TITAN SURFACE MECHANICAL PROPERTIES FROM THE SSP ACC–I RECORD OF THE IMPACT DECELERATION OF THE HUYGENS PROBE

R. Lorenz,[*] G. Kargl,[†]
A. Ball, J. Zarnecki, M. Towner, M. Leese,
T. McDonnell, K. Atkinson, B. Hathi, A. Hagermann [‡]

Abstract

The *Huygens Probe* landed on Titan at 11:38:11 UT on 14 January, 2005. The main impact event lasted approximately 20 ms, with possible bounce and rocking for up to 2 s thereafter. The peak deceleration was 15 g. The deceleration was characterized by several accelerometers as well as a penetrometer: we focus on the Surface Science Package ACC–I accelerometer whose sole function was to record the surface impact. This sensor sampled deceleration along, but offset 0.325 m from, the probe's axis at 500 samples per second. Simple mechanics suggests the probe decelerated over a stroke of 0.15 m to 0.2 m, although whether it subsequently bounced or slid out of that cavity is not clear. Comparison of the deceleration amplitude with models of various target mechanical properties suggests that sand, soft clay or lightly packed snow are appropriate analogs. However, the fairly sharp onset of the deceleration peak argues against a target that increases in hardness sharply with depth such as dry sand – a more cohesive (perhaps damp) target seems more likely. Interestingly, the deceleration record implies a target strength several times weaker than that indicated by the penetrometer – one possible interpretation is that a number of cobbles on the surface, rather than the curved bottom of the probe, acted to define the contact area with the surface material during the impact event. The relatively soft impact meant that the deformation of the probe was not significant (as evidenced by the lack of any probe or instrument failures at impact) and thus, to a first order, the event may be reproduced in physical or numerical models that assume the probe is rigid. We will review the latest simulations and interpretations of the impact event.

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[*] *Lunar and Planetary Lab, University of Arizona*
[†] *IWF Graz*
[‡] *PSSRI, The Open University*

1 Introduction

The experiments on the *Huygens Probe* had to be designed against ignorance – solid or liquid, representing a very large dynamic range of surface properties. The prevailing model of Titan's surface at the time when the experiments were selected was that of a global hydrocarbon ocean, and thus many elements of the payload (notably several of the subsystems on the *Surface Science Package* (SSP)) were optimized for that scenario.

It will be recalled that because of the uncertainty in surface environment, there was no specification on impact tolerance imposed on the mechanical design of the Huygens probe, although explicit measures were taken to ensure that battery energy, communications link performance and thermal budgets would permit surface operations for at least 3 minutes after the longest possible descent. Since atmospheric profile and parachute performance uncertainties (among other factors) introduced a roughly ±15 minutes uncertainty in descent time, a likely opportunity for $\sim$18 minutes of surface operations was expected.

Prospects for surface operations became improved in several respects as the mission evolved. First, the rescoping of the *Cassini* mission (with the deletion of a small dedicated probe relay antenna on the orbiter, and the use of the High Gain Antenna from longer distances, thus keeping *Cassini* high in the sky for longer) allowed a longer communications window. Second, an analysis of the structural loads at impact (Lorenz, 1994) suggested that post–impact survival of the probe as built (which despite having no specific impact attenuation hardware, did have a thin metal shell and a 5 cm thick layer of insulating polyurethane foam which would both absorb some impact energy) would be fairly likely for sandy or softer surfaces. Further, a parachute drop test of the probe in 1996 ended with a model of the probe landing on packed snow, on which it continued to operate without perturbation.

Finally, the delivery and relay geometry was adjusted once more as *Cassini* approached Saturn, in response to a hardware problem discovered in the probe relay receiver on the orbiter. The *Cassini* trajectory was changed to reduce the line–of–sight doppler shift in the probe signal in order to improve the synchronization of the bitstream, with the result that the flyby distance was increased. The final trajectory kept *Cassini* above the horizon as seen at the *Huygens* landing site for approximately one hour after the longest expected descent.

2 Impact data

The probe impact was measured directly by three sets of sensors. First, the SSP penetrometer (Lorenz et al., 1994; Lorenz et al., 2000) recorded contact and noted a short spike, followed by a quasi–steady force of $\sim$50 N. The sensor measured force for 50 ms with a 10 kHz sampling rate. Second, and in the focus of this paper, is the SSP impact accelerometer (Zarnecki et al., 1997). This was optimized to measure medium–hard impacts (in a range of ±90 g), and was recorded with a 500 Hz sempling rate. The sensor was mounted close to the periphery of the probe experiment platform, on the SSP electronics box. The raw (see below) peak deceleration was measured to be 178 m/s^2 ($\sim$18 g), with a pulse width of about 50 ms. A third, independent, measure of the impact was made by the HASI accelerometer. This triplet of piezoresistive sensors measured the 3–axis acceleration at the center of the experiment platform, at a lower rate (200 Hz). The measured profile was essentially similar to that of SSP, but with a "negative spike" superimposed, which has subsequently been attributed to a fundamental structural vibration mode of the experiment platform (Bettanini et al., 2008).

The descent velocity just prior to impact was estimated from the variation of pressure with time by HASI, by doppler shift in the radio signal, and by successive ranges–to–surface measured by the Huygens radar altimeter and by the acoustic properties measurement on SSP (Towner et al., 2006). These various investigations suggest an impact velocity of just under 5 m/s, and agree with the integration of the impact deceleration records.

Two independent lines of evidence suggest that the probe was more or less left resting on the surface. First, the camera system (DISR) provides a "knee high" view, and parallax between its various systems and the sharpness of focus indicate that the ground was about 45 cm beneath the camera head (Karkoschka et al., 2007). Second, the Huygens signal strength measured by Cassini as it set on the western horizon faded in a characteristic pattern due to constructive and destructive interference of the direct ray from the probe antenna and a ray reflected from the surface. This interference pattern is strongly diagnostic of the height of the antenna above the reflecting surface (Perez–Ayucar et al., 2006) and indicates the phase center of the antenna to be $\sim$ 76 cm above the ground, again consistent with the base of the probe resting on the surface.

Reconciling the post–impact position of the probe with the deceleration stroke required (i.e. the distance traversed during the measured deceleration pulse, some 15 cm or so) is challenging – one interpretation we discuss below is that the probe landed on solid (perhaps ice) "cobbles" (i.e. rounded blocks 10–15 cm in diameter, like large pebbles) and pushed these into the ground. Another possibility is that the probe bounced or skidded out of the depression it made at impact.

3 Interpretation

The raw ACC–I profile requires some caution in interpretation, since the transfer function of the front–end electronics tends to emphasize 'jerky' accelerations (jerk is the second derivative of velocity, acceleration being the first). It may be noted furthermore that the raw signal does not return to zero after the pulse, but settles at a slightly negative value. Applying deconvolution procedures, knowing the impulse response, rectifies this effect, and slightly modifies the inferred peak deceleration.

In this connection, fairing a smooth curve through the HASI PZR curves indicates a peak deceleration of only 15 g or so. Fundamentally, however, the interpretation does not change substantially. Two zero'th order interpretations of the deceleration can be made. First, the peak deceleration can be equated to a force via Newton's 2^{nd} law – the 178 m/s multiplied by the probe mass at impact of 205 kg corresponds to 30 kN. Further, taking a 15 cm penetration depth and knowing the radius of the probe fore–dome of 1250 mm,

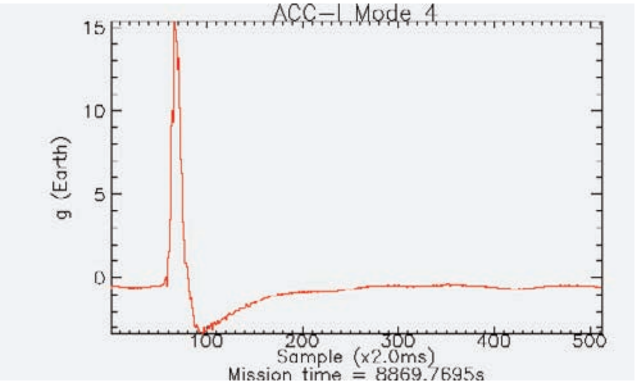

Figure 1: Raw ACC–I impact record. Note the 15.5 g peak and the apparent negative deceleration after impact, an effect of the conditioning electronics.

simple trigonometry indicates the contact area as ~ 1 m^2. The bearing strength one calculates by dividing the force by the area is thus ~ 30 kPa.

A second measure may be derived, noting that stress has the dimensions of (energy/volume). The probe's kinetic energy at impact can be divided by the volume swept out by the probe at impact, again assuming a radius of 1250 mm. (As discussed in Lorenz (1994), the probe is not a simple hemisphere, but the penetration depth is so low that the only part that interacts with the surface is a spherical cap, so this spherical analytic approach may be used here). The swept volume corresponding to 15 cm penetration is ~ 0.1 m^3, giving an energy per volume of ~ 25 kPa, much as above.

Note that these two measures of strength do not generally yield equivalent results, see Figure 2, since the energy/volume measure depends on the inverse cube of the penetration depth, while the force/area one relates to the inverse square. On this occasion, however, they do.

The result of 25–30 kPa is a factor of 8–10 smaller than the result implied by the penetrometer. There may be several reasons for this result, as listed below:

1. The areas assumed for the penetrator and/or the probe are not correct. If the probe landed on cobbles and pushed them into a soft substrate, the relevant area would be that of the cobbles – larger for the penetrometer (implying a softer substrate than indicated) and smaller for the probe (implying a material stiffer than 30 kPa).

2. The penetrometer struck a locally stiffer material than the average of the material under the probe.

3. The "strength" determined by the acceleration was in fact that of the probe which deformed, not the surface material.

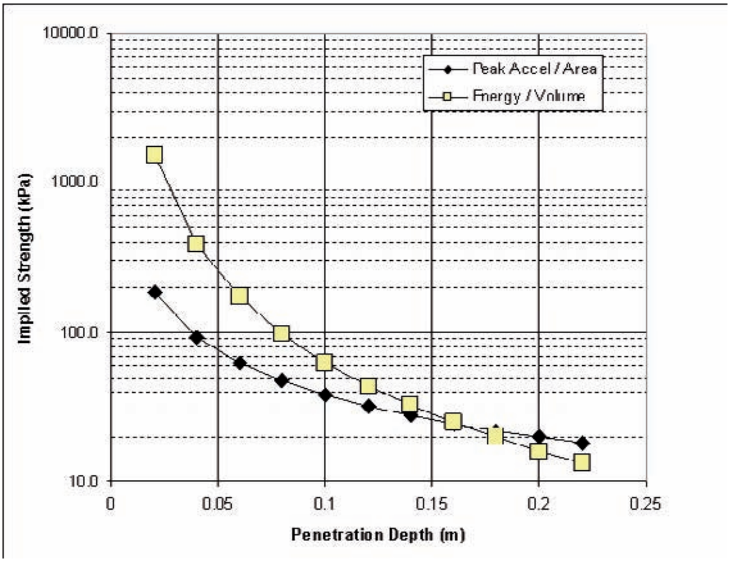

Figure 2: Inferred surface strength from dividing peak load by final contact area, and by dividing kinetic energy by swept volume.

For hypothesis (3) to be correct, however, the deformed probe would have had to bounce back into shape, such that the probe's upper parts (radio antenna and DISR) were at their observed heights post–impact. Hypothesis (2) similarly requires a bounce or skid out of the hole. Only hypothesis (1) explains all the data easily.

One of the most striking features of images from the landing site is the abundant presence of rounded cobbles (10–15 cm in diameter) from immediately under the probe towards the south. The existence of similar surface roughness to the west is implied by the multi–path fading of the probe signal (Perez–Ayucar et al., 2006). Thus it is reasonable to accept the influence of cobbles on the landing/penetration dynamics of the probe.

The qualitative interpretation, that the underlying surface is "soft" is robust — factors of a few stiffer than 30 kPa are still consistent with surface material descriptions as "soft clay" (note in all cases a mechanical, rather than compositional, equivalent is implied), "wet sand", "packed snow" or the famous "creme brulee".

The interpretation that the fine–grained substrate material contains methane (with some unknown amount of ethane) is supported by the evolution of methane into the heated inlet of the GCMS instrument (Niemann et al., 2005). This was apparently due to the ground being damp with liquid methane, since the surface material was efficient at removing heat from the inlet, consistent with wet sediment or solid bulk materials, but not dry sediments (Lorenz et al., 2006). Since the mechanical impact data show that the surface was not a bulk solid (like a sheet of ice) the combination of data leads to the wet sediment interpretation. The effective heat sink meant that the inlet temperatures were not enough to decompose clathrate ices, and thus methane released must have been present as liquid.

4 Comparison with pre–mission expectations

While the *Huygens Probe* itself had no mechanical design specifications related to impact loads, the instrumentation clearly had to assume some range of interest, and some theoretical and analogue investigations were made (Lorenz, 1994). Notably this meant from arbitrarily soft impacts (fluffy aerosols, powder snow) through possible liquid impact ("splashdown", for which an analytic framework is fairly well established) through arbitrarily hard surfaces with large impact loads. In the latter case, the probe itself would be expected to deform, and thus the deceleration measurement would be determined by the probe stiffness rather than that of the ground. In such a case interpretation (beyond establishing a lower limit) would be difficult. Of course, the probe would be able to tolerate only a certain (undetermined) amount of deformation before it failed, and thus for the hardest–surface cases such as a flat sheet of ice, it might be that the probe would not survive and no data would be obtained.

Lorenz (1994) attempted to model elements of the probe structure to assess how the deceleration profile might depend on soil parameters. Some example data are shown in Figure 3, with the surface material parameterized as a strength P vs penetration distance x of the form

$$P(x) = k_1 + k_2 x \tag{1}$$

k_1 denotes a "bearing strength", the pressure that the undeformed surface can exert on a body resting or pushing onto it. k_2 is a "subgrade modulus", the increase in strength with depth. Cohesive materials like clay or packed snow typically have $k_2 \approx 0$, while unconsolidated materials have $k_1 \approx 0$.

It can be seen from the figure that shifting the observed deceleration profile in time allows both types of curve to be partially fit, but the fit and in particular the rise time and peak seems most consistent with a cohesive ($k_2 \approx 0$) material.

An additional comparison may be made with the experimental drop tests by Seiff et al. (2005). These tests were in fact conducted as a proposal preparation activity in 1989, but only published in the open literature by the first author of the present paper in 2005, Al Seiff himself having passed away in the interim. These tests involved 1/3 and 1/9 scale models with spherical noses (based on the Phase–A probe configuration, the final design having not yet been finalized). It was found that a scaling relationship captured the peak deceleration quite well. Specifically, dry sand impacts should cause a peak deceleration of

$$\begin{aligned} \mathrm{G}_{\max} &= 0.2\, V^2 \rho \frac{R_N^2}{m} \\ &\sim 0.2 \times 25 \times 1000 \times \frac{1.3^2}{200} \sim 42\ \mathrm{g} \end{aligned}$$

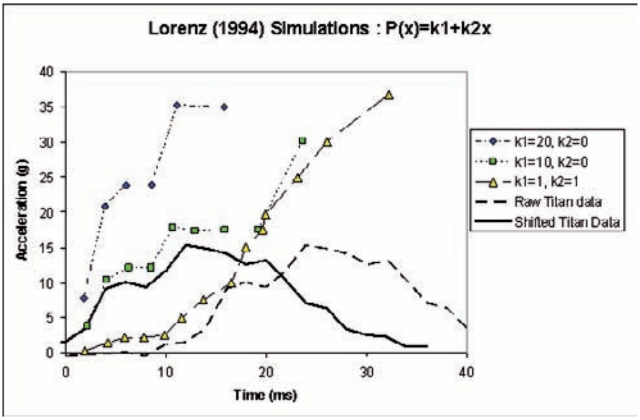

Figure 3: Simulations of the Huygens impact made in 1994, compared with the flight data. The rapid onset of the deceleration pulse suggests a cohesive material (i.e. $k_1 > 0$, $k_2 \approx 0$). The disagreement of the last data point of the $k_1 = 10$, $k_2 = 0$ curve relates to the model, which allowed no relaxation of material (and thus no decline in resistance.)

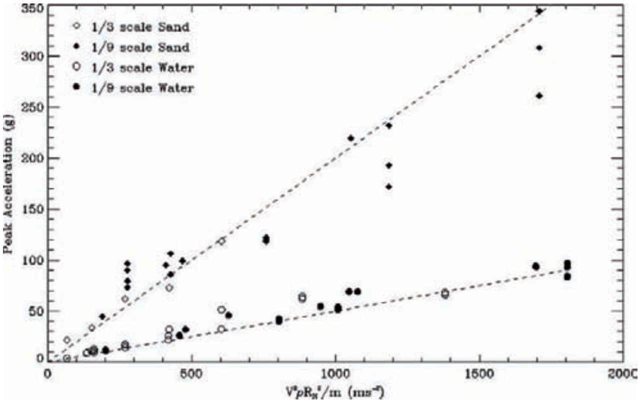

Figure 4: Scale model experiments by Seiff et al. (2005) with 1/3 and 1/9 scale Huygens probes (Phase–A configuration) suggest peak loads vary with parameter $V^2\rho R_N^2/m$, with a factor of 0.05 for water impact and 0.2 for dry sand impact.

This is in moderately good agreement with the $k_1 = 1$ N/cm^2, $k_2 = 1$ N/cm^3 "sand-type" model in the Lorenz (1994) simulations. The fact that the actual *Huygens* impact saw a lower peak deceleration relates to the faster rise time of the deceleration (due to the material cohesion, higher k_1) and/or the influence of the surface cobbles.

5 Conclusions

The impact investigation on SSP was successful, and provided the hoped–for documentation of the impact event and yielded constraints on the mechanical properties of the surface material. Fortuitously, the target strength lay in the useful regime embraced by both the penetrometer and accelerometer capabilities.

The lack of a full–scale impact test programme with a fully representative structural model of the probe limits the ultimate fidelity of interpretation of the data. Tests of scale models into wet and dry granular targets may give some insight into whether these can be discriminated with this type of data alone (although in the case of the Huygens landing site, other investigations suggest the ground was damp). Comparison of the Lorenz (1994) simulations with the flight data, as well as a cursory comparison of the penetrometer record with laboratory materials, seems to suggest a cohesive material (i.e. one that offered resistance before it had been appreciably penetrated) – much like wet clay or packed snow, rather than an unconsolidated one.

The heterogenous nature (cobbles) of the landing site makes a declaration of a "final" figure for the bearing strength of the surface rather meaningless, but a range of 30 kPa to 250 kPa, with a most probable value of ∼100 kPa is supported by the data. Of course it is also clear from other Cassini data (near–IR and radar imaging) that Titan's surface is extraordinarily variable (e.g. Lorenz and Mitton, 2008) — the alluvial streambed on which *Huygens* landed is only one of many surface types, which include mountainous regions, cryovolcanic lava flows, sand dunes and lakes. Nonetheless, the landing site is the one (soft) area on which we have hard information.

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