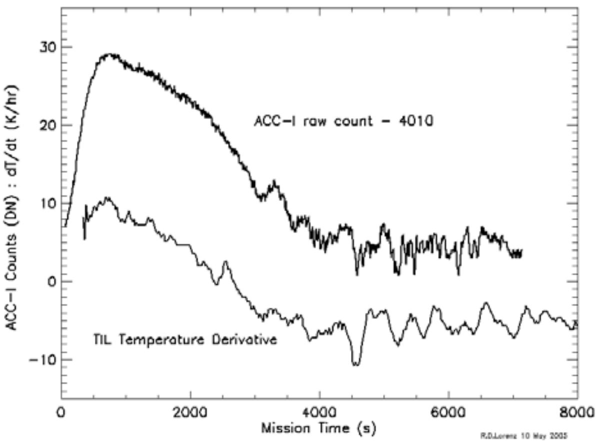

Figure 1. Raw signal from the piezoelectric accelerometer ACC-I, and the rate of change of temperature observed by a nearby sensor. The correlation suggests that temperature variations are responsible for the long-term evolution of the ACC-I signal.

Significant temperature changes are not expected on timescales smaller than some tens to hundreds of seconds, due to the thermal mass of the sensor and the SSP electronics box to which it is attached. Shorter-term variations may therefore be due to real accelerations. Figure 2 shows the count (usually 2 or 3) of variance of the ACC-I signal (sampled at 500 Hz over a 400 ms interval during each 1 s measurement cycle., smoothed to yield a more useful curve, rather than a forest of spikes with quantized length.

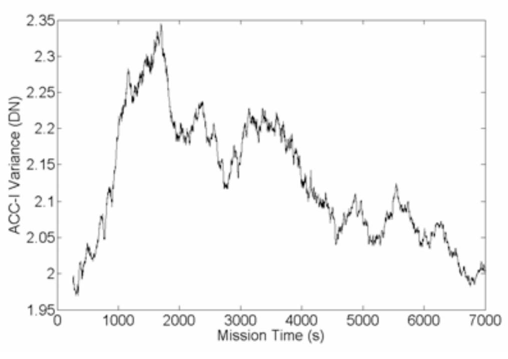

Figure 2. ACC-I Variance. This is the excursion of the ACC-I signal within a 400 ms interval, telemetered every 1 s. This is an integer value of DN in each interval – generally around 2. The heavy quantization of this signal requires a long smoothing window (400s) to yield the curve above.

It is not certain to what extent this variance signal represents real accelerations. In many respects the curve resembles that of the ACC-I raw value which appears temperature-rate dominated, although some buffeting component may be present. Indeed, the broad peaks around 1500 s and 4000 s are somewhat consistent with other data (e.g. from the TIL sensors described later in this paper).

As a final treatment of the ACC-I data, a long-term (100 s) running mean can be subtracted from the signal (the method is similar to the image processing technique of 'unsharp masking') and the residual, a forest of positive and negative-going spikes generally of 1 or 2 DN in amplitude, is then itself smoothed. The result is shown in figure 3.

These data seem to show variations of around 50 s period, after about 3600 s. However, so far no substantiation of this signature is evidenced in other sensors, so caution must be taken before asserting this signature indicates real probe motion.

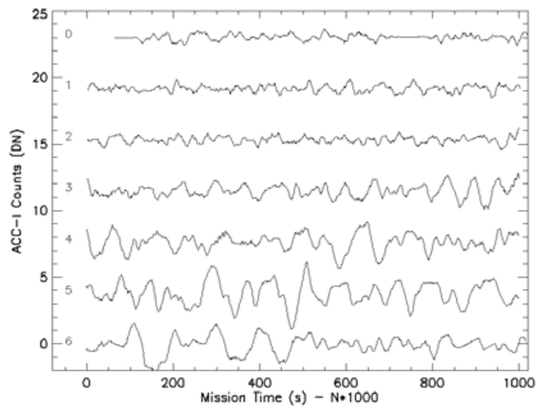

Figure 3. 'unsharped' ACC-I signal – the filtered difference between the ACC-I signal and its long-term mean. Curves are labeled 0 to 6 for the intervals 0-1000s, 1000-2000s etc. ACC-I data is not available for the last part of descent when the instrument went into an impact detection mode. It is not clear that the variations in this signal are real dynamic motions or simply noise amplified by the signal processing.

3. DENSITY SENSOR

An ocean density sensor (DEN), based on a small float cantilevered on an epoxy resin beam instrumented with a strain gauge, observed high-frequency variations during descent – see figure 4.

In effect, the sensor, also sampled at 1 Hz, works as a weakly-damped accelerometer along the probe's spin axis. The cylindrical float, designed to provide buoyancy in a Titan liquid to thereby measure its density, acts as the seismic mass of an accelerometer.

Strain gauges display considerable temperature dependences, and much of the long-term variation seen in figure 4 may be temperature-related. However, the character of short-term variations (presumably not due to temperature changes) also changes throughout descent, suggesting variations in the dynamical environment that are also seen in other data (see next section).

As a demonstration of the DEN sensor's potential utility, the acceleration to a new terminal velocity when the main parachute is released is clearly observed (figure 5).

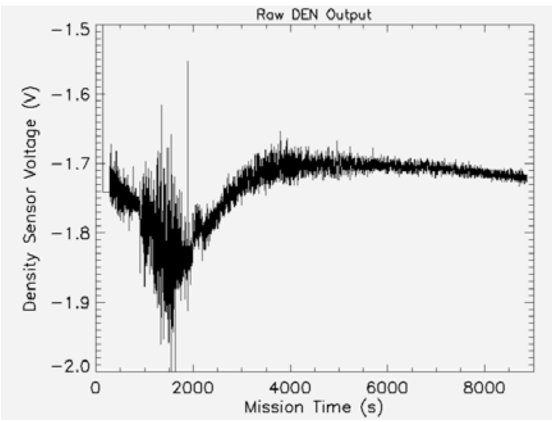

Figure 4. Raw DEN output during descent. Although initially unpromising, these data may yet prove useful in characterizing the descent dynamics of the probe.

Future work will investigate the temperature dependence and the short-term variations in the DEN data. It has been noted, for example, in scale model drops of the Huygens probe from model aircraft [5] that – perhaps counter-intuitively, given the observed motion - the signature of pendulum motion is more prominent in axial accelerometer data than in transverse accelerometer readings. The DEN data may be particularly useful in this regard.

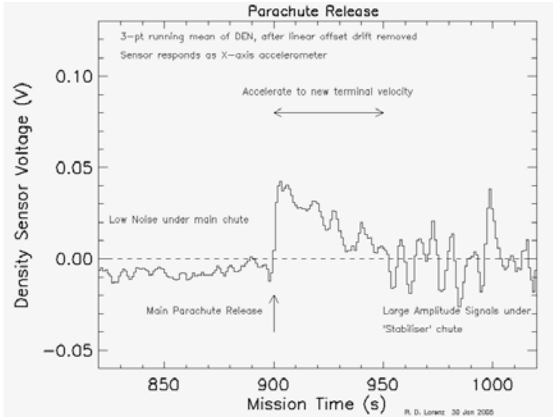

Figure 5. Detection of the release of the main parachute by the DEN sensor, acting as an X-axis (nominally vertical) accelerometer. After firing of the separation pyros at 900 s, the probe enters a free fall under one Titan gravity (~1.3 m s^{-2} at this altitude) minus an ever-increasing drag component. The e-folding timescale over which the new terminal velocity of ~80 m/s is reached is ~ 80/1.3 ~ 50 s Notice how the character of short-term motions changes between main chute and stabilizer.

4. TILT SENSORS

Two electrolytic tilt sensors (wherein a pattern of electrodes on the inside of an annular glass vial allows the resistive determination of the position of a small slug of a conductive liquid that acts as a pendulum) were carried on the SSP. A principal objective for these sensors was to measure any motion due to wind-driven waves in the event that the probe landed on the surface, although it was recognized that the TIL data would be useful during descent.

The raw and 100 s smoothed sensor outputs are shown in figs 6 and 7. Note that the TIL-X and TIL-Y axes are not aligned with the probe X and Y axes [6]. The sensors are ~36 cm from the probe X-axis (figure 8). The principal expected difference was that a centripetal acceleration due to probe spin would add a smoothly-varying offset to the X-tilt sensor. The expectation was that some steady pendulum motion might be expected, with a few degrees amplitude.

The data from the flight was much more dynamic than anticipated, with considerable short-term variation, and amplitudes reaching the saturation value of the sensors (60°). Clearly the pre-mission paradigm of a gentle long-period simple pendulum motion ($P = 2\pi(L/g)^{0.5}$ where L~12 m, g~1.35 m s^{-2}

giving P~19 s) was not realized and the probe motion was both more rapid and more complex.

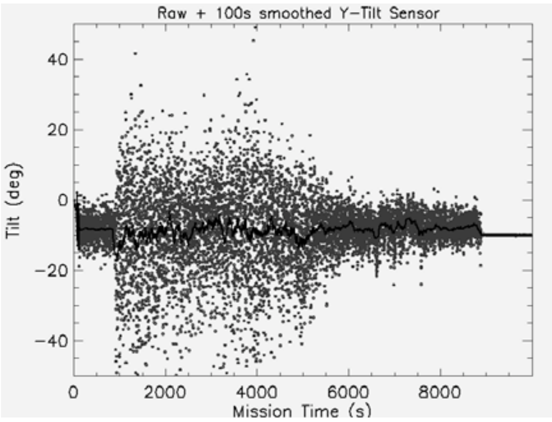

Figure 6. Y-axis tilt. Notice the distinct phases of the mission: 0-900 s somewhat quiescent under the main parachute, then more vigorous motions, with particular activity around 1500 s and 4000 s. Motion decays substantially beyond 5500 s, although occasional discrete 'spikes' occur. The signal is essentially constant on the surface (t>8870 s). The solid line is a 100 point running mean.

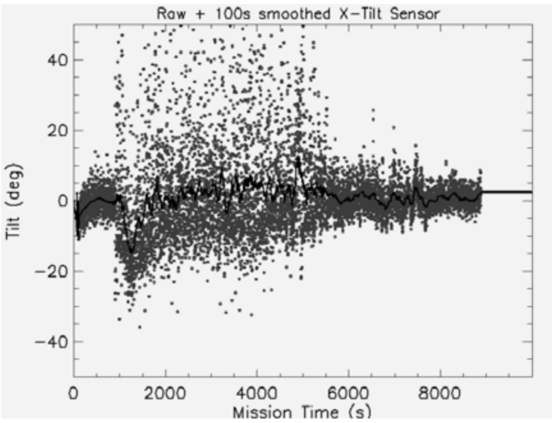

Figure 7. As figure 6, but for the radial (TIL-X) sensor. The mean signal tends to track the probe spin rate [7]. Note that the data points are more tightly clustered on the –ve side of the mean than on the +ve side Several prominent spikes occur during the latter part of descent in the relatively quiescent troposphere.

The actual probe motions are under investigation, and indeed there are other anomalies [7] such as a rather unexpected evolution, and in fact reversal, of the probe spin rate. Although the raw output of the tilt sensors indicates tilts of many tens of degrees that should have led to loss of lock of the radio link, the fact that the link remained robustly locked throughout descent suggests that attitude deviations were not this large. It is probable, then, that the indicated tilts include substantial dynamic components (i.e. sideways accelerations, perhaps best described as 'buffeting', which cause an effective tilt of the local vertical, but which do not indicate an actual rotation of the probe with respect to the Titan horizon).

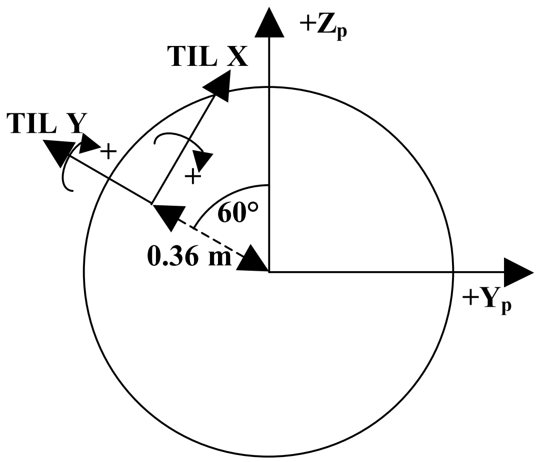

Figure 8. Schematic view looking down onto the probe, showing the position and orientation of the tilt sensor's axes with respect to those of the probe.

The TIL data indicate several distinct episodes during the probe descent. These episodes seem broadly consistent between the two axes, and also – at least upon first inspection – consistent with the DEN sensor fluctuations and indications from probe system accelerometers (not shown in this paper).

The clearest discontinuity is at 900 s, when the main parachute was released and descent became considerably faster, leading to higher aerodynamic loads (and presumably higher fluctuations in loads) on the descent module itself. Several slow variations in the amplitude of the TIL variations occur, which may be related to the evolution of the descent speed and thus the Reynolds and Mach numbers: however, the non-monotonic character of the envelope variation suggests that at least a component of the signal is due to changes in the turbulent variations in ambient windspeed at different altitudes on Titan.

The data show a persistent offset, particularly in the TIL Y axis, where it amounts to ~-8°. Although not yet fully explained, two possibilities are that the probe was tilted by asymmetric drag (more formally, an aerodynamic moment), or that there was a systematic offset in the sensor reading.

Collaborative investigation with other experiments may resolve this.

The X-TIL sensor was purposely aligned in a radial direction, such that a (negative) offset would be observed. The offset is nonlinear and altitude dependent, being equal to $\tan^{-1}(\omega^2 r g^{-1})$, where ω is the spin rate, r is the distance from the spin axis (0.36 m) and g is the acceleration due to gravity. Indeed, the rapid rise in spin rate can be seen in the smoothed data (figure 7) where a peak occurs around the maximum spin at 1245 s.

A curious signature observed in the data, and not yet conclusively explained, is that the data are highly skewed. Even by eye it is apparent that the data points are asymmetrically distributed about the mean – the excursions are much larger in the positive direction than in the negative. This feature will be the subject of future investigation – one working hypothesis is that one of the bridle legs may be repeatedly collapsing and then becoming taut due to the buffeting motions. The snapping taut may give an impulsive acceleration tending to give instantaneously high TIL-X readings.

An additional topic of further study will be the periodic character of the tilt motions. Figure 8 shows a spectrogram of the TIL signals. To generate this, the two-axis tilt (θ_x,θ_y) is expressed as the complex number $\theta_x + i\theta_y$ and FFTs performed with a 256 s-wide moving Hanning window. The output is shown as two spectrograms, corresponding to clockwise and anticlockwise motion of the TIL vector.

5. CONCLUSIONS AND LESSONS LEARNED

It would be trivial to include much more sensitive accelerometers and solid-state gyros today. These are now inexpensive and reliable, used in recreational applications and automotive airbag actuation – it is even possible to instrument spinning toys with such devices [8]. Such sensors would be preferred in a modern experiment to the fluid-in-loop devices that were the best sensors available when SSP was designed over 15 years ago.

With the benefit of hindsight there are of course ways in which the experiment could have been better optimised, in terms of sampling schemes and rates, and the mounting locations of sensors. For example, it is clear that the motions of the probe were more complicated than expected, so higher sampling rates (at least for intervals of the descent) would have better characterised them.

Even from the SSP data alone, it is evident that the Huygens probe endured rapid and complex short-term motions during its parachute descent. The attribution of the signals to specific modes of translational and rotational probe motions is still under way: although much of the motion appears somewhat stochastic, the existence of non-monotonic variations suggests that there are signatures of Titan atmospheric winds in the probe motions and thus in the SSP data.

Further analysis of the SSP data, in conjunction with data from other experiments and engineering data, will aim to isolate and identify this environmental excitation.

6. ACKNOWLEDGEMENTS

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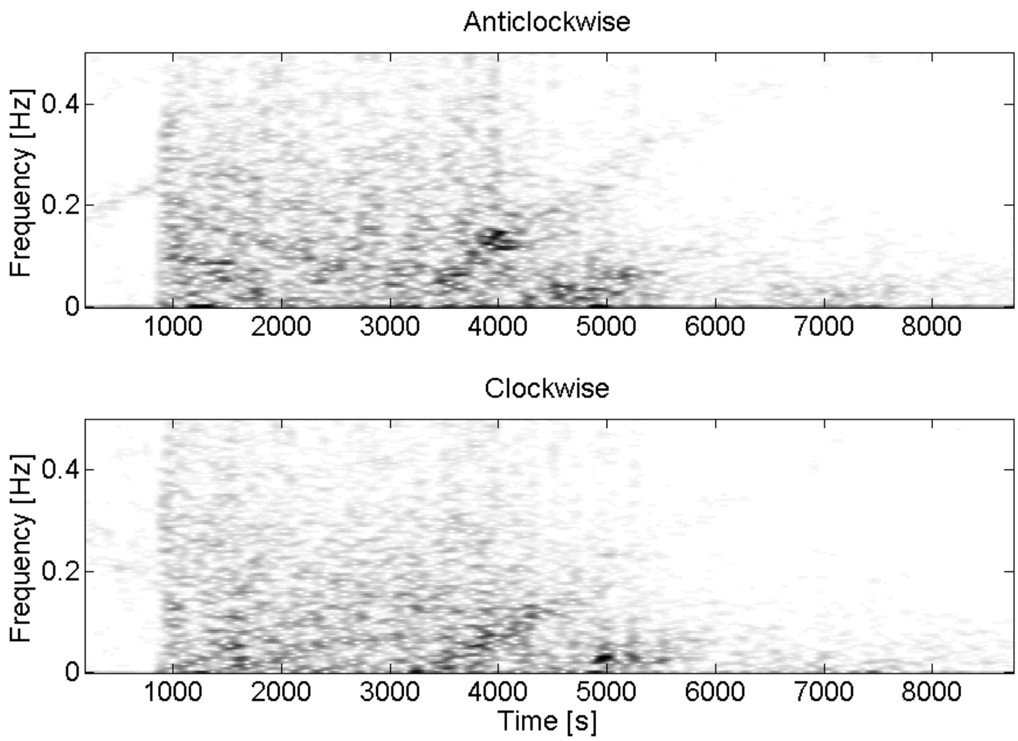

Figure 8. Spectrogram of the two-axis tilt data; tilt values from the two axes are combined as a complex number for the purposes of performing an FFT. The output shows the evolution of amplitude vs. frequency over the duration of the descent, for both clockwise and anticlockwise motion of the tilt direction.