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An impact penetrometer for a landing spacecraft

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Abstract. The design, development and calibration of an impact force transducer or penetrometer, for use on the Huygens spacecraft scheduled to land on the surface of Saturn's moon Titan, is described, The thumb-sized transducer employs a piezoelectric sensing element and is capable of working at cryogenic temperatures. Use of the sensor on a spacecraft imposes several reliability and safety constraints, as well as the desire to minimize mass (the sensor mass is 15 g). The impact force profile, measured at 10 kHz by the sensor, allows estimation of the density and cohesion of the surface material, and its particle size distribution. Sample profiles for terrestrial materials (sand, gravel and clay) are given.

1. Introduction

Saturn's giant satellite Titan is currently an object of intense scientific interest and will be the focus of attention of the joint NASA/ESA Cassini mission, which will arrive in the Saturnian system in 2004 [1, 2].

The mission includes a European-built probe, named Huygens, which will descend by parachute to the surface of Titan. The nature of Titan's surface [3] is largely unknown at present, with only hints from ground-based radar and telescope observations, and the results of the 1980 encounter with the Voyager 1 spacecraft. Possible surface candidates [4] are a hydrocarbon (liquid methane/ethane) ocean, fluffy deposits of organic aerosols and ice or rocky regolith.

The Huygens probe includes an instrument suite, the Surface Science Package (SSP, [5, 6]), which will determine the nature of the surface of Titan at the Huygens impact site (the spacecraft's survival after impact is not guaranteed [7]) with a variety of sensors. Among these, the ACC-E subsystem, or penetrometer, will measure the mechanical properties of the surface material, and is the subject of the present paper. These measurements will help identify the surface material and the geological processes that have formed it.

2. A brief overview of penetrometry

Soil mechanical properties are measured on Earth for a variety of civil engineering and exploration purposes, principally for assessing the suitability of soils for buildings or roads and for estimating the trafficability of soils or snows for aircraft landings or vehicle movement. The methods and techniques used to measure terrestrial soil strength vary widely [8]. Table 1 summarizes the various types of measurement. In addition to the two space missions mentioned in table 1 impact accelerometry on penetrators has been proposed for a number of space missions and was a favoured concept for early Moon exploration [19, 20].

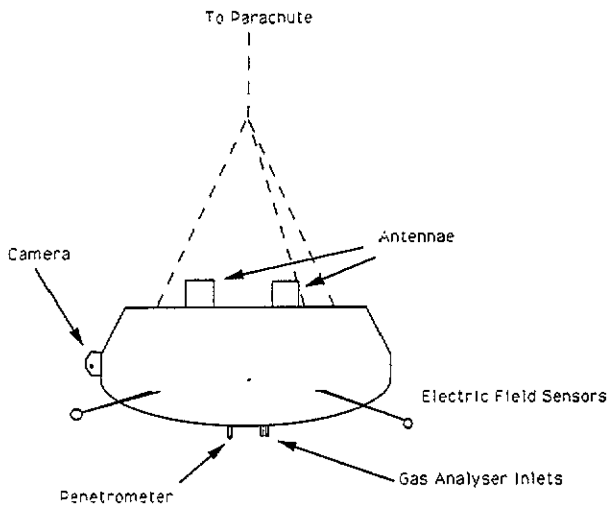

Figure 1. The Huygens probe, showing location of the penetrometer.

Table 1. Penetrometer types.

Type	Penetration driver	Measurement	Application	Reference
Ram penetrometer	Hammered	Depth of penetration	Snow hardness/avalanche safety	[9]
Ram penetrometer	Inertia of 'penetrator' dropped from a frame	Depth of penetration	Coastal sediments	[10]
Dutch cone	Hydraulic ram	Force (strain gauge)	Civil engineering	[8, 11]
Field penetrometer	Electric motor/screw	Force (strain gauge)	Agricultural soil evaluation	[12]
Acoustic penetrometer	Hydraulic ram	Force plus microphone	Civil engineering	[8, 13]
Apollo penetrometer	Weight of astronaut	Force (mechanically recorded)	Lunar soil evaluation	[14]
Aerial penetrometer	Inertia of heavy rod inside light bomb case (air-dropped)	Depth of penetration (via optical encoder on rod)	Assessment of terrain for aircraft landing	[15]
Sea-ice penetrometer	Inertia of 'penetrator' (air-dropped)	Accelerometer	Measurement of sea-ice thickness	[16]
Luna-13 penetrometer	Rocket-powered cone (mounted on arm)	Depth of penetration (by arm joint position)	Lunar surface evaluation	[17]
Venera-13 penetrometer	Dropped cone (mounted on arm)	Depth of penetration (by arm joint position)	Venus surface evaluation	[18]

Typically these measurements allow determination of the bearing strength of the soil material as a function of depth. However, additional information may be obtained. An interesting variant of the standard cone penetrometer is the acoustic penetrometer: as well as a force transducer, the penetrometer incorporates a microphone to measure the noise generated by the soil as the penetrometer is driven slowly at a few centimetres per second into it. Noise emission typically peaks in the 2–5 kHz frequency range and the intensity correlates with the soil particle size [8, 13].

3. Measurements on the Huygens probe

The probe is a 210 kg instrument capsule, of about 1.3 m diameter (figure 1), which will spend 2–2.5 h descending by parachute through the atmosphere of Titan. It is equipped with instruments to sample the atmosphere and the organic aerosols, measure atmospheric properties and winds, and image the surface. The prime objectives of the probe are to study the atmosphere and surface during descent; survival of impact is not guaranteed (which is unsurprising, given our ignorance of the nature of the surface). However, since, in the thick atmosphere and low gravity of Titan, the impact velocity is only about 5 m s^{-1}, prospects for survival seem moderately good.

If the probe does survive, imaging and measurements of physical properties will continue. Additionally the gas analyser is equipped with heated inlets to vapourize any volatile components (such as ices) of the surface material and determine their chemical composition.

The probe is equipped with accelerometers for measuring the atmospheric density at high altitude during the hypersonic entry phase, and with an internal impact accelerometer (ACC-I), which is part of the Surface Science Package. These accelerometers will characterize the mechanical properties of the surface if it is a liquid or a soft solid, see [21] for details. It is, however, extremely difficult to measure the strength of surface material that is more rigid than the probe itself (which, not being designed explicitly for impact, has a flexible outer shell). In this 'hard' surface case, the force–acceleration coupling that is so straightforward for penetrators no longer applies. It was realized therefore that an accelerometer measurement was not appropriate, but rather a force measurement. As the sensor was originally envisaged to be an accelerometer [5], it bears the historical designation ACC-E (Accelerometer-External), but it is, in fact, a force transducer.

4. Transducer mechanical design

To transmit the force exerted by the surface material to the sensing element in a reliable fashion, the ACC-E subsystem has a rigid hemispherical penetrator head, directly behind which is mounted the transducer (figure 2). These are attached to a short rigid pylon on the SSP 'Top Hat' sensor accommodation structure (figure 3), which holds it at the front of the probe. A hemispherical head was chosen over the conical head used in some previous applications for the following reasons:

(i) it has a simpler mechanical impulse response (fewer and higher-frequency 'ringing' modes),

(ii) it has a faster initial rise of impact signal, allowing faster detection of impact,

(iii) it is safer during probe integration (won't poke anyone's eye out), and

(iv) it is less sensitive to errors in impact angle.

After initial experiments with steel and aluminium penetrator heads, titanium (appropriate, perhaps!) was selected for the penetrometer head: steel is heavy and could present magnetic cleanliness problems; aluminium, while lighter, is too soft (it is hard enough for most impacts that are survivable by the probe, but during testing when the penetrometer is struck with metal objects, an aluminium head would be damaged.)

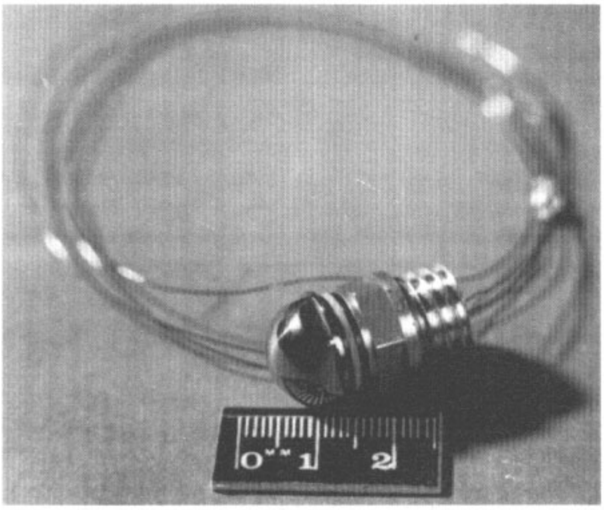

Figure 2. A photograph of the penetrometer sensor head.

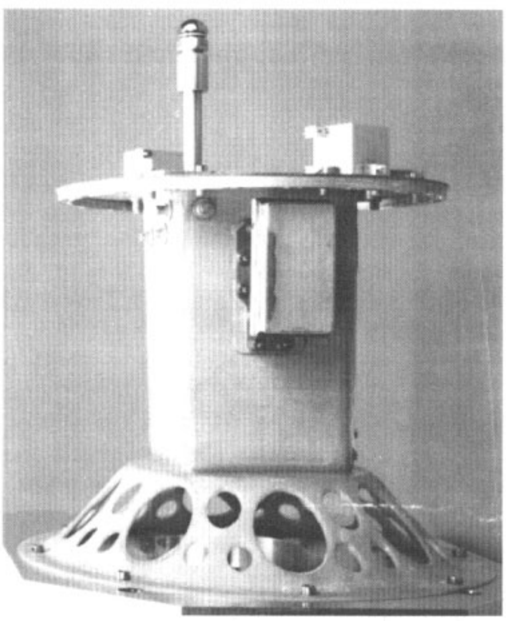

Figure 3. The penetrometer mounted on the mast of the structural/thermal model of the Surface Science Package, in preparation for a vibration test.

Following a suggestion by Al Sieff, a penetromet with rim around the transducer was investigated, su that the penetrometer head could only move vertical (that is, it acted as a piston pressing on the transduce However, this sensor design proved very difficult manufacture and assemble, and gave results no bett than the configuration currently adopted, and so w rejected.

The transducer was made as small as possible, minimize weight. A diameter of 14 mm was f to be the smallest size for which assembly would l straightforward.

The transducer is a simple 'washer' of PZT-5 (A donor-doped lead zirconate titanate piezoelectr ceramic), which generates a charge proportional to t stress on it. For background information on piezoelectr

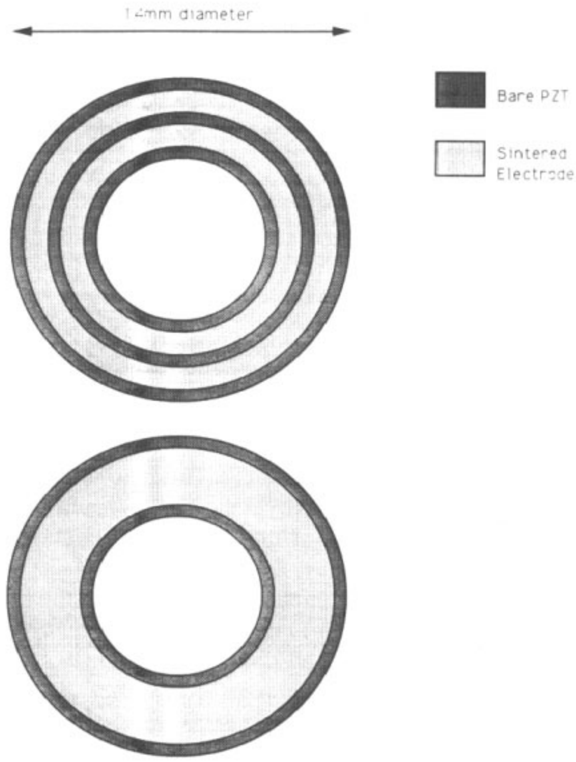

Figure 4. The piezoelectric sensing element, showing the electrode pattern. The disc is 1 mm thick.

materials, see [22, 23]. The material PZT-5A was selected for its high sensitivity and good temperature and age stability. The disc of PZT is held on to its electrical connections and the penetrator head by means of a central bolt, which holds the assembly under compression. An additional electrode allows the transducer to be stimulated in-flight for health and sensitivity drift checks during the long cruising phase.

The configuration of the piezoelectric washer is illustrated in figure 4. The common electrode is one side of the disc, while the sense and stimulus electrodes are 1 mm wide rings arranged concentrically around the the central whole, through which the bolt passes. The electrodes are as large as practicable, allowing a suitable gap between them and the bolt. The electrodes are ring-shaped (radially symmetric) in order to simplify assembly and to allow at least partial operation in the event of a crack in the washer.

Electrodes are formed on the transducer by silk-screen printing: a paste of ground glass and silver is deposited onto the PZT and sintered on. Care must be taken when soldering to these as (i) high temperature could locally de-pole the PZT and (ii) the silver electrodes can alloy with the solder and be accidentally removed.

The PZT element is sandwiched between two insulating washers made of the polyimide Vespel SP-1 (Vespel is a trademark of Du Pont): the washers have grooves cut in them to allow a small gap for the wires to pass through to reach the electrode, while keeping the PZT mechanically intimate with (but electrically isolated from) the titanium head and aluminium mounting collar. Vespel was selected for

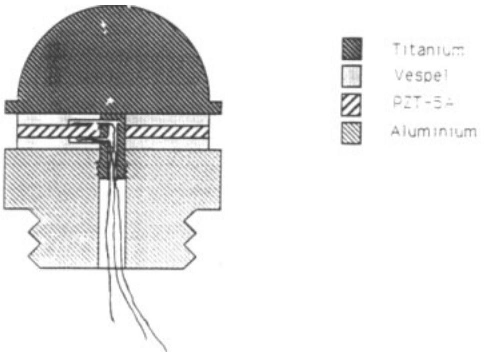

Figure 5. Section of the transducer, showing the individual components.

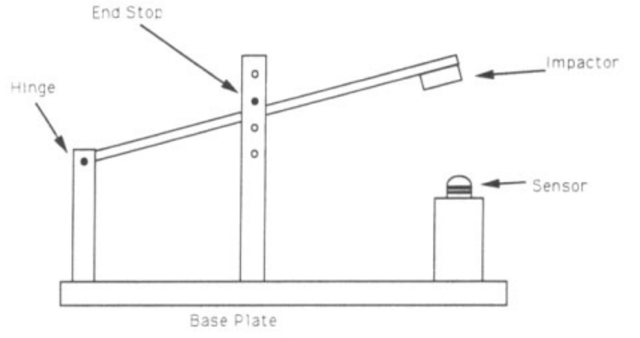

Figure 6. The pendulum jig for providing a known force pulse for instrument calibration.

its hardness, machinability, space qualification (such as low outgassing) and creep resistance (under compression for 8 years, polytetrafluoroethylene (PTFE) would creep, reducing the effectiveness of the mechanical connection between plastic and PZT).

To ensure good mechanical contact between the head and the PZT, the sandwich is held under compression (a pre-load) by the titanium bolt down the centre (figure 5). The wires to the electrodes pass down the centre of this bolt. While this design makes assembly awkward, it is robust. (Early experiments used sandwiches held together with epoxy adhesive, which had a tendency to crack after a few trials. Further, spacecraft safety requirements dictated that the head could not be held on by adhesive.) By having the bolt down the centre (rather than fixing on the outside) the bolt mass is minimized, and it is possible to inspect the PZT for cracks without dismantling the transducer.

The pylon on which the sensor is mounted is an aluminium tube. The transducer should be able to measure forces as low as a few newtons, while the upper limit of about 2000 N used as a working maximum figure is driven by the failure load of the support structure. For the about 1 cm^2 frontal area this corresponds to a soil bearing stress of 2000 N cm^{-2}, a value comparable with the bearing strength of some rocks and polymers. In practical terms, the 2000 N figures can be attained by a light blow with a wooden mallet, for example, see also the following section. Designing the measurement system (structure plus transducer) for loads much higher than 2000 N would be futile, since surfaces likely to generate these loads would probably cause the probe to fail in any case.

Clearly it is desirable to mount the transducer as far forward of the probe base as possible, to minimize probe structural effects on the transducer dynamics and to maximize the possible depth of penetration. However, there are clear limits to how far the transducer may project: an extendable or deployable boom (or, indeed, an ejectable penetrometer) was ruled out on cost and complexity grounds. The transducer is mounted as near as possible to the apex of the probe (also nearby are the inlets of the gas-sampling instrument) and as far forward as could be permitted, bearing in mind that the heat shield of the probe is mounted just in front. The outside of the heat shield reaches 900 °C during the hypersonic entry phase: it is jettisoned at the end of entry, at an altitude of 170 km, about 135 min before the probe reaches the surface. In fact, a small cut-out in the rear part of the heat shield was negotiated, to allow the penetrometer to project slightly further forward than would otherwise be possible.

5. Sensor electrical response and calibration

The calibration of the sensor is non-trivial, for two reasons. First, the robust construction necessitated for this application means that only a part of the impact force passes through the piezoelectric sensing element, and second, the device is not DC-sensitive, so calibration loads cannot be static. In other words, it is not possible simply to place a weight on the sensor: a known dynamic load must be used.

To generate a known force over a short period, masses were dropped using a swinging arm (pendulum) onto the sensor (see figure 6), with the sensor head impacting onto a plane surface of an elastic material. The impact of a spherical nose onto a plane semi-infinite surface can be modelled numerically (and indeed, analytically [19]). The force pulse has an approximately sinusoidal shape, with a peak magnitude proportional to $m^{0.6}E^{0.4}V^{1.2}$, where m is the mass of the impactor, E is Young's modulus of the impactor and V is the impact velocity.

The mass of the impactor could be determined by weighing; the impact velocity is determined from energy considerations, knowing the height over which the mass has been dropped. Two impactors were used, one made of PTFE, the other using a standard pencil eraser (synthetic rubber).

The impact forces ranged from about 30 N to 115 N for the rubber impactor and from 209 N to 585 N for the PTFE impactor. There is an uncertainty of order 40% in the absolute value of these forces, due mostly to an uncertainty of a factor of two in Young's modulus of the impactors. Work is underway to improve this uncertainty by *a posteriori* analysis of the duration of the force pulse.

Some description of the theoretical derivation of the transducer response is appropriate here, since the electrode areas of the transducer are not the same as the load-bearing area, so standard relations (such as in [23]) do not apply.

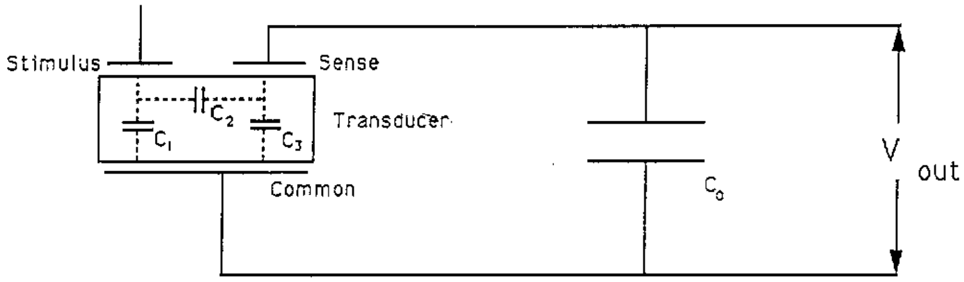

Figure 7. Circuit diagram for sensor calibration measurements, showing the internal capacitances of the lead zirconate titanate transducer.

Applying a capacitance meter across the sense and common electrodes yields (at room temperature) a value of about 590 pF. This is because what is being measured, C_s, is the sum of C_1 and the series combination of C_2 and C_3 (see figure 7). Measuring capacitance across the other pairs of electrodes allows the three capacitances to be determined: $C_1 \simeq 520$ pF, $C_2 \simeq 90$ pF and $C_3 \simeq 720$ pF. C_1 and C_3 are rather higher than might be expected from the electrode areas alone, due to edge effects. At liquid nitrogen temperatures, measurements yielded capacitances 3–3.5 times lower (manufacturer's data [23]) suggest capacitance should be about 2.5 times lower.)

The open-circuit voltage yielded by the transducer (area A, thickness t) when compressed with an effective force F_e is $g_{33}F_e t/A$, where g_{33} is the piezoelectric voltage constant, 24.8×10^{-3} V m N^{-1} at room temperature, but somewhat larger (by a factor of about 1.5, according to manufacturer's data) at liquid nitrogen temperature [23]). The effective force F_e may be lower than the applied force F by a factor k due to some of the applied force passing through the central bolt. An equal-deformation argument suggests that k is 2.5 at room temperature, or 2.1 at 80 K (lower due to the Vespel washers becoming stiffer): in practice k may be much lower (about 1) since the bolt is under tension and hence appears 'slack' to an applied compressive force.

The voltage actually measured will depend on how large a capacitance C_0 is loaded onto the circuit, since the charge generated by the transducer, $V_{oc}(C_1 + C_3)$ must be shared between C_0 and C_s.

Thus

$$V_{out} = \frac{F g_{33} t (C_1 + C_3)}{kA(C_s + C_0)} \qquad (1)$$

For this transducer (t = 1 mm, A = 104 mm^2), and C_0 = 15 nF, at room temperature we may predict $V_{out}/F = 0.0073$ V N^{-1} for $k = 2.5$, or 0.018 V N^{-1} for $k = 1$. At liquid nitrogen temperatures, the relation is more like $V_{out}/F = 0.0038$ V N^{-1} for $k = 2.1$, or 0.007 V N^{-1} for $k = 1$. Thus the drop in sensitivity at low temperature is by a factor of about 1.9.

Experimental results are given in figure 8 for room temperature and liquid nitrogen temperature. It is seen that the transducer appears linear for the force range investigated to date for both room temperature and liquid nitrogen temperature tests. The constants of proportionality are about 0.011 V N^{-1} for room temperature and 0.006 V N^{-1} for liquid nitrogen. These values are within the range suggested above. The drop in sensitivity at low temperatures is also in good agreement with predictions, at a factor of about 1.8.

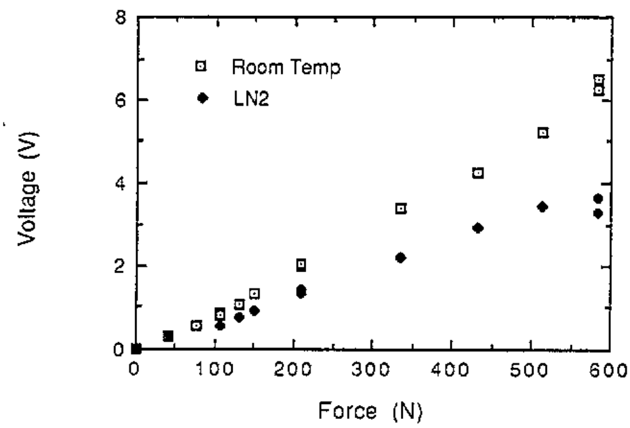

Figure 8. Transducer output for various force pulses at liquid nitrogen and room temperatures.

6. Radiation effects

Piezoelectric materials are relatively insensitive to radiation effects and are routinely used to monitor vibration levels in nuclear reactors. However, to satisfy ESA product assurance requirements, a radiation test was performed.

During the long transit to the Saturnian system, equipment on the probe may receive a radiation dose of about 10 kRad from the on-board radio-isotope thermoelectric generators and radio-isotope heater units (used to generate power on the orbiter, and keep the probe warm respectively), Saturn, Jupiter magnetospheric particles, solar wind and galactic cosmic rays. Therefore, allowing a safety of 2, operation of all probe systems must be demonstrated after a dose of 20 kRad.

Samples of the piezoelectric discs were irradiated to 20 k Rad using a cobalt-60 γ-source at the National Physical Laboratory: no noticeable change in response was noted when these discs were checked against control samples kept in the laboratory.

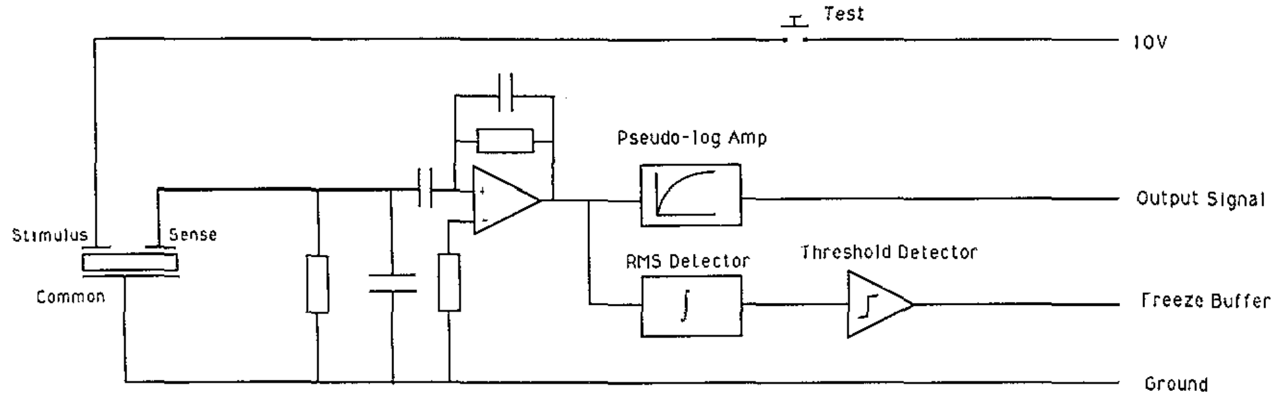

Figure 9. Schematic diagram or the sensor circuit in flight configuration.

7. Signal conditioning

In order to cope with the large dynamic range of expected signals while keeping the data volume low, the signal is amplified by a pseudo-logarithmic amplifier. The amplifier used has three linear segments in its input/output characteristic, but approximates closely a logarithmic response. The characteristic used in the development unit has the form $V_{out} = 0.7 + 2.5\log_{10}(V_{in})$ for signals in the range of interest, but the exact characteristic may be 'tuned' prior to launch to optimize the science return.

While the low-end sensitivity is dictated by the lower response of the transducer at low temperature, and the required sensitivity of the measurement system as a whole, the high-end amplification (or, in fact, attenuation) is dictated by the maximum allowable impact at room temperature.

In worst-case scenarios, such as careless treatment with a hammer during ground test, the voltage generated by the transducer could be high enough to damage the amplifier. Thus, there is a 'charge attenuator', namely a capacitance in parallel with the transducer, to absorb excess charge to protect the circuitry. This capacitance C_0 dictates the sensitivity of the transducer (see section 6).

The amplifier output is passed to an A–D converter (8 bits) for digitization and storage, and also to an integrator/filter (based on a root-mean-squared converter chip). When sufficient energy is deposited in this device over a short interval of time, a voltage threshold is reached and the 'impact' flag is raised. This impact signal is used to freeze the sampling buffer.

Figure 9 shows a schematic diagram of the sensor circuit in its 'flight' configuration.

8. Sampling strategy

For the anticipated probe terminal velocity at the surface of 5 m s^{-1}, the sampling rate of ACC-E has been chosen to be 10 kHz, giving a depth resolution (applying the Nyquist theorem) of the order of 1 mm. Thus, in addition to estimating the density and bearing strength of the surface material, it may be possible to identify any layers in the surface (such as a 'crust' over a softer material) or particle size, if the surface is not a uniform solid.

Note that after about 5 cm penetration (about 10 ms after first contact) the fore dome (outer shell) will have begun to deform significantly, and equipments and experiments on the probe will begin to transmit loads to the experiment platform, slowing the probe down. From this point on, ACC-E measurements become slightly degraded, but will still contain some useful information.

To minimize load on the SSP processor at the high sampling rate, the data is stored continuously in a FIFO (first in–first out) buffer, with impact detection implemented in hardware (see section 7).

The buffer is 512 words long, and samples and stores data continuously until 448 samples have been taken after the 'impact' flag has been raised. The first 64 samples contain readings prior to detection of impact, and will contain therefore zero-force samples, plus the onset of impact (before the flag was raised.) The buffer length corresponds to about 25 cm penetration, which is about the maximum expected.

After impact, a 'quick-look' data set is transmitted, comprising the peak value of the impact profile, the time to reach the peak, and the time of the rising and falling half-peak values. If transmission should fail suddenly soon after impact, this data set will allow at least an estimation of the surface type. Subsequently the full 512 words are transmitted to allow detailed examination of the force profile.

9. In-flight testing

It was required that all probe sensors be capable, to the maximum extent possible, of being tested during the long (7 year) interplanetary cruise to Titan. Direct mechanical stimulation of the ACC-E sensor is clearly impracticable, but by including an additional electrode on the PZT washer, a stimulation signal can be injected into the sensor right at the start of the measurement chain. This test signal (nominally a short pulse) is coupled to the sense electrode of the sensor by its piezoelectric response and by the capacitance between these two electrodes.

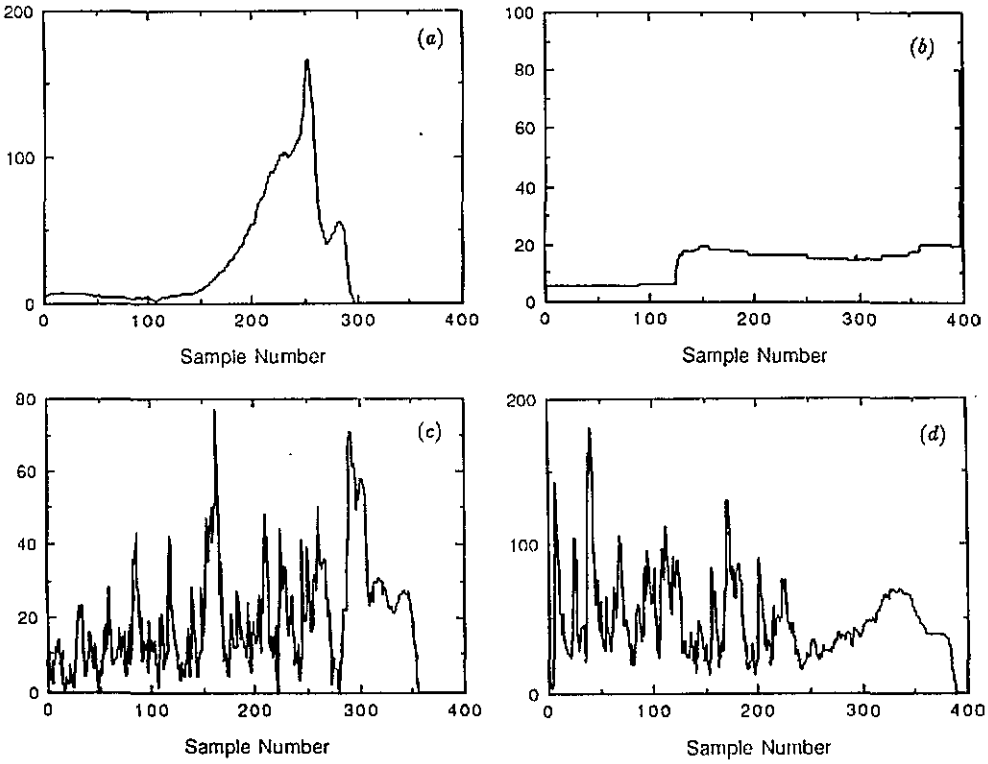

Figure 10. Sensor output (after pseudo-log amplification; units are arbitrary) for transducer drops at 5 m s^{-1} into various materials. Samples are at 10 kHz, so sample number 200 corresponds to 20 m s, or 10 cm depth. Materials are (*a*) sand, (*b*) clay, (*c*) fine gravel (particle size about 8 mm) and (*d*) medium grade gravel (particle size about 15 mm).

This allows the gain of the amplifier and the health of the transducer to be verified after the rigours of launch. For example, a cracked (but still functional) transducer would be indicated by a drop in its response.

10. Laboratory and field testing

The ACC-E subsystem on the probe has its data read by the SSP computer, formatted into telemetry packets with other SSP data, and sent to the probe on-board data handling system, which in turn puts these data, with those from other experiments, into telemetry frames and broadcasts these via a dual-redundant S-band uplink to the orbiter spacecraft, which eventually re-broadcasts the data to Earth for analysis.

For laboratory testing, the amplifier output is passed to the stimulus and monitoring unit (SMU): this is a desktop PC equipped with A/D interfaces and software to permit inspection and archiving of test and calibration data.

It is clearly impracticable (desirable as it might be) to drop an entire 200 kg probe model with the sensor attached to obtain test data in a variety of materials. However, it was realized that, as long as the transducer velocity did not vary appreciably during the impact event, the force on the transducer would be representative of that encountered during probe impact at the same speed. Thus the transducer was attached, by means of a screw fitting attached to its support, to a set of steel discs, forming a mass of 3–8 kg, giving it enough inertia to maintain its velocity for the about 20 ms impact event. A guard structure was also attached to prevent the transducer burying itself too deeply.

A portable data-acquisition system was set up to enable field tests to be performed; it is easier to take a small sensor to locations of interest, rather than bringing large amounts of heavy samples into the laboratory. A Zenith notebook PC was procured, together with a Pico Electronics ADC-10 analogue-to-digital converter (able to sample at up to 13 kHz with 8 bit resolution). The amplifier circuit was powered by two 9 V batteries. The entire electronic equipment fits in a small briefcase and weighs only about 3 kg.

11. Results and data analysis strategy

In order to investigate what may be learned from the impact signature, the penetrometer was dropped onto a variety of terrestrial surface materials. The penetrometer was held vertical during impact by dropping it down a perforated drainpipe, which had only a small clearance. The speed of impact was controlled by dropping the penetrometer from a predetermined height: for 5 m s^{-1} impact velocity and terrestrial gravity, the drop height is about 135 cm. To compensate for drag and air resistance caused by dropping in the tube, the actual height used to achieve 5 m s^{-1} was about 190 cm, the speed being verified using standard laboratory 'ticker

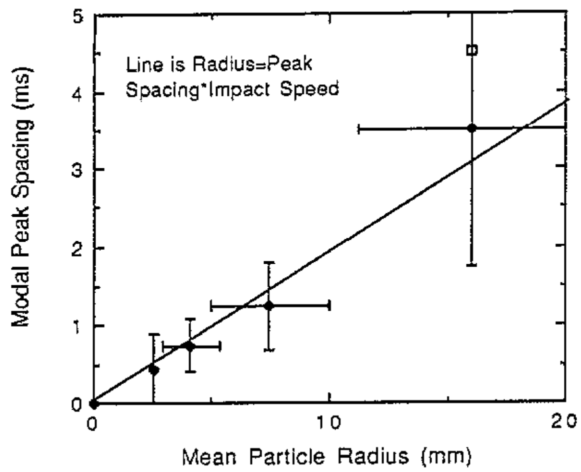

Figure 11. Correlation of peak spacing with particle size. A moving average is subtracted from the impact signature, and the spacings between positive-going crossings of the 3σ levels are placed into bins 0.5 m s wide. The location of the most popular (modal) bin is plotted again particle size.

tape'. The impact signatures were found to be only modestly sensitive to variations of order 10–20° impact attitude or 20% in impact velocity.

The sample results are shown in figure 10. Sand ramps up approximately quadratically, while clay has a fairly constant resistance throughout the impact event. After 200 samples (corresponding to 20 m s, or about 10 cm of penetration), the plate and weights hit the surface, and the data become corrupted; the characteristic 'bound' due to plate impact is clearly seen in the sand data, and to a lesser extent in the other figures.

While sand and clay have fairly smooth profiles, impacts on granular materials are very spikey. There appears to be a correlation between the height of the spikes for impacts onto gravel material, and the size of the gravel lumps (compare with the results of acoustic penetrometers, where the magnitude of the acoustic noise correlates with particle size [13]). Additionally, there is a correlation between the spacing of peaks and particle size (see figure 11). Since peak height is probably correlated somehow with the mass of the lumps, it may perhaps be possible to constrain both particle size and the density of the particle material.

It is clear that much can be learned from the impact signature. Additional experiments will investigate these potential results and will examine more rigourously the instrument's sensitivity to impact angle and velocity.

12. Conclusions

An impact penetrometer using a piezoelectric transducer has been developed for the ESA Huygens probe to Titan. This instrument, complying with rigourous spacecraft standards, will operate at about 94 K after a 7 year cruise in space. It will provide data on the surface material at the Huygens landing site, thereby constraining the nature and origin of that material. Penetrometers of this type may find application on other space missions, such as the forthcoming Rosetta mission to deposit a small lander on a comet.

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References

[1] Lebreton J-P and Matson D L 1992 An overview of the Cassini mission *Nuovo Cimento* **15** 1137–47
[2] Kohlhase C 1993 Meeting with a majestic giant: the Cassini mission to Saturn *Planetary Rep.* **13** 5–10
[3] Lunine J I 1993 Does Titan have an ocean? A review of the current understanding of Titan's surface *Rev. Geophys.* **81** 131–49
[4] Lorenz R D 1993 The surface of Titan in the context of the ESA Huygens probe *ESA J.* **17** 275–92
[5] Zarnecki J C *et al* (23 co-authors) 1992 A surface science package for the Huygens Titan probe *Proc. Symp. on Titan Toulouse September 1991* (ESA) pp 407–9
[6] Zarnecki J C 1992 Surface science package for the Huygens Titan probe *J. Br. Interplanetary Soc.* **45** 365–70
[7] Lorenz R 1992 Huygens probe – The surface mission *Proc. Conf. on Titan, Toulouse, September 1991* (ESA) pp 359–64
[8] Mitchell J K 1987 New developments in penetration tests *Int. Symp. on Penetration Testing, Balkema, Rotterdam, 1987* ed J De Ruiter pp 245–61
[9] Perle R and Martinelli M 1975 *Avalanche Handbook* (USA Agriculture and Forestry Service)
[10] Nikalchtar B 1987 Classification of ocean bottom sediments by dynamic penetrators *MSc Thesis* Louisiana State University
[11] De Ruiter J 1971 Electric penetrometer for site investigations *J. Soil Mech. Foundations Div. Am. Soc. Civil Eng.* **97** 457–72
[12] Olsen H J 1990 Construction of an electronic penetrometer for use in the field *Computers Electron. Agriculture* **5** May 65–75
[13] Tringale P T and Mitchell J K 1982 An acoustic penetrometer for site investigations *Proc. 2nd European Symp. on Penetration Testing, Amsterdam, May 1982* pp 909–14
[14] Mitchell J K, Bromwell L G, Carrier III W D, Costes N C, Houston W N and Scott R F 1971 Soil mechanics

experiment *NASA SP-289 'Apollo 15 Preliminary Science Report'* (NASA)
[15] Marten V R and Hansen V 1976 *An Inexpensive Aerial Penetrometer* AFWL-TR-74-56 (Albuquerque: Sandia Labs)
[16]. Young C W and Keck L 1971 *An air-dropped Sea-Ice Penetrometer* SC-DR-71 0729 (AD-731 991) (Albuquerque: Sandia Labs)
[17] Cherkasov I I, Gromov V V, Zobachev N M, Musatov A A, Mikheyev V V, Petrukhin V P and Shvarev V V 1968 Groundmeter/penetrometer used on the automatic lunar station 'Luna-13' *Nauka* **179** 829–31 (translation NASA CR-94587)
[18] Kemurdzan A L *et al* 1983 Preliminary results of the determination of physico-mechanical properties of the Venusian ground by Soviet automatic stations Venera-13 and Venera-14 *Kosmicheskii Issledovania* **21** 323–30 (in Russian)
[19] McCarty J L and Carden H D 1962 *Impact Characteristics of Various Materials Obtained by an Acceleration-Time-History Technique Applicable to Evaluating Remote Targets*
[20] McCarty J L, Beswick A G and Brooks G W 1964 *Application of Penetrometers to the Study of Physical Properties of Lunar and Planetary Surfaces* NASA TN-D-2413
[21] Lorenz R 1994 Huygens probe impact dynamics *ESA J.* at press
[22] Van Randeraat J and Setterington R E 1974 *Piezoelectric Ceramics* (London: Mullard)
[23] Vernitron Ltd 1991 *Piezoelectric Ceramics* (Southampton: Morgan Matroc, Vernitron Division)