The Huygens Surface Science Package

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The Surface Science Package (SSP) consists of nine independent subsystems with the primary aim of characterising Titan's surface at the end of Huygens' descent through Titan's atmosphere in late 2004. In addition, many useful atmospheric measurements will be made during the descent phase. Seven of the subsystems are mounted inside or on the lower rim of a cavity in the Probe's foredome, and are thus exposed to Titan's atmosphere and surface material. Of these subsystems, the penetrometer is mounted in front of the Probe in order for it to be the first point of contact with the surface, and the acoustic sounder is mounted pointing vertically downwards to view Titan's surface. Two subsystems, which do not require exposure to the atmosphere or surface, are mounted on the electronics box on the experiment platform upper surface. The system is controlled and its data processed by a microprocessor-based system that allows the varied data types to be transmitted in packet format on the Probe's dual-redundant interface and transmitters. The instrument weighs 4.2 kg and consumes approximately 10 W of power during descent.

1. Scientific Objectives

The Surface Science Package (SSP) consists of a suite of instruments to conduct in situ measurements of Titan's surface after Huygens' impact. In particular, the package will:

- determine the physical nature and condition of Titan's surface at the landing site
- determine the abundances of the major ocean constituents, placing bounds on atmospheric and ocean evolution
- measure the thermal, optical, acoustic and electrical properties and density of any ocean, providing data to validate physical and chemical models
- determine wave properties and ocean/atmosphere interactions
- provide ground truth for interpretating the large-scale Orbiter Radar Mapper and other experimental data.

The SSP will also conduct measurements in Titan's atmosphere on a best-effort basis. The thermal properties, acoustic velocity and electrical permittivity subsystems may provide useful science measurements of various atmospheric properties.

The performance of the SSP on Titan's surface is biased towards a liquid landing but will provide useful data for the full range of possible surface states. Each sensor can determine its own designated property to high accuracy, resulting in a physical description of any surface liquid. The thermal conductivity, density, speed of sound, refractive index and electrical permittivity are all basic physical properties that can help to constrain the surface composition. Beyond the combined scientific return, each measurement will yield a simple property of the surface of another world. The accuracy of the various sensors and their ability to determine the composition of a Titan ocean is discussed in detail in Section 4.

It is the accelerometers and penetrometer that will return the most interesting data on impact with a solid surface. Analysis of the penetrometer output will yield a measure of the granularity of the surface regolith or, in the case of a cohesive surface, the resistance to penetration. If the surface is slushy or fluffy, the accelerometer (which has a lower sample rate than the penetrometer) can furnish an idea of the surface cohesivity through the deceleration profile. The tilt sensors will also return the Probe's final attitude.

For both the liquid and solid surface scenarios, the acoustic sounder will provide an idea of surface topography on a scale intermediate to that provided by analysis of the Probe's radar altimeter data or from Orbiter remote sensing.

Huygens' survival, and by implication that of the SSP, cannot be guaranteed because of the surface's unknown nature, but it is a design aim. Experience from other missions and analysis of Huygens impact dynamics (Lorenz, 1994b) and the Probe drop test (Jäkel et al., 1996) suggest that survival is very likely for most surface types.

2. System Design

2.1 General

The SSP addresses these science objectives through a suite of nine measurement subsystems selected to provide at least a partial characterisation of either a solid or liquid surface. Seven require intimate contact with the surface and are housed in a 100 × 100 mm square cross-section cavity, known as the Top Hat, cut out of the Probe's foredome and extending to the main experiment platform (Fig. 1). Venting of this Top Hat is achieved through a 5.5 mm inner diameter tube from the Top Hat to the Probe's top surface. The Top Hat sensors are summarised in Table 1, and those mounted on the electronics box in Table 2. The resources allocated to SSP are summarised in Table 3.

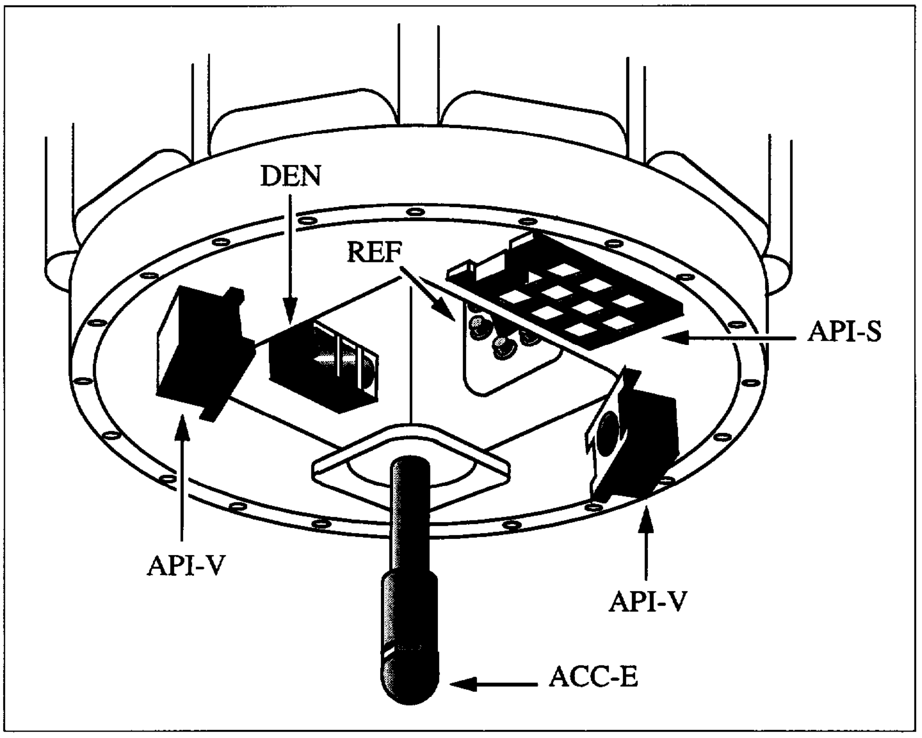

Fig. 1. Surface Science Package layout.

Table 1. Top Hat measurement subsystems.

Subsystem	*Acronym*	*Description*
External Accelerometer	ACC-E	Piezoelectric force transducer to characterise impact
Acoustic Properties — Velocity of Sound	API-V	Piezoelectric transducers for the determination of the velocity of sound in Titan's atmosphere and any liquid surface
Acoustic Properties — Sounder	API-S	Sonar-type sounder. Atmospheric and surface sounding, depth of any surface liquid
Density	DEN	Archimedes flotation sensor to determine density of a liquid surface
Permittivity	PER	Parallel plate sensor to determine electrical permittivity of atmosphere and any liquid surface, resistance measurement to check for polarised particles in liquid surface
Refractometer	REF	Linear critical angle refractometer to determine the refractive index of a liquid surface or any condensates during descent
Thermal Properties	THP	Transient hot-wire sensor to determine the temperature and thermal conductivity of Titan's atmosphere and surface

Table 2. Electronics box measurement subsystems.

Subsystem	*Acronym*	*Description*
Internal Accelerometer	ACC-I	Commercial piezoelectric transducer (single axis)
Tilt	TIL	Commercial electrolytic tilt sensor (two axis)

Table 3. SSP allocated experiment resources.

Mass	4.2 kg
Power	10 W
Data Rate	63 bit/s during Mode 1 189 bit/s during Modes 2-3 696 bit/s during Modes 4-6

2.2 Mechanical structure

The SSP Top Hat structure consists mainly of components manufactured from advanced composite material — a glass-reinforced epoxy resin, selected for its thermal conductivity characteristics. The structure consists of a box-like section (Top Hat) open at both ends, a support cone to attach the structure to the Probe, and a metallic funnel to attach the main structure to the vent tube. All these components are adhesively bonded (and mechanically fastened). The structure's design allows the ingress of Titan's atmosphere and ocean into the Top Hat.

The sensors are attached to the Top Hat using threaded inserts adhesively bonded to the structure. The sensors are electrically connected to the electronics box through a copper flying lead harness. The whole of the structure is surrounded by Basotect thermal insulation foam through which the harness is routed. The foam is formed into machined blocks that fit together like a three-dimensional jigsaw puzzle around the harness. New methods were developed to machine the foam into blocks. The foam is surrounded by a fine Kapton mesh to prevent the shedding of particles during vibration, and this is covered with aluminised mylar to provide a suitable thermal interface.

A seal is effected at the interface between the Top Hat and the Probe's foredome. Below this interface is the SSP Electromagnetic Compatibility (EMC) screen. This is a lightweight metallic mesh providing a continuation of the Probe's Faraday cage and EMC protection for the instrument, while allowing access to the Titan's environment.

The support cone provides the main interface to the Probe's lower experiment platform. The cone is perforated for mass reduction and also to provide a low conductance thermal path. There is a simple mechanical interface between the vent tube exhaust and the Probe's top platform.

The electronics box (SSPE) is of conventional design and provides the accommodation for most of the SSP electronics. The seven printed circuit boards (PCBs) are supported in card guides with a motherboard backplane. The box is finished in Chemglaze Z306 black thermal control paint. The TIL sensor is on top of SSPE and the ACC-I sensor is on an extension to one of the mounting feet.

2.3 Electronics

The SSPE is a 7-board electronics box. The PCBs are allocated as: power supply, Probe interface, processor, redundant Probe interface, acoustic sensors electronics, high resolution measurement electronics and low resolution measurement electronics. The box size is kept to a minimum, given the fixed processor board size, by direct connection of the sensor and Command and Data Management System (CDMS) harness to PCB-mounted D connectors at the front of the box. Each board can be individually removed from the box.

The processor (a Matra Marconi Low Power Processor) interfaces to the front-end electronics by a redundant data routing bus. This is configured to provide maximum reliability, together with the provision of redundant elements on the front-end boards where possible. The component count is reduced as much as possible by the use of the processor to provide clocking for the sensor electronics. The SSP realtime clock counter (resolution 1 ms) is synchronised to the Probe's broadcast pulse. The processor detects the impact time and signature, and switches data collection modes appropriately. It provides data storage and compression for several sensors, particularly for the impact event. The mode selection algorithm will also use the broadcast data (time and altitude) during the descent phase.

The electrical design also takes into account the need to provide calibration and/or test stimuli to simplify ground testing and in-flight checkout. Modular DC-DC converters are used to provide redundant 12 V and 5 V supplies from the Probe's +28 V power supply. Filter units are included to reduce electromagnetic emissions and susceptibility. The SSP electrical system is shown in Fig. 2.

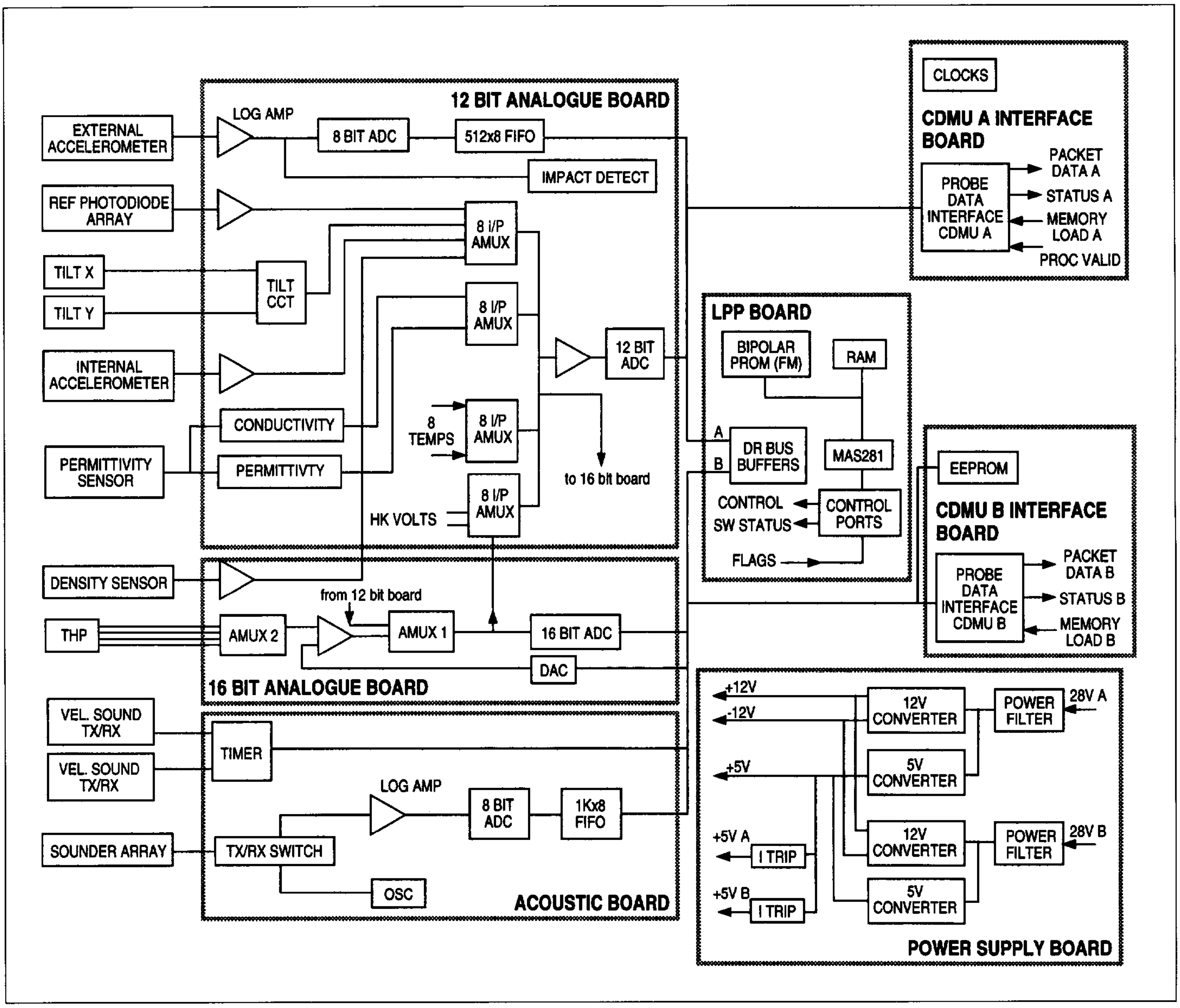

Fig. 2. SSP electrical system.

2.4 Thermal design

Mathematical thermal models have been developed to predict temperatures and heat fluxes during the cruise and descent mission phases. During cruise, the thermal boundary conditions are assumed to remain constant (stationary) in time. However, during descent, the experiment's thermal environment changes significantly as the Probe moves from the Orbiter's controlled environment to Titan's atmosphere. That cold atmosphere gives rise to unusual problems in the thermal design and analysis of the descent phase. The descent's most significant thermal constraints are the mean and maximum heat loss rate from the experiment to Titan's atmosphere, which must be minimised. To achieve this, the Top Hat and vent tube are surrounded by Basotect foam, the thickness optimised to minimise the heat leak. As the Top Hat's profile is square and the foam's outer profile is circular, a geometric shape factor for heat transfer through the foam was calculated using a 3D finite element model. A wiring harness is routed through the foam connecting the Top Hat sensors to the SSPE electronics box. As the sensors experience cryogenic temperatures of ~ 80K and the electronics box remains at about 290K, the heat leak down the harness must be carefully controlled. To facilitate this, the harness cables were originally proposed to be manufactured from cupro-nickel (60% Cu/40% Ni) and copper. However, due to financial constraints and technical difficulties involved with the use of cupro-nickel (constantan), an all-copper harness (with the cross-sectional area of the harness wires minimised) was adopted for the flight model. The effective thermal length of the harness mass is determined from finite element models of the harness embedded in the foam.

Although there are seals to minimise the rate that cold atmospheric gas enters the warm experiment interior, it must be assumed that cold gas comes into contact with the foam's warm surface, and hence conductive heat transfer from the experiment interior to Titan's atmosphere will occur. This conductive link is large and increases during the descent.

The foam surrounding the Top Hat cannot be installed in one piece. Instead, many blocks of foam are glued together around the Top Hat structure. The presence of cracks and voids in the foam will enhance the heat leak from the Top Hat to the atmosphere by convection. Detailed modelling of this problem suggests that the heat transfer through the foam is increased by approximately 40%.

3. Measurement Subsystems

3.1 ACC-E

A penetrometer, based on a piezoelectric force transducer, is used to measure the small-scale mechanical properties of Titan's surface. The sensor, described more fully in Lorenz et al. (1994), carries the historical designation 'ACC-E' (Accelerometer-External) since it was originally envisaged (Zarnecki, 1992) to be based on an accelerometer. However, measurement of force directly eliminates most of the effect of the structural response of the Top Hat and Probe, which would compromise the use of an accelerometer for this measurement.

The sensor measures the force exerted by the surface material on a small (14 mm diameter) titanium alloy hemisphere attached ahead of the SSP Top Hat by a short (5 cm) pylon. Forces in the range 5-2000 N are recorded at a sampling rate of 10 kHz, giving a depth resolution of 1 mm at the nominal (~5 m/s) impact speed. The force is measured by a disc of piezoelectric ceramic PZT-5A, which generates a charge proportional to the applied force. PZT-5A was chosen for its good temperature and ageing stability.

The charge generated by the transducer is dumped into a capacitor (to reduce the voltages present in the circuit, which could otherwise be high) and the voltage across the capacitor amplified by a pseudo-logarithmic amplifier (to reduce the data volume requirement). The digitised (8 bits) output is stored in a circular First In First Out (FIFO) buffer of 512 samples (corresponding to ~50 ms, or 25 cm depth) which is frozen 6.4 ms after a preset voltage threshold is exceeded.

As the charge generated by the transducer in response to a constant force leaks away, it is difficult to calibrate the transducer simply by applying static loads (e.g. by attaching weights). A known, but varying, force must be applied. This is achieved with a small pendulum, which impacts a block of material (synthetic rubber, or for larger forces, PTFE) on to the transducer at a known speed, corresponding to the drop height of the pendulum. This calibration method produces a force pulse with a width typically of a few milliseconds; matching the observed voltage pulse with computer-generated simulations allows the uncertainty in the Young's Modulus of the impacting material to be reduced, and allows the sensor to be calibrated to an accuracy of ~5% (Lorenz, 1994a). For flight calibration, a pendulum incorporating a reference force transducer has been developed, which should further improve the calibration accuracy.

Investigations have indicated that the transducer's sensitivity drops (principally due to change in the dielectric constant of the PZT material) by a factor of ~1.8 at liquid nitrogen temperatures (77K, close to the operating temperature at Titan's surface of ~94K) compared with room temperature operation.

Interpretation of the force profiles for the impact with Titan is based on comparison with impacts on to representative planetary surface materials in the laboratory. The sensor was attached to a set of weights and dropped from a height of ~1.3 m (giving impact speed at 1 *g* of ~5 m/s; the measurement is relatively insensitive to small changes in impact angle or speed) into a receptacle of material (typically sand, gravel or clay), and the signal recorded. The mass of weights used (typically ~5 kg) was not important — it matters only that the transducer/weight ensemble has sufficient inertia not to be slowed appreciably during the first ~5 cm of penetration.

Some sample force profiles are shown in Fig. 3. Sand exhibits an increase in mechanical resistance with depth, while clay has an approximately constant resistance. Granular materials (gravel with mean particle diameter of ~8 mm and ~15 mm are shown) give spikey signatures, with both the amplitude and spacing of the spikes correlating with particle size. If the particle size of the surface material is fairly uniform (as for fluvially-sorted sediments, for example), then it may be possible using both peak spacing and amplitude information to discriminate between low density (e.g. ice) and high density (rock) particle materials (Lorenz, 1994a).

3.2 ACC-I

The ACC-I (Accelerometer-Internal) subsystem comprises an Endevco 2271AM20 piezoelectric accelerometer, mounted on the SSP electronics box. Its prime function is to record the Probe's deceleration history at impact, at a 500 Hz sampling rate, to infer the mechanical properties of the surface material.

The sensor is a simple, commercial device. Its charge output is proportional to the acceleration, and is simply measured and digitised at 12 bits resolution. Like ACC-E, therefore, it is not DC-sensitive and is unable to monitor slowly-varying accelerations (e.g. during entry). However, it is able to measure much higher g-loads than the Huygens Atmospheric Structure Instrument (HASI) accelerometers, which are optimised for higher sensitivity for atmospheric measurements and can measure accelerations only up to 20 *g*. The measurement range of ACC-I, up to 100 *g*, spans

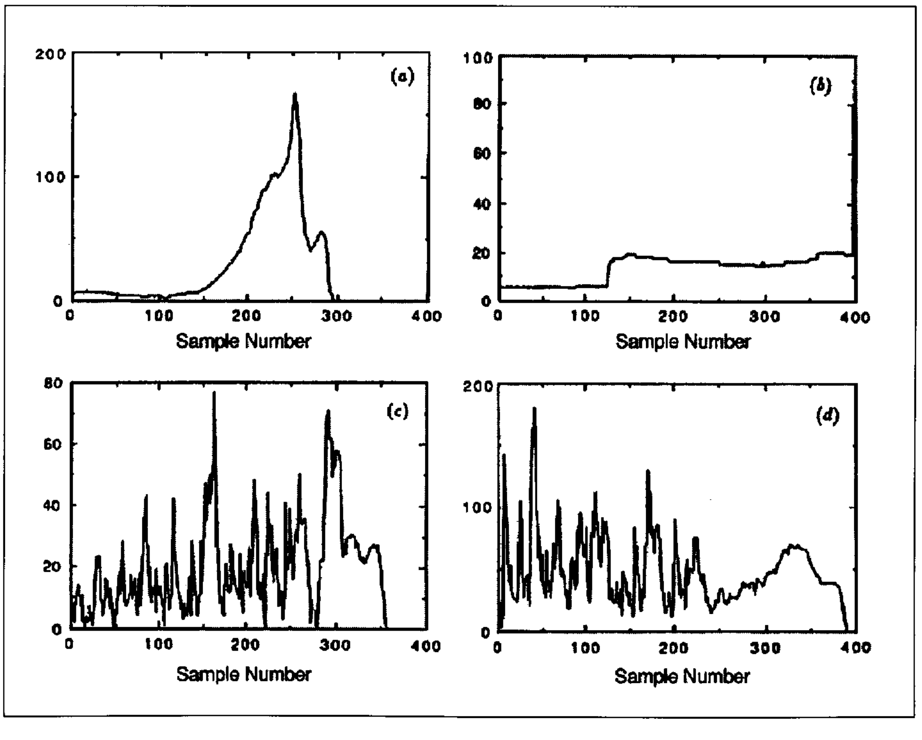

Fig. 3. Examples of experimental ACC-E profiles, with the ordinate in arbitrary units of time (the full range corresponds to about 0.5 s). The abscissa is in arbitrary units of force. Note that different units are used in profiles (a) to (d). Materials are (a) sand, (b) clay, (c) fine gravel (particle size about 8 mm) and (d) medium grade gravel (particle size about 15 mm). Adapted from Lorenz (1994a).

all impacts that are likely to be survivable. Like ACC-E, the transducer output is stored in a circular buffer, frozen when the integrated deceleration exceeds a preset threshold.

A significant complication for impact accelerometry on Huygens is that the Probe is not infinitely rigid, but itself deforms on impact. Lorenz (1994b) performed computer simulations of Probe impact with various solid surfaces, taking the Probe's finite strength into account with a many-element non-linear spring model.

For soft materials (e.g. fluffy aerosol deposits, perhaps resembling terrestrial snow), the decelerations are of the order of 10 g, and are not sensitive to the Probe's rigidity. Harder materials, such as regolith or sand, give loads of 25-30 g. The deceleration histories (and peak values) are somewhat affected by the Probe's deformation. Surface materials that are harder still will give higher decelerations, but may lead to mechanical failure of the Probe before meaningful data at high-g could be collected.

As discussed in Lorenz (1994b), the variation of mechanical strength with depth may be estimated by examination of the ~50 ms-long deceleration profile. It seems possible to discriminate cohesive (sludgy or wet/sticky) materials from non-cohesive materials. Impact into a hydrocarbon ocean would give splashdown loads peaking at about 10 g, although the rise time for the load is much faster than for a fluffy material giving a similar peak load. Thus, plotting peak load against rise time allows a quick-look identification of the surface material (Lorenz, 1994a).

3.3 API

The primary scientific objectives of the Acoustic Properties Instrument (API) subsystem are to:

- measure the speed of sound in the atmosphere as a function of altitude. From the speed of sound the mean molecular weight can be inferred
- measure the surface topography for a solid or liquid surface
- measure the depth of any surface ocean
- measure the speed of sound in the liquid surface (if relevant)
- measure the Probe's lateral speed, which will be strongly correlated with the horizontal wind speed.

The secondary objectives are to:

- measure the true Probe altitude over the descent's final 100 m
- measure the direction of the lateral velocity.

Also of interest but not yet proven to be feasible are to:

- provide information on precipitation (snow, rain or hail) and turbulence in the atmosphere below 50 km
- measure the surface acoustic impedance
- measure liquid acoustic impedance.

The API is divided into two parts. One (API-V) will measure the speed of sound in the atmosphere during the descent and in the liquid in the case of landing in an ocean or lake. The other (API-S) consists of an acoustic sounder/altimeter.

The speed of sound, c, in an ideal gas is given by

$$c = \sqrt{\frac{\gamma R T}{M}} \qquad (1)$$

where γ is the ratio of the specific heats, R is the molar gas constant, T is the temperature and M is the mean molecular mass.

The temperature can be accurately measured by other instruments and thus the molar mass can be calculated from the speed of sound measurements. Using this, for an atmosphere composed of only two major gases, their mixing ratio can be estimated to an accuracy of better than 1%. For three or four major constituent gases, limits on their mixing ratios can be set.

An atmospheric profile for the speed of sound based on the present nominal Titan atmospheric model is shown in Fig. 4.

The acoustic sounder may provide information on precipitation (snow, rain or hail) and turbulence in the atmosphere below 50 km. The acoustic energy returned by rain or hail is proportional to the drop diameter to the sixth power and to the number of drops in the pulse volume. The pulse volume is the physical volume that in a certain instant carries the acoustic energy.

The sounder will give information on surface roughness and acoustic back-scattering properties of Titan's surface during the last few hundred metres. The surface return signal is a function of the surface acoustic impedance, topography and incident angle. The topography of solid surfaces cannot easily be described analytically, so statistical models have to be used. A statistical model can be characterised by an r.m.s. surface deviation from the average level and a correlation length for these deviations. Liquid surfaces can, in some cases, be modelled by a simple wave pattern where the wave height and wave length are the characteristic parameters. Acoustic and electromagnetic wave propagation and interaction at interfaces show many similarities. This enables the use of the same equations, models and databases, after minor modifications, to be applied to both cases. The surface roughness measurements complement data from the Huygens radar in range and resolution. The API-S provides higher resolution but is active only over a limited area around the landing site (≈ 1000 m^2, assuming first contact at 100 m altitude).

If the Probe lands in an ocean, the depth (up to 1 km) will be measured. The maximum depth that API-S can sound depends on the composition of the liquid.

Titan is particularly well suited for acoustic experiments at high frequency because of the lack of water vapour and the low temperature. This keeps the atmospheric attenuation to a minimum compared to Earth's atmosphere. In addition, the higher surface pressure and low temperature increase the atmosphere's acoustic impedance, which allows the use of small, simple sensors.

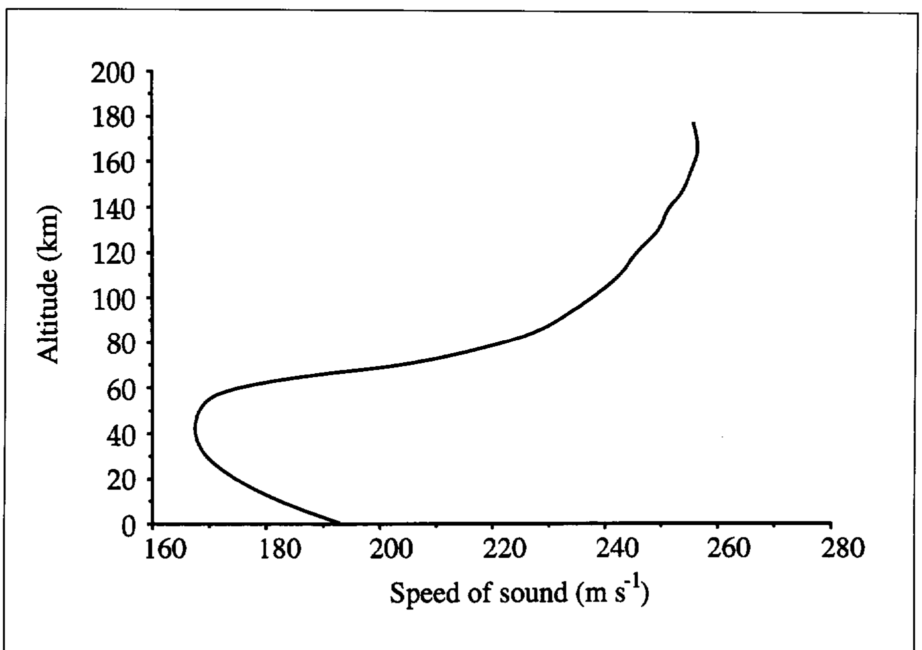

Fig. 4. Nominal profile of speed of sound in Titan's atmosphere.

The speed of sound is measured by a short ultrasonic pulse transmitted and received by two resonant piezoelectric transducers and an accurate timing circuit that can determine the delay over a fixed distance. The transducers have been electrically and mechanically tuned to optimise bandwidth and sensitivity. The pulse carrier frequency is 1 MHz and the pulse length is about 5 μs. The time delay is measured for the pulse in opposite directions to compensate for any motion of the gas with respect to the transducers, caused by the motion of Huygens through the atmosphere. The data are sampled every 1 s, resulting in a spacing of the data points of about 10 m. The API-V is operated in the same mode throughout the mission.

The sounder consists of an array of 10 resonant piezoelectric plates that form an acoustic beam with a full beamwidth of about 20°. A short 15 kHz pulse is transmitted and received by the same transducer and the return echo is sampled at 1 kHz and pre-processed onboard. The sounder operates in two modes: an atmospheric mode above 7 km, and a proximity mode below. The proximity mode is also used in the ocean but with a modified beam acquisition scheme.

In the atmospheric mode, the pulse length is 10 ms and the data from within 50 m below the Probe is integrated, binned and stored. Data are sampled once every 2 s.

In the proximity mode, the pulse length is initially 10 ms, but between 1-0 km altitude (given by descent data broadcast, DDB) is reduced to 2 ms (near-surface mode). The data points around the average surface distance are sampled at maximum resolution and data points further away from this point are binned together. The shorter pulse length gives improved resolution in distance at the expense of reduced sensitivity. This is not a problem because, at close distance, the signal is strong enough. Data are sampled every 3 s.

The API-V and API-S flight model transducers are shown in Fig. 5.

3.4 DEN

The density sensor of the SSP applies Archimedes' principle to measure the density of any Titan ocean. A small buoyant body is attached to the SSP's wall by a flexible beam. When immersed in a fluid, its upthrust bends the beam. This bending moment induces strain on the beam surfaces, which is then measured using strain-gauges. The basic principle is shown in Fig. 6. (The actual float used is cylindrical, and is seen here in cross-section).

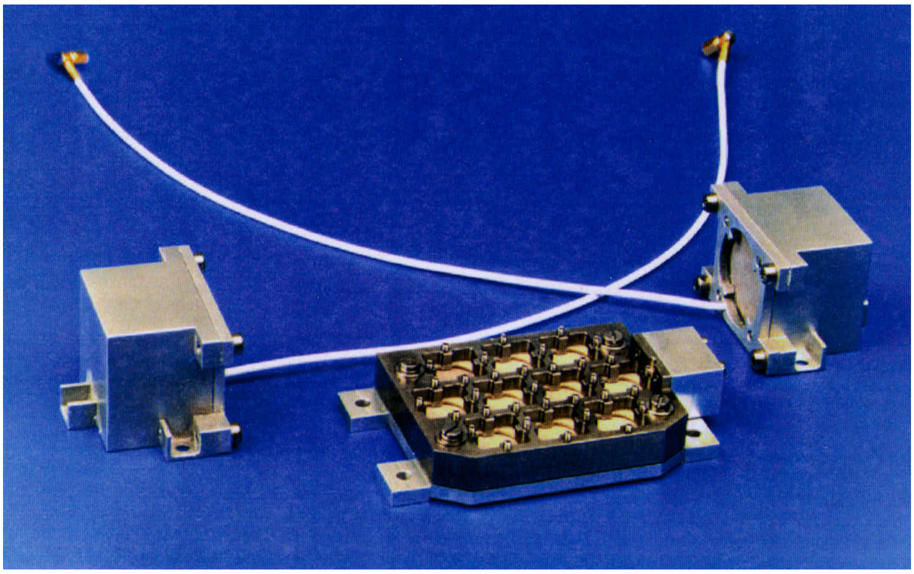

Fig. 5. API-V and API-S flight model transducers.

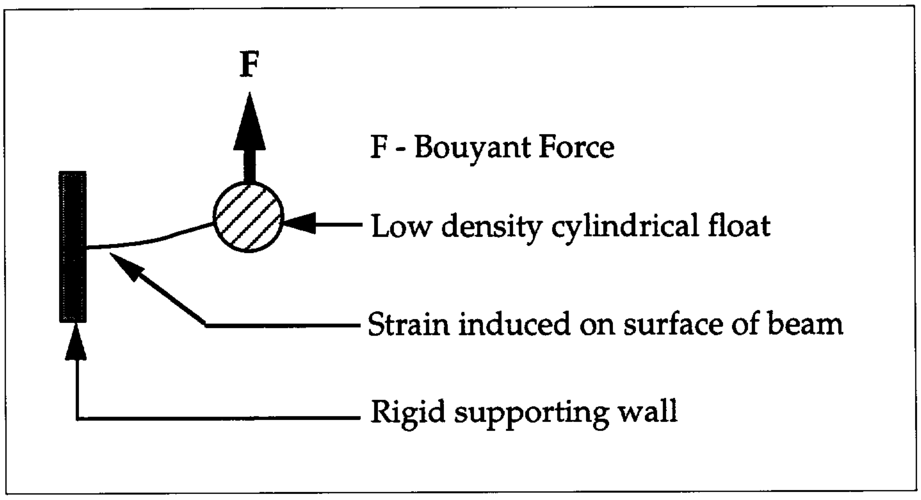

Fig. 6. The basic layout of the Density sensor.

In order to satisfy the constraints of vibration, mass and science return, the beam was cast from epoxy resin. This material allows low mass, high flexibility and high mechanical strength. Torsion effects, due to uneven fluid flow (for example) were ameliorated by splitting the beam into two parts, one at each end of the float. This also aids in reducing torsional mode oscillations. As the sensor output relies upon the effects of the buoyant force, which is proportional to the difference in density of the float and the liquid, the float is cast from a low density sealed cell foam.

Four strain gauges are bonded to the beam surfaces, two on the upper faces, and two on the lower. These are connected in a Wheatstone bridge circuit, which not only allows a greater sensitivity of measurement, but also a degree of temperature compensation. Implementation of the wiring is in the supporting plate for the beam, which is directly behind the sensor. Output from the sensor was calculated, and measured, to be linear with the density of the liquid in which the sensor is immersed. The resolution of the final instrument meets the science requirement of ± 2 kg/m^3 (at a density of 550 kg/m^3 and a measurement range exceeding the 400-700 kg/m^3 range, calculated for pure methane to pure ethane at Titan surface temperatures). This was specified to give the ethane mole fraction of binary methane to ethane mix of the proposed ocean to within 1%.

Further work (English, 1995) has shown that if nitrogen is included as a solute in liquid methane (Kouvaris & Flasar, 1991), and propane as a second major photolytic product (following Raulin, 1987), then a measure of density will still give the ethane mole fraction (English, 1995). The presence of argon (recently limited in the atmosphere to <0.1 by mixing ratio by Strobel et al., 1993) in the ocean may add a further free parameter (due to its non-detection) in any ocean density model. Fig. 7 shows how ocean density is highly argon-dependent. The abundance of atmospheric argon (as measured by the Gas Chromatograph and Mass Spectrometer, GCMS, for example) would constrain this oceanic component.

The resolution of the flight DEN at cryogenic temperatures is ± 1 kg/m^3, which allows the ethane mole fraction to be determined to better than 0.01, once the presence of argon has been quantified.

The development to flight model included a study of the effect of radiation (to 40 krads) and temperature effects on the properties of the materials used in its construction (English, 1995). It was found that radiation had no measurable effect. The temperature effects were explicitly included in DEN's design to arrive at the final density resolution. Though the sensor cannot measure the atmospheric density, it is activated from SSP switch-on to end of mission, in order to monitor temperature effects on the sensor offset voltage.

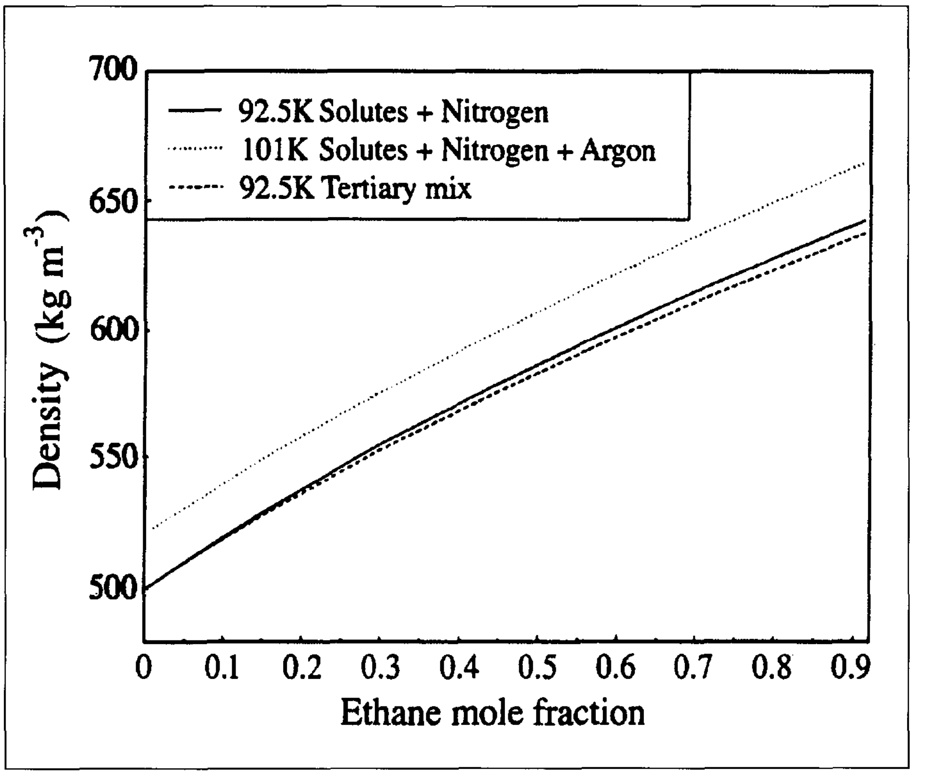

Fig. 7. Density against ethane mole fraction for several Titan ocean compositions.

3.5 PER

The prime function of the PER sensor subsystem is to measure the static permittivity of Titan's surface to an accuracy of ±0.003. This measurement corresponds to determining the mixing ratio of ethane to methane to 1%. In addition, the sensor performs a resistance measurement that will investigate the presence of polar molecules that could be present in any surface liquids (Raulin, 1987).

The Clausius-Mossotti function (see equation 2) is characterised by being almost constant over a wide range of temperature and pressure, thus the electrical permittivity measurement can yield density in moles per unit volume. This can be combined with the density (mass per unit volume, measured by the DEN subsystem) to provide an estimate of the mean molecular weight.

$$\alpha = \frac{3\epsilon_0(\epsilon_r - 1)}{\rho N_A(\epsilon_r + 2)} \qquad (2)$$

where ρ is density in moles/unit volume, α is molecular polarisability and N_A is Avogadro's number.

The refractive index of the Titan ocean, μ, (determined by the refractometer subsystem) would equal $\epsilon_r^{0.5}$ if there were no change in ϵ_r between DC and optical frequencies (assuming a magnetic permittivity of unity). In reality, a comparison of these two measurements may give an indication of the molecular and orientational polarisations of the ocean constituents.

The permittivity sensor consists of a 22-plate open capacitor with 1 mm spacing and a functional area of 550 mm^2. The range 250-275 pF is sensed to an accuracy of 0.25 pF, corresponding to an ethane to methane mixing ratio determination of 1%. In addition, the sensor has a pair of exposed planar metal plates to sense the presence of any ionic substances. The PER sensor houses a temperature sensor that gives approximately 0.5K resolution.

3.6 REF

The SSP refractometer (REF) is a linear critical-angle refractometer, as described by Geake (1969, 1970, 1975). It uses a sapphire prism with a cylindrical active face, and covers the refractive index range 1.250 to 1.450 with a discrimination of 0.001, corresponding to measuring, to better than 1%, the relative abundance of methane and ethane in the expected mixture in the liquid on Titan's surface. Two LEDs at 635 nm provide alternative modes of illumination, internal and external, the former being for general use and for in-flight testing, and the latter being useful if the liquid is found to contain scattering material. The refractometer output image shows a cut-off edge, whose position is a linear function of refractive index. The image intensity profile is sensed by a photodiode array and digitised; it is then differentiated numerically, as this is found to enhance the discrimination and may also give information about any suspended matter. The differentiated profile shows a sharp peak at the point of maximum gradient, and this is found to occur at the true position of the cut-off edge; the pixel number at which this occurs is proportional to the refractive index of the liquid, and constitutes the output signal. All the data processing and control functions are carried out by software in the Low Power Processor (LPP) of the SSP

It is intended to transmit just the peak position, giving the refractive index value, as the first quick-look output, followed by transmission of the whole differentiated profile, if survival time permits, as this may contain further information about the liquid, such as turbidity and the nature of any suspended matter. In addition to its use on Titan's surface, it is intended to switch REF on during the descent through Titan's cloud layers, in the expectation that cloud droplets and condensate collected by the prism will enable useful measurements.

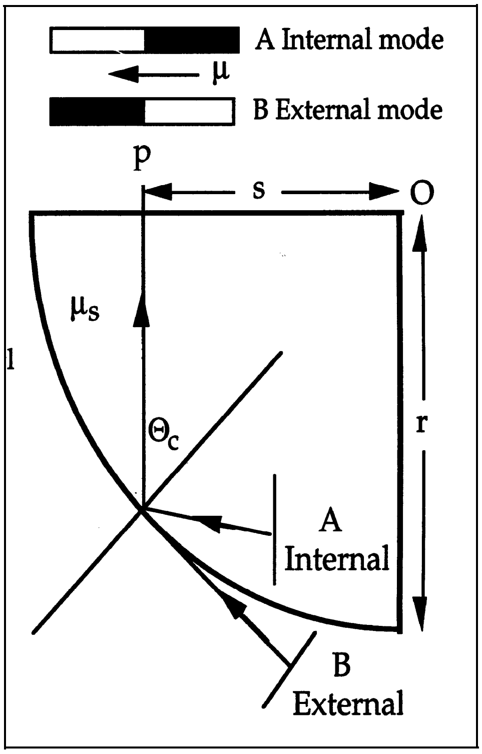

Fig. 8. REF operation principle.

The instrument is as shown in Fig. 8. Its essential feature is a prism with a cylindrical active face, and it is this that gives it its linearity and other useful properties. The prism is made of sapphire because of the high refractive index (about 1.766), durability and radiation resistance. The instrument structure is of titanium, which has a coefficient of thermal expansion very close to that of sapphire's. This is advantageous in preserving the integrity of the prism mounting, as the prism temperature is expected to fall to about 95K on Titan's surface. A thermal barrier is provided between the prism and the upper box containing the detector and head electronics, by truncating the prism to provide a gap, and by supporting it on thin-walled tubes.

The detector is a self-scanning linear photodiode array of 512 elements used in pairs. It is mounted directly on the PCB carrying the head electronics. Light is provided by two LEDs, via glass-fibre light guides, giving alternately internal or external illumination, depending on which LED is switched on. Crucial to the performance of REF is a system of baffles, used to block unwanted rays and to minimise internal scattered light.

REF was constructed at UMIST in collaboration with RAL; a brief description is given in Geake & Mill (1992). It is the space version of an instrument designed for laboratory use, which is described in Geake et al. (1994); this gives a fuller explanation of the principle and properties of this new type of linear differentiating refractometer.

In the flight model REF sensor, the detector and its pre-amplifier circuit board are mounted within the foam of the Top Hat. The flight model sensor (Fig. 9) has been tested and shown to function at cryogenic temperatures. Three diode temperature sensors, mounted at the linear photodiode array and at the top and bottom of the sapphire prism, will enable the measurements to be corrected for temperature effects.

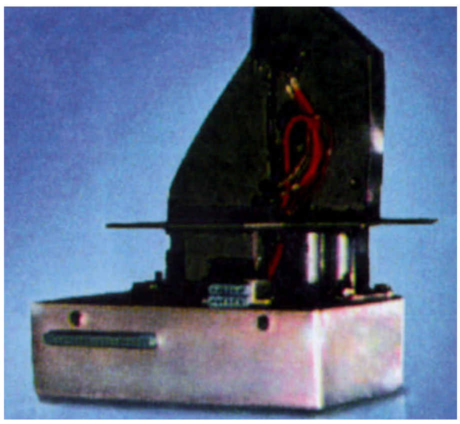

Fig. 9. Flight model of the REF sensor.

3.7 THP

The Thermal Properties subsystem (THP) will measure the temperature, thermal conductivity and perhaps thermal diffusivity of Titan's atmosphere during descent and, if possible, surface liquids after impact (Birchley et al., 1992).

The THP sensor consists of two redundant pairs of platinum wire sensors, one pair optimised for atmosphere measurements, and one for liquid measurements. These elements are configured as four wire resistance thermometers, with a high drive current available to provide power for measurements using a transient hot wire technique.

The expression for the temperature rise of a long thin wire heated with a constant power is given by (Healy et al., 1976):

$$\Delta T = \frac{q}{4\pi\lambda} \ln\left(\frac{4\kappa t}{a^2 C}\right) \tag{3}$$

where ΔT = temperature rise of wire, λ = thermal conductivity of medium, κ = thermal diffusivity of medium, q = power per unit length of wire, a = radius of wire, t = time, $C = e^g$, where g = Euler's constant. If a graph of ΔT *vs* $\ln(t)$ is plotted, then the thermal conductivity is given by:

$$\lambda = \frac{q}{4\pi A} \tag{4}$$

and thermal diffusivity is given by:

$$\kappa = \frac{a^2 C}{4} \exp\left(\frac{B}{A}\right) \tag{5}$$

where A = gradient of ΔT-*vs*-$\ln(t)$ graph, and B = intercept of ΔT-*vs*-$\ln(t)$ graph.

The platinum wire sensors are housed inside individual cylindrical cells. These perform two main functions. Firstly, they protect the wires during integration and fluid in-rush following impact. Secondly, they reduce forced convection, which can cause errors in the thermal properties results.

3.8 TIL

The tiltmeter is primarily intended to provide information on ocean wave properties on Titan. Should the landing occur on a solid surface, the Probe's repose will be returned, perhaps providing an indication of the metre-scale relief. In either case, the tiltmeter will also provide information on the Probe's motion during descent, perhaps allowing information on winds and atmospheric turbulence to be determined.

Probe motions after impact on a liquid surface can be used to determine a variety of ocean and atmospheric properties. After the impact oscillations have damped out, the Probe can be regarded as a buoy. Thus by measuring its vertical acceleration, using the low frequency accelerometer in the HASI experiment, and its deviation from the local horizontal in two axes with the tiltmeter, it will be possible to calculate the wave motions. Much of our understanding of the properties of surface gravity waves, and in particular the growth rate of wind waves, is based on empirical observations taken in laboratory tanks or from measurements taken at sea. By extending the parameter range covered by observations, it will be possible to test how general these empirical observations are. Modelling of waves under possible Titan conditions (Srokosz et al., 1992) indicates that a Titan ocean will occupy a very different parameter space from terrestrial oceans, with typical waves having much longer wavelengths and larger amplitudes for a given (plausible) wind velocity (maximum of a few m/s).

The sensor is also operated during the descent phase. Work by Lorenz (1994a) has shown that the reconstruction of wind gusts from the Doppler Wind Experiment

(DWE) data can be improved by using the TIL data and analysing the complex pendulum motion of the Probe on its parachute system. TIL data may also provide the Probe spin rate if this is greater than the maximum rate measured by the Radial Accelerometer Sensor Unit (RASU, 15 rpm).

The selected device consists of two orthogonally mounted tilt sensors, comprising small glass vials partially filled with an electrically-conductive fluid. When the sensor is at its equilibrium position, the fluid's electrical resistance from the centre electrode to each of two outside electrodes is balanced. Tilting the sensor disturbs this condition, and the resistances change in proportion to the angle of tilt. The design accuracy for the sensor subsystem is ±0.50° in both axes.

4. Analysis of SSP Ocean Composition Measurement

Accuracy for the separate sensors was specified in terms of the determination of ocean ethane content. This science requirement (see Table 4) was based on the assumption of a binary mix for the ocean, with a determination of the ethane fraction to 1%. Further work (Lorenz, 1994a), has shown that at best performance with no argon present, but with solutes (nitrogen, propane and other hydrocarbons), the ethane fraction may be determined to about ±2%. This is from the combined data of all sensors, and is shown in Fig. 10. With argon present up to 4%, the uncertainty in ethane fraction increases to ±7%.

Beyond knowledge of the surface's physical state, an approximate age for the ocean can be derived from the ocean depth (as measured by API-S), and the methane-to-ethane ratio if the liquid is a large-scale ocean and not an isolated lake (for which age

Table 4. The original SSP science requirements, with worst case estimates of operational range. Adapted from Lorenz (1994a).

Sensor	*Design Spec.*	*Worst Case Accuracy Expected*	*Justification*
PER	±0.001	±0.003	1% ethane/methane ratio specification
THP	±0.001 W/m/K	±0.005 W/m/K	1% ethane/methane ratio specification. Degraded accuracy due to turbulence effects. See Birchley et al., 1992
API-V	±5 m/s	±20 m/s	Speed of sound 2000 m/s: transducer separation (~140 mm) known to ±0.5 mm
DEN	±1 kg/m^3	5 kg/m^3	1% ethane/methane ratio specification. Susceptible to fluid motion
REF	±0.001	±0.002	1% ethane/methane ratio specification. This is also the 'as built' performance of prototype

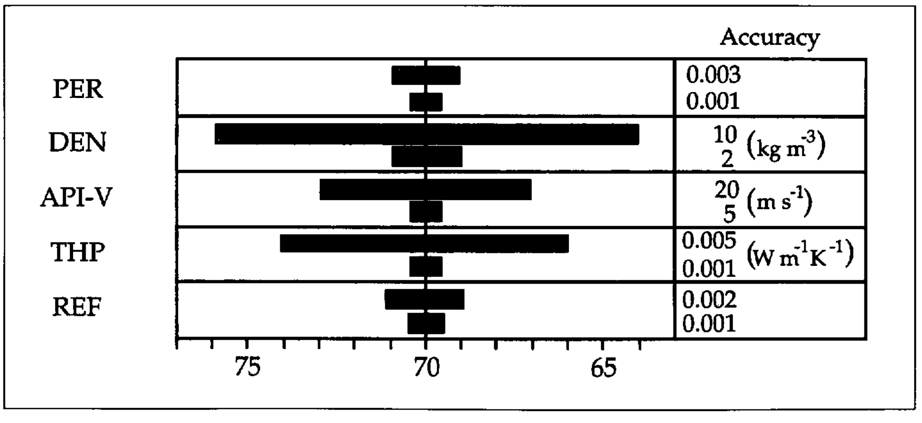

Fig. 10. Accuracy of ocean composition determination by SSP sensors when immersed in a methane-ethane ocean with a 70% ethane molar fraction. Bars indicate the range of composition that are compatible with each measurement, for the sensor's stated accuracy. Adapted from Lorenz (1994a).

determination is lost). Rearranging equation (5) from Dubouloz et al. (1989) leaves an expression for the age of the ocean (assuming constant photochemical rates for dissociation of methane and production of ethane) in terms of measured depth and methane-to-ethane ratio:

$$\Delta t = \frac{N_A h}{F_e V_k^e}\left(1+\frac{\chi_m V_k^m}{\chi_e V_k^e}\right) \tag{6}$$

where Δt is ocean age, χ is mole fraction, F is the ethane production rate, N_A is Avogadro's number, V_k is the molar volume, and h is the measured depth (subscript 'm' denotes methane, 'e' ethane).

5. Operating Modes

The SSP experiment operates in the following modes during Huygens' descent:

Mode 1 (Upper Atmosphere) Mode 1 is initiated at experiment switch-on (t_0) (nominal altitude: 153 km) and continues until t_0+10 min (nominal altitude: 12 km), i.e. the switch in overall SSP data rate from 3 packets per cycle to 8 packets per cycle. (See Section 6 for a description of the packet structure).

Mode 2 (Mid Atmosphere) Mode 2 is initiated at t_0+10 min and continues until t_0+85 min (nominal altitude: 18 km), i.e. the switch in SSP data rate from 8 packets per cycle to 11 packets per cycle.

Mode 3 (Lower Atmosphere) Mode 3 is initiated at t_0+85 min and continues until Probe altimetry data indicates that Huygens has reached a nominal altitude of 7 km.

Mode 4 (Proximity Mode) Mode 4 is instigated internally by SSP from altimetry data when the Probe reaches a nominal altitude of 7 km. The mode ends at impact detection or on a backup timeout. For the API-S subsystem, there is a sub-mode instigated from Probe altimeter data for a nominal altitude of 1000 m to 0 m.

Mode 5 (Surface Mode) Mode 5 is initiated by impact detection (t_{impact}), internally by SSP, and continues until t_{impact}+3 min.

Mode 6 (Extended Surface Mode) Mode 6 begins at t_{impact}+3 min with an internal SSP telecommand and continues until the end of the Huygens mission (loss of link with Orbiter).

Each SSP subsystem will sample data at the rate appropriate to the scientific aims, with certain subsystems not operational during some modes. The modes during which each sensor will be sampled are indicated in Fig. 11.

6. Onboard Data Handling and Telemetry

The SSP experiment has a MAS281 processor incorporated to perform data acquisition and spacecraft commanding/telemetry handling. This processor is radiation-hard due to its Silicon-On-Sapphire fabrication, and adheres to MIL-STD-1750a, which defines the processor architecture. The design of the software had to take into account the nine different sensors, each with their own data acquisition and timing requirements. To do this, a small, multi-tasking kernel was written that could process each task independently and check the timings for each sensor to ensure that they did not interfere with each other.

The data are transmitted to the main spacecraft in 126-byte packets. The maximum

	Atmospheric Modes			Surface Modes		
SENSOR	SSP Mode 1 Upper Atmosphere	SSP Mode 2 Mid Atmosphere	SSP Mode 3 Lower Atmosphere	SSP Mode 4 Proximity Mode	SSP Mode 5 Post Impact	SSP Mode 6 Extended Surface Mission
ACC-I	<----------------------Sampled at 1Hz---------------------->			Monitor ACC-I Impact Buffer	Readout ACC-I Impact Buffer	Sampled at 1Hz
ACC-E	x	x	x	Monitor ACC-E Impact Buffer	Readout ACC-E Impact Buffer	x
REF	x	Internal, external modes and dark scan every 3 minutes		Single set of scans	Internal, external modes and dark scan every 3 minutes	
THP	x	<---------------Sampling in atmospheric mode-------------->			<------Sampling in surface mode------->	
API-V	x	<--------------------------------Sampled at 1Hz (in alternate directions)-------------------------------->				
API-S	x	Sampling in atmospheric mode		Sampling in proximity mode	Sampling in surface mode	Extended surface mode
DEN	<--Sampled at 1Hz throughout-->					
TIL	<---------------------------2 axes at 1Hz sampling rate----------------------------->				<------2 axes at 2Hz sampling rate----->	
PER	<--Sampled at 1Hz throughout-->					

Fig. 11. SSP data sampling requirements (x = not sampled during this mode).

packet rate for SSP is 11 packets/cycle (16 s). The low data rate coupled with the disparate data rates of the sensors meant that a technique had to be found to transmit the sensor data efficiently. To do this, statistical multiplexing techniques developed for data communications were used. The data from a sensor are fed into a data stream associated with that sensor. When a packet can be transmitted, a packet builder polls each data stream in turn to see whether there is enough data volume in the data stream to fill a packet. If there is, data are read from the data stream and put into the packet. A word in the packet header identifies the origin of the data and the sequence count for the sensor; this enables the source of missing packets to be identified. The packet is then ready for transmission. The data for each sensor can be recovered simply by de-multiplexing the packets and reconstructing the data streams back on the ground.

Identical data for SSP are transmitted on the prime and redundant CDMU channels. A delay is introduced between the two channels by the Probe before transmission to the Orbiter.

7. Ground Segment

The EGSE for the Surface Science Package is designed to:

1. provide for full testing of the flight sensors during the pre-launch project phases
2. assist in the flight operations by providing SSP checkout and realtime telemetry data processing
3. provide data processing facilities for post-flight analysis of mission data.

The Special Check-Out Equipment (SCOE) is built around an Instrument Workstation (IWS) and a stimuli subsystem. The Instrument Workstation is a powerful PC providing commanding, communications, data processing and display facilities. The display facilities may also be available on a secondary IWS connected to the primary IWS. The stimuli subsystem itself comprises a central computer (Stimuli Monitoring Unit, SMU), plus the API-S stimulation unit. By monitoring pre-integrated sensors and generating control signals from stimulation units, the SSP electronics can be developed and fully tested. For flight operations, the stimuli subsystem becomes redundant but, due to the commonality of all SCOE computers, may be reconfigured as either a spare IWS or an extra display station.

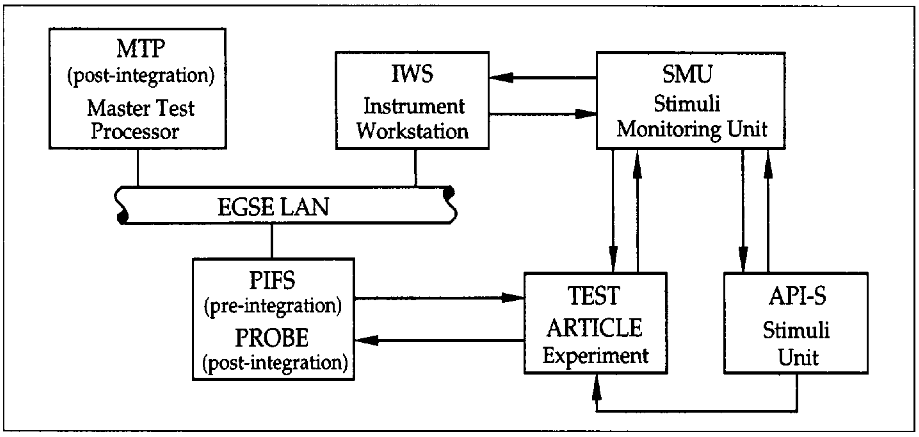

Fig. 12. SSP Electrical Ground Support Equipment (EGSE).

8. Calibration

The flight model SSP sensors were calibrated individually before Top Hat integration in a calibration facility at UKC. As a minimum, sensors were calibrated in liquid methane and liquid ethane (where relevant) over the Titan surface temperature range. Following the flight model programme, flight-representative prototype sensors (and, after launch, flight spare sensors) will be calibrated over as wide a range of ocean compositions as proves possible.

A further, more detailed description of the UKC calibration facilities and the results for particular sensors can be found in Garry & Zarnecki (1996).

9. Project Organisation

The SSP design, manufacture, test and calibration results from the collaborative efforts of several institutions. Table 5 lists the institutions and their responsibilities. In addition to those activities listed, all groups are expected to take part in the data analysis, concentrating where appropriate on data from sensors for which they have specific responsibility.

Table 5. Institutional members of the Surface Science Package consortium.

Institution	*Responsibility*
University of Kent at Canterbury, UK	Principal Investigator, project management, sensor development and calibration (ACC-E, ACC-I, DEN, THP and TIL), ground support equipment
Rutherford Appleton Laboratory, UK	Structural, thermal and electrical design and manufacture, sensor development (PER), software development, integration and test facilities
University of Manchester Institute of Science and Technology	Sensor development (REF)
ESA Space Science Department, ESTEC, The Netherlands	Sensor development (API)
Space Research Centre, Academy of Sciences, Poland	Electrical design, sensor development (THP)
Observatoire de Paris, Meudon, Paris, France	Correlation with HASI experiment, calibration facilities
Institute of Oceanographic Sciences, UK	Titan ocean modelling
University of Arizona, USA	Data analysis
Martin Marietta Astronautics Group, USA	Data analysis

Acknowledgements

The work at the University of Kent, the Rutherford Appleton Laboratory and the University of Manchester Institute of Science and Technology is supported by the UK's Particle Physics and Astronomy Research Council.

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