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Scientific objectives and implementation of the Pressure Profile Instrument (PPI/HASI) for the Huygens spacecraft

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Abstract. The Huygens entry probe will be deployed into the Titan atmosphere by the Cassini spacecraft. During the 3 h descent the Huygens Atmospheric Structure Instrument (HASI) will observe a comprehensive set of variables and phenomena, encompassing pressure, temperature, density and atmospheric electricity. The Titan atmospheric vertical pressure profile will be recorded by the Pressure Profile Instrument (PPI/HASI) provided by the Finnish Meteorological Institute (FMI).

The principal sections of the PPI are:

- sensor boom extending out of the Huygens main body,
- Kiel probe with pitot tube in the end of the sensor boom,
- pressure sensors (Barocap®) inside the Huygens body, and
- pressure hose conveying the pressure signal from the Kiel probe to the pressure sensors.

The decision to measure total pressure instead of static pressure and the design of the Kiel probe was based on aerodynamic simulations. Simulations were performed for the airflow around the Huygens probe and in the vicinity of the tip of the sensor boom.

During the descent the Huygens probe is constantly changing its attitude. Hence a pitot tube alone would not give a reliable pressure reading. By using the Kiel probe the total pressure reading is insensitive to the angle between the streamlines and the Kiel probe up to 45°.

The PPI uses pressure sensors with three different sensitivities to cover the pressure range of 0–180 kPa. The sensor technology is a heritage from a concept that has been applied in earlier space and terrestrial applications.

The PPI starts measurements at an altitude of 160 km, producing 28 bits of data per second. Measurements are designed to continue beyond the time of impact on the surface of Titan until Huygens stops operating.

The flight unit has been integrated to the Huygens entry probe and tests have been successful. A special balloon test session of PPI and other HASI instruments simulating the actual mission of Huygens was carried out successfully in 1995.

1. Mission and scientific objectives

1.1. *HASI/Pressure Profile Instrument mission*

The Cassini/Huygens is a NASA/ESA/ASI joint mission, for which NASA and ESA provide the Cassini orbiter and the Huygens probe, respectively (Scoon *et al.*, 1989). The probe is 2.7 m in diameter and weighs 343 kg. The payload weighs 48 kg and comprises six instruments (Lebreton *et al.*, 1994). The Huygens Atmospheric Structure Instrument (HASI) will observe a comprehensive set of variables and phenomena, including pressure, temperature, density, and atmospheric electricity. The Titan atmospheric pressure profile will be recorded by the Pressure Profile Instrument (PPI/HASI) provided by the Finnish Meteorological Institute (FMI).

The mission launch is nominally slated for 6 October 1997. The duration of the flight is approximately seven years, during which the payload of the Huygens probe will be in hibernation, interrupted only by six-monthly health and status checks (Hassan *et al.*, 1994).

In early November 2004 the Huygens probe will separate from the Cassini orbiter, after which the probe

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will continue unpowered on an impact trajectory for three weeks resulting in descent into Titan's atmosphere nominally on 27 November 2004 (Lebreton *et al.*, 1994).

The HASI observations are expected to begin at about 170 km above Titan's surface. The descent is estimated to take 120–150 min with some power reserved for measurements at the surface, in case the probe survives the impact. The probe's mission will be over when either the batteries are drained (maximum time of operation is 153 min) or when the Cassini orbiter descends below the horizon and the radio contact is lost.

The instrumentation on board Huygens is designed to provide a whole spectrum of new information on the clouds, the atmosphere, and the surface of Titan (Lorentz, 1994). The properties and phenomena investigated by the Cassini/Huygens mission are

- atmospheric composition,
- distribution of trace gases, atmospheric chemistry with special emphasis on organic compounds and aerosols,
- meteorology: winds, clouds and lightning, and
- ionisation state of the upper atmosphere and its interaction with the Saturnian magnetosphere.

The Huygens Atmospheric Structure Instrument (HASI) focuses on the physical structure of the atmosphere by measuring the upper atmosphere and stratosphere density, pressure and temperature, as well as the pressure and temperature in the troposphere. The HASI will also investigate the electric properties of and phenomena occurring in the atmosphere by observing the atmospheric electric conductivity and ionisation processes, wave electric fields, and atmospheric lightning, as well as measuring acoustic noise due to turbulence and thunder.

The HASI is prepared to continue operations after surface impact, if the probe survives. The HASI has the capability to determine, e.g., the nature of the surface (liquid or solid) and its dielectric properties. Some information on the surface winds, may also be inferred via surface wave motion, if the surface turns out to be liquid.

1.2. *Pressure Profile Instrument's mission and scientific objectives*

The primary scientific objective of the PPI instrument is to determine the vertical ambient pressure profile of the atmosphere of Titan during the Huygens descent. The PPI measurements start at the altitude of 170 km at the Mach number of about 0.6 and continue a few minutes beyond the impact to the Titan surface, if the Huygens probe survives the landing.

To obtain the Titan atmospheric pressure profile, a thorough amalgamation of all the HASI data has to be carried out. Moreover, data from the altimeter, the wind experiment, and the surface science package (Lebreton *et al.*, 1994) will be used. The profiles of atmospheric pressure, density, temperature, and the mean molecular weight will be obtained by solving the following descriptive equations via iterative means for each data point along the descent trajectory:

$$\begin{cases} \rho = -\dfrac{2ma_{\mathrm{s}}}{C_{\mathrm{D}}A\mathbf{V}_{\mathrm{r}}^2} \\ \dfrac{\mathrm{d}p}{\mathrm{d}z} = -\boldsymbol{g}(z)\rho(z) \\ T(z) = \dfrac{p(z)\mu}{R\rho(z)} \end{cases} \tag{1}$$

where ρ is the atmospheric density, m is the Station mass, a_{s} is the acceleration along the path of the Huygens probe, C_{D} is the drag coefficient, A is the cross-sectional area of the Station, $\mathbf{V}_{\mathrm{r}}$ is the Station speed relative to the atmosphere, p is the atmospheric pressure, $\boldsymbol{g}$ is the acceleration of gravity, z is the altitude from the surface of Titan, T is the atmospheric temperature, μ is the mean molecular weight, and R is the gas constant.

The PPI instrument yields a time series of measurements of total pressure. Thus the height and velocity of the flow relative to the probe as a function of time must be known. These can be derived from the pressure and temperature measurements (Ruffino, 1996) when combined with one of the following conditions in the following order of preference:

- The surface pressure is known, i.e. the probe and the PPI instrument survive the landing and send some data after that.
- The near-surface velocity profile is known, i.e. it is retrieved from the radar altimeter data.
- Some general assumptions about the structure and dynamics of the atmosphere of Titan are made.

The information above gives a horizontal descent trajectory measurement independent of the onboard accelerometer, and by combining these two with the Doppler wind experiment data a reliable reconstruction of the descent profile can be obtained. Applying this to the original pressure data, the main scientific objective is achieved, taking into account the various sources of error (Mäkinen, 1996).

The secondary objective is the detection of various anticipated atmospheric phenomena. The resolution is anticipated to be sufficient for detection of both the gravity waves (Friedson, 1994) in the upper part of the measuring region, as well as the discernible boundary layer effects (Allison, 1991). The PPI resolution may not, however, be sufficient for probing the region of turbulence directly (Hoppe *et al.*, 1990). The gravitational tide (Lorentz, 1991) is likely to remain undetected as well because of its minute amplitude compared to the error limits in the determination of the probe trajectory.

2. Measurement concept

2.1. *Pressure probe configuration*

A special pressure probe is needed on the tip of the sensor boom to enable accurate pressure sampling in the flow field around the Huygens probe. The first issue to study was whether a total pressure tube, or a static pressure tube should be used. An additional issue in the former case was to evaluate the importance of having a Kiel type shielding around the pressure tube to make the pressure measurement sufficiently insensitive to the changes of the angle of attack α, the angle between the Huygens probe main axis and the flow field.

The decision to measure total pressure instead of static pressure and the design of the Kiel probe was based on aerodynamic simulations that were performed for the airflow around the Huygens probe, and in the vicinity of the tip of the sensor boom. During the descent the Huygens probe changes its attitude to such an extent that a Kiel type shielding around the pressure tube was expected to be necessary. The significance of the Kiel type tube was investigated by simulations.

The results of the aerodynamic simulations proved that to preserve the high accuracy of the PPI sensors, it was necessary to use a pitot tube surrounded by a Kiel type shielding. This combination is called the pressure probe assembly (PPA), as depicted in Fig. 4.

2.2. *Evaluation of the pressure probe readings*

An object moving through an atmosphere is always surrounded by a flow-induced pressure field, where the local static pressure differs from that of the undisturbed atmosphere. A non-dimensional pressure coefficient is defined as

$$C_p = \frac{p - p_\infty}{q} = \frac{p - p_\infty}{(\gamma/2)\, p_\infty Ma^2} \tag{2}$$

where p is the local pressure, p_∞ the undisturbed static pressure, q the kinetic pressure, γ the specific heat ratio and Ma the Mach number. If at some location $C_p \approx 0$, the static pressure could be measured directly as it is done on an aeroplane for, e.g. altimetric purposes. If, however, $C_p \neq 0$ at the pressure tap location, the measured pressure p_m is contaminated by the flow and must be corrected as follows:

$$p_\infty = p_m - C_p q \tag{3}$$

Stagnation pressure corresponds to a well defined value of C_p, and can be sampled quite easily, essentially eliminating the uncertainty in C_p. At low Mach numbers ($Ma < 0.2$) the stagnation pressure coefficient $C_p = 1$ with good accuracy; at higher Mach numbers the stagnation pressure coefficient is greater than unity. Thus, lacking a location where C_p stays low enough to make the correction unnecessary, measurement of total pressure and correcting it for kinetic pressure will lead to a smaller uncertainty in the determination of atmospheric pressure.

The measured total pressure has to be converted into the desired static pressure using either the correction formula (3) or the well-known relation

$$p_\infty = p_m \left(1 + \frac{\gamma - 1}{\gamma} Ma^2\right)^{-\frac{\gamma}{\gamma - 1}} \tag{4}$$

The Mach number has to be known to make the correction possible. In the case of PPI the Mach number will be provided by the Huygens velocity profile and the speed of sound measurements performed by the Huygens Surface Science Package instrument (Lebreton, *et al.*, 1994). The Mach number correction will be appreciable in the beginning of the measurement cycle, at high altitude, when the speed of the spacecraft is still relatively high. At the low speeds in the denser lower regions of the atmosphere the correction will be negligible.

2.3. *Flow simulation around the spacecraft body*

The flow field around the spacecraft body during its descent was computed by performing flow simulations for a number of cases (Laine *et al.*, 1991) by using the FINFLO flow solver (Siikonen, 1995). The FINFLO code solves the Navier–Stokes equations numerically by using a finite-volume technique by using a structured curvilinear mesh. For an arbitrary fixed region V with a boundary $\mathbf{S}$ the flow equations can be written in the following integral form

$$\frac{d}{dt}\int_V U \, dV + \int_S \mathbf{F}(U) \cdot d\mathbf{S} = 0 \tag{5}$$

where $U = [\rho, \rho\mathbf{V}, \rho E]^T$, $\mathbf{F}$ is a flux-vector, ρ is the density, $\mathbf{V}$ is the velocity, and E is the total internal energy. In the evaluation of the inviscid fluxes, Roe's method (Roe, 1981) is employed. For spatial discretization a MUSCL-type TVD-scheme (Siikonen *et al.*, 1990) is applied to approximate advective volume-face fluxes. The discretized equations are integrated in time using an approximate factorisation with spatially varying time-step until a steady state is reached. Time-accurate calculations are made by adding a three-level time derivative approximation on the residual.

The main emphasis of the calculations was to determine the static pressure field and flow direction around the spacecraft and especially near the location where the pressure tube could be installed. The simulations were performed at Mach numbers of 0.3, 0.5 and 0.6 and at several angles of attack up to $\alpha = 10^\circ$. These Mach numbers correspond to high altitudes, where the ambient pressure is low, and hence the Reynolds number (Re) based on the spacecraft body diameter is in the range of 47,000 to 87,000. At lower altitudes Re is much higher. It can be assumed that higher Reynolds numbers will not produce appreciable changes in the flow field near the pressure tube.

The boundary layer was assumed to be fully turbulent. The grid size was $128 \times 48 \times 40$ in three-dimensional cases. At the $\alpha = 0^\circ$ case a two-dimensional simulation was performed with a grid size of 128×48. The calculated pressure coefficient distribution at $\alpha = 0^\circ$ and $Re = 47{,}000$ is given in Fig. 1. It can be seen that at the final location of the pressure tube $C_p = 0.13$. The angle between the velocity vector at the selected position of the pressure tube and the symmetry axis of the spacecraft is 19°. In the calculated results this angle varies from 14–30°.

Close examination of the computed flow field revealed no location suitable for a static pressure tap or probe. Therefore total pressure measurement was selected. Given the predicted large variations in flow direction a total pressure probe insensitive to this was desirable. A shielded Kiel type Pitot tube, which has excellent insensitivity to

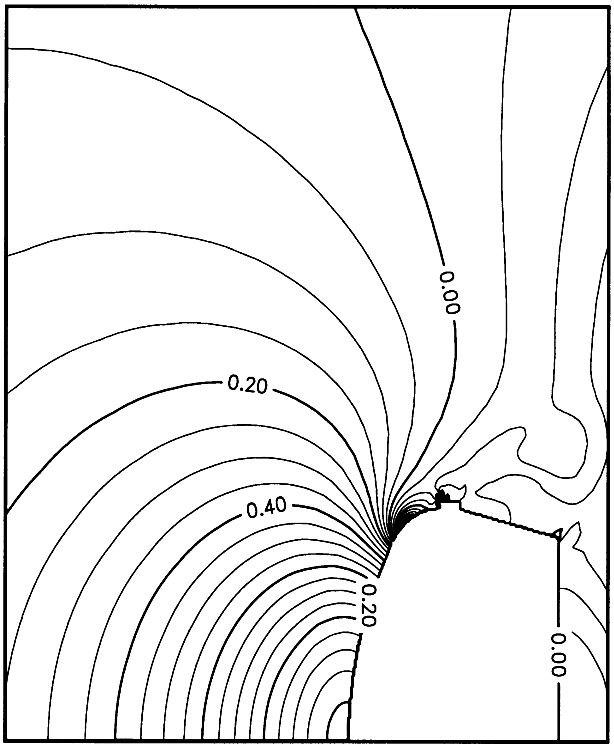

Fig. 1. The pressure coefficient distribution around the Huygens probe at $\alpha = 0°$, $Re = 47{,}000$ and $Ma = 0.3$

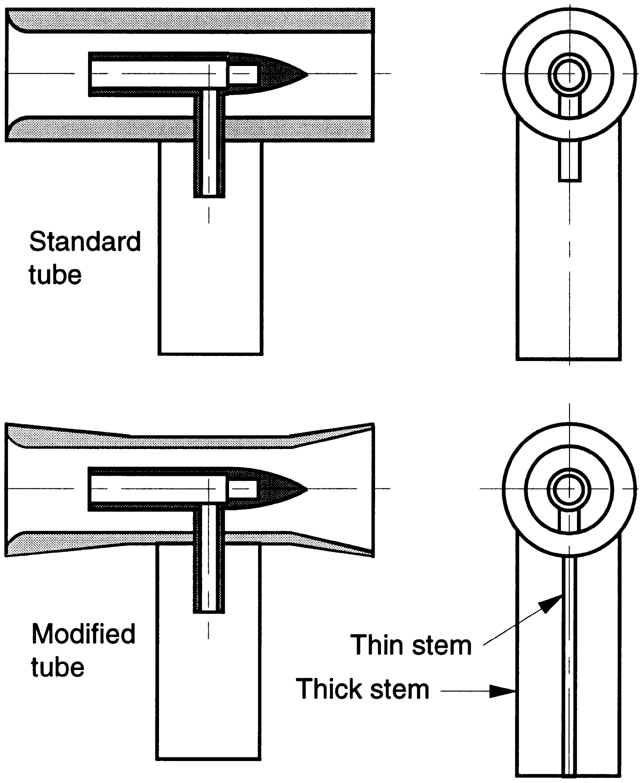

Fig. 2. Standard and modified Kiel tube geometries used in the flow simulation and in the wind tunnel tests

flow inclination (Ower and Pankhurst, 1966), was selected for closer examination.

2.4. *Flow simulation on the total pressure probe*

To save weight the Kiel probe geometry was modified compared to the standard solution as shown in Fig. 2. To verify the performance of the design flow simulations (without the stem) and wind tunnel tests were undertaken for the tube itself. In these calculations (Hoffren *et al.*, 1992) the flow was assumed to be undisturbed, i.e. the effect of the spacecraft itself on the flow was neglected. At an altitude of 160 km the Reynolds number based on the tube diameter is 910, and the flow was assumed to be laminar. The second flow case is at an altitude of 35 km where the Reynolds number is 56,000. The flow was assumed to be transitional. Simulations were made at several angles of attack up to 40°.

The FINFLO flow solver (Siikonen, 1995), being a finite volume method, requires a computational grid. These simulations were performed by making use of a grid consisting of 11,520 cells, with 128 cells in the longitudinal and 96 cells in the radial direction. The grid was extended 15–20 outer tube radii away from the tube. Free stream conditions were specified at the outer boundary. The three-dimensional cases were calculated by modelling half of the Kiel probe using 32 cells in the circumferential direction.

The axisymmetric simulations failed to converge to a steady state except for the high altitude case with the unmodified tube. Time-accurate simulations revealed cortex shedding on the outer tube, leading to high frequency

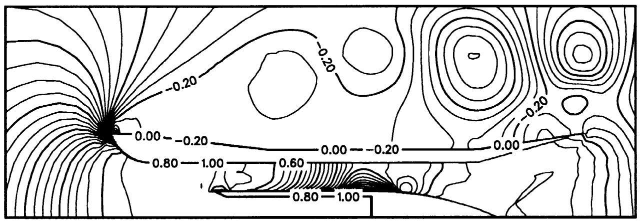

Fig. 3. An example of the simulated instantaneous pressure distribution around the Kiel probe assembly at $\alpha = 0°$, $Re = 910$ and $Ma = 0.5$

oscillations (1.16–2.1 kHz) in the inner tube. The mean pressure deviated up to 0.5% from the stagnation pressure; in most cases the deviation was much smaller. An example of the instantaneous pressure distribution is shown in Fig. 3.

The three-dimensional calculations also showed time-dependent behaviour, but because of the excessive computing time required, only steady-state calculations were made. The amplitude of the pressure oscillations becomes larger at the higher angles of attack, but the error in the total pressure inside the measuring tube remains small, in all cases less than 0.3%.

2.5. *Wind tunnel tests*

The most important aim of the wind tunnel test was to verify that sufficient insensitivity to flow direction was obtained as indicated by the flow simulations. A secondary goal was to produce validation data for the simulations. For this purpose oil flow tests and limited hot wire surveys were made.

The tests were performed in the 2 × 2 m low speed wind tunnel of the Helsinki University of Technology (Renko *et al.*, 1992). The combination of relatively high Mach numbers and very low Reynolds numbers encountered at high altitudes in the beginning of the PPI function cycle could not be reproduced in this tunnel. In this region the flow simulation must be relied on.

In order to provide adequate resolution in oil flow and survey tests upscaled (scale 4 : 1) models of the Kiel tube were used. Three different models were tested (Fig. 2):

- a standard design with thick stem (reference model),
- the low-mass design with thick stem, and
- the low-mass design with a thin streamlined stem.

The thick stem design was of interest because, at first, placement of the pressure sensors and their electronics into the stem was considered. Eventually it was decided to place these items in the more controlled environment inside the spacecraft body.

All models were tested at tunnel speeds varying from 10–25 m/s and varying angles of attack. The pressure from the model was directly compared, by means of a sensitive micro manometer, to the total pressure acquired from a total pressure (pitot) tube carefully aligned with the tunnel flow. In the tests the reference model performed as expected. The low mass models were tested up to $\alpha = 65°$. The performance was flawless up to over $\alpha = 50°$ with a C_p of 0.995 at an angle of 55°. Above this angle the pressure coefficient decreased rapidly.

Accordingly, a viable solution for the Kiel type pitot tube was designed, and the design was verified by wind tunnel tests.

3. PPI instrument structure

3.1. *The main sections*

The principal sections of the PPI are (Fig. 4):

- sensor boom extending out of the Huygens main body,
- Kiel probe with pitot tube in the end of the sensor boom,
- pressure sensors (Barocap®) and electronics inside the Huygens body, and
- pressure tube conveying the pressure signal from the Kiel probe to the pressure sensors.

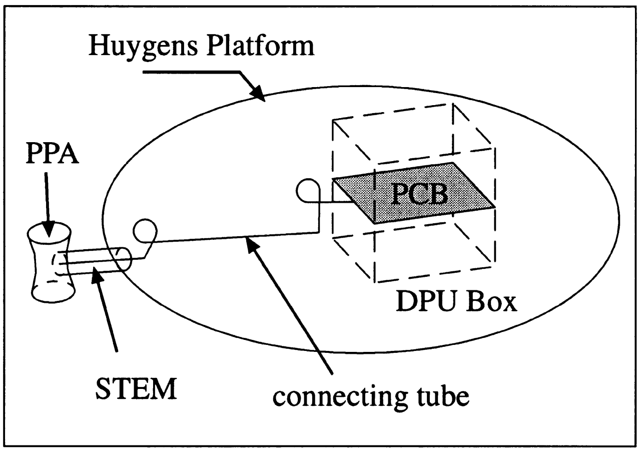

Fig. 4. Sketch of the Huygens Platform, showing the PPI Printed Circuit Board (PCB) in the HASI DPU Box, the connecting tube, the Stem, and Pressure Probe Assembly (PPA)

The Kiel type pitot tube is mounted in the Pressure Probe Assembly (PPA) in the end of the sensor boom (Stem) together with the temperature sensors. The pressure signal goes via the pressure hose to the capacitive pressure sensors (Barocap®) inside the Huygens body. The pressure sensors are mounted on the PPI electronics board, which is located inside the central electronics box of HASI Data Processing Unit (DPU). This is illustrated by the PPI block diagram in Fig. 5.

3.2. *Mechanical configuration*

Physically, PPI consists of three parts: (a) the Pressure Probe Assembly, located on the end of the Stem outside the Huygens probe body, (b) the PPI card inside the HASI DPU Box (PCB), and (c) a stainless steel tube connecting the two. Figure 4 is a sketch showing the relative location of the parts. The Stem and PPA are outside the Huygens Probe.

The PPI card contains the pressure and temperature sensors, a plenum chamber, the sensor electronics, and tubing connecting the wall fitting (where the tube from the Kiel probe is attached on the outside) to the plenum chamber. All of the pressure sensors, except two reference sensors, are connected to the plenum chamber. The PPI card also carries the Radar Altimeter (RAE) board in a piggy-back arrangement.

The Kiel probe consists of a pitot tube inside a tube that is designed to convert the outside dynamic pressure (i.e. including both the static pressure and the motion of the Huygens Probe) to a stagnation pressure, which is conveyed to the plenum on the PPI card via the tubing. This arrangement reduces the sensitivity of the measurement to misalignment of the axis of the sensor to the direction of motion. (See detail inset in Fig. 5.)

The connecting tubing is in two parts, one mounted in the Stem, the other connects the tubing in the Stem to the wall fitting on the DPU box. The Kiel tube is directly connected to the tubing in the Stem when it is physically mounted on the end of the Stem.

3.3. *Mass*

The mass budget, as estimated two years before delivery and as delivered, is presented in Table 1. The figures are based on the following assumptions:

- All the PPI electronics are mounted in the HASI DPU Box.
- The mass related to mounting of PPI electronics in the HASI DPU Box is not included.
- The mass of the stub boom (i.e. Stem) is not included.
- The mass related to RAE card is not included.

As can be seen from the table, the delivered equipment

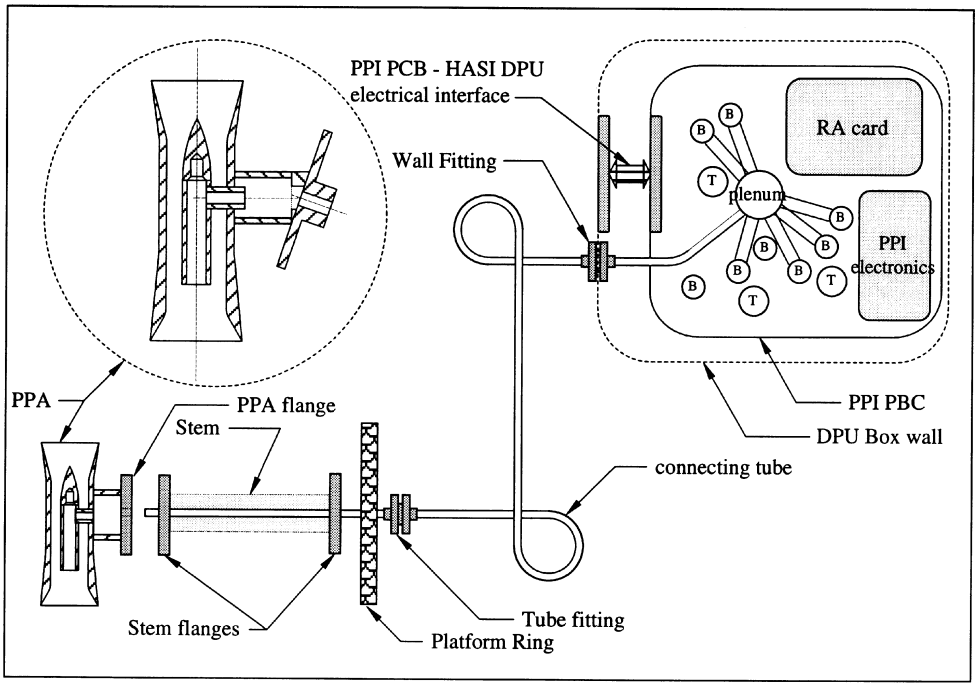

Fig. 5. PPI configuration and interfaces. Details of the Pressure Probe Assembly (PPA) are shown in the inset sketch

Table 1. PPI Mass Budget estimates (26 October 1993) and as delivered (23 March 1995)

PPI Mass	Mass (g) 26 October 1993	Mass (g) 23 March 1995
PPI inside the probe:		
PPI-electronics unit		
PCB (electronics only)	140	
Sensor heads (on the PCB)	24	
Electrostatic shielding	50	
Miscellaneous	40	
Subtotal	254	222.0
Wall fitting	30	30.4
Pressure tube		
PT-1	35	38.6
PT-2	26	38.0
Supports (2)	54	59.0
Subtotal	115	135.6
Kiel probe assembly	35	24.6
Total mass	434	
Contingency	43	
Total mass budget	477	412.6

came well within the estimated budget, even without contingency.

3.4. *Mechanical interface requirements*

Designing the interfaces was one of the more complex tasks in the PPI project. In essence, it had to be possible to remove and replace any part whatsoever during the assembly, integration and test phase, without disturbing any other parts. For example, the wall fitting, in addition to being the point of attachment for the external conduction tube, was required to:

- provide electrical connection between the PPI board and the Kiel probe, for grounding and shielding reasons,
- preserve electrical insulation from the DPU box, in order to avoid ground loops,
- allow the tubing to be connected and disconnected while the DPU box remained stationary,
- allow the DPU box to be removed while the tubing remained stationary, and
- allow the PPI card to be remove from the DPU box while everything else remained stationary.

Of course, the break in the connecting tube had to be designed so that the Stem could be removed, or the connecting tube between the DPU Box and the Stem could be removed. Finally, the Kiel probe mounting had to be designed so that the Kiel probe could be removed from the Stem, if necessary. At the same time all joints had to be leak tight in order to guarantee the integrity of the pressure measurements, and were tested at several stages before and during assembly, integration and test phase.

3.5. *Thermal considerations*

The PPI card generates so little electrical power that overheating was not a design issue. The thermal connection (conduction through the cards, convection in the gas, and radiation) is more than sufficient to assure that the card has the same temperature as its surroundings. However, as any gas measurement is subject to error due to error in temperature, PPI includes three temperature sensors on the card (one with each pressure sensor pair) which provide the temperature needed in data reduction.

At the same time, the outside temperature is much colder than the inside of the Huygens Probe for part of the descent, and much hotter as the Probe heats up going through the atmosphere. One can well ask whether the tubing and the gas in the tube can thermally couple the outside with the PPL card, which would lead to a great uncertainty in the measurement, possibly leading to a requirement of measuring the temperature at some point along the tube, or even in the Stem or the Pressure Probe Assembly (PPA).

Finally, thermal analysis showed that the conduction along the tube was so poor (due to the material as well as the thinnes of the wall) that the tube would be in thermal equilibrium with the immediate environment all the way along the path from the Kiel probe to the plenum chamber.

4. The PPI sensor system

4.1. *Sensor overview*

The PPI uses Barocap® capacitive pressure sensors with three different sensitivities to cover the pressure range of 0–180 kPa. The sensor technology is a heritage from a concept that has been applied in earlier space and terrestrial applications (Harri *et al.*, 1995).

PPI includes three groups of Vaisala pressure sensors (Barocap®):

- three high pressure sensors (calibrated 0–1800 hPa),
- three medium pressure sensors (calibrated 0–1400 hPa), and
- two low pressure sensors (calibrated 0–1200 hPa).

Additionally, in order to compensate for Barocap®s' temperature dependence, there are three temperature sensors (Vaisala Thermocap®s), one for each group of Barocap®s.

The high pressure sensors are capable of measuring the whole pressure profile of Titan (0–1450 hPa), up to 2000 hPa. They are more sensitive and stable at the upper part of their pressure range.

The medium pressure sensors behave like high pressure sensors except that they are more sensitive and the working range is limited to approximately 1400 hPa (until the capacitor plates touch each other). The Vaisala company manufactures these sensors in quantities for barometric systems.

The low pressure sensors are more sensitive and stable at the low end of their pressure range (0–1200 hPa). Their resolution is nearly in proportion to pressure.

The two high, middle and low pressure sensors are intended to read the total pressure profile during descent phase: they are connected to the Kiel probe via the pressure hose. The one high pressure and the one middle pressure Barocap® measure the internal pressure in the inside of the HASI DPU box. This measurement serves also housekeeping purposes. The internal pressure differs from the free flow pressure due to time lag and aerodynamical factors.

In PPI the different pressure sensors serve as a sort of reference senor for each other: high pressure sensors produce a linear pressure profile, medium sensors produce a long term stability reference near 1000 hPa and low pressure sensors give better resolution and accuracy below 400 hPa. The housekeeping Barocap®s can also be used to verify the behaviour of sensors exposed to the external pressure.

The PPI measurement quality can be expressed by the absolute accuracy and resolution. By the absolute accuracy we mean an error in absolute pressure at any altitude, and by resolution the ability to distinguish a change in pressure. The absolute accuracy of better than 1% is expected, taking into account all the error sources including converting total pressure to static pressure.

However, PPI accuracy is not linear, since it consists of three types of sensors, whose sensitivity have a hyperbolic dependence on pressure. The low pressure sensors are more sensitive to pressure near vacuum and the other two types of sensors are more sensitive when approaching the upper end of their operating range. This kind of behaviour is due to the fact that the capacitive sensors' plates nearly touch each other causing a substantial change in capacitance.

Figure 6 illustrates the hyperbolic characteristics of the Barocap® sensor showing the sensitivity of each type of the Barocap® used by PPI. The Barocap® resolution behaves as the counter value of sensitivity, i.e. higher sensitivity results in lower noise level and better stability. As a result the lowest resolution of the PPI is around the 400 hPa pressure (see Table 2).

The three types of Barocap®s with different sensitivities are used, one type of them at a time being the principal

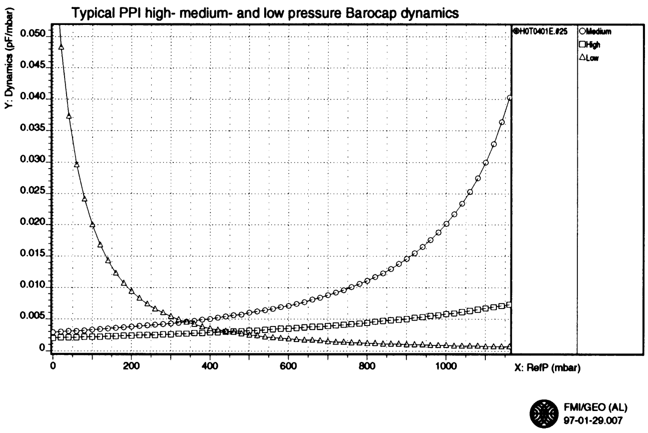

Fig. 6. The sensitivities of the three type of Baracap® sensors

Table 2. The expected PPI resolution (in hPa) dictated by the HASI 16-bit data word

	Pressure (hPa)				
Sensor type	5	100	400	850	1300
Med-P-Sensor	0.22	0.19	0.14	0.07	0.02
High-P-Sensor	0.23	0.22	0.17	0.1	0.05
Low-P-Sensor	0.006	0.02	0.08	0.25	—
PPI resolution	0.006	0.02	0.08	0.07	0.02

sensor type. The time of transition is dictated by two principles: which of the three sensor types (low, middle or high pressure) is most accurate at each time, and the fact that overflow of the middle pressure sensors will take place at pressure level 1300–1500 hPa. The exact overflow pressure depends on the characteristics of an individual sensor.

Resolution of PPI is dictated by the 16-bit HASI data word, in which PPI data is stored. The deviation in pressure (hPa) that causes a one bit change in PPI data is depicted in Table 2. Pressure levels 400 and 850 are selected because they are the transition points when PPI switches from low pressure mode to medium pressure mode (or high pressure mode, accordingly). The low pressure sensors are not exposed to as high pressure as 1300 hPa.

The PPI sensors were selected out of a batch of about one hundred Barocap®s. The batch of sensors was exposed to environmental screening tests and long term surveillance for a period of more than one year.

4.2. *Sensor electronics*

The PPI electronics is based on oscillator transducers that convert the output of the capacitive sensors into frequency. The HASI DPU interfaces to the PPI frequency channels and samples each sensor head one at a time. The frequency measurement is performed as period measurement. Just prior to the actual reading the DPU takes a prescaler sample to determine the number of counts needed for the reading to take roughly the same integration time for all the sensors.

The operational power consumption of the PPI type sensor transducer is about 3.5 mA of a 5 V line. Each transducer is capable of interfacing to six capacitive sensors. The PPI instrument has three transducers running continuously during the descent of the Huygens probe. Accordingly, the total PPI operational power consumption is 11.5 mA. PPI regulates linearly the power from the 15 V power line provided by the HASI instrument.

5. PPI operations and data production

The PPI starts measurements at an altitude of 160 km, producing 28 bits of data per second. Measurements are designed to continue beyond the time of impact on the surface of Titan, until the Huygens probe stops operating a few minutes after landing.

Two sensor readings, each consisting of an average of five samples, will be made every 2.4 s throughout the descent. The sensor readings are organised in pairs for optimisation of data acquisition. Every sensor reading is scaled to a 16 bit HASI data word and the variance of the five samples is scaled to 8 bits. The two words are then concatenated to produce a 24 bit data word for each sensor reading.

PPI has three sensor families each optimised for a specific pressure range. The transition points are around 400 and 800 hPa, as presented by Table 3. Changing the active sensors from one family to the next sensor family is carried out smoothly such that PPI all the time uses sensors of the two sensor families best fitted to the current pressure range. As a result, a pair of best fitted pressure sensors are sampled every 4.8 s and the second best fitted sensor pair is sampled two times more seldom, that is, every 9.6 s. Finally, as a temperature compensation and housekeeping service, the three PPI temperature sensors, the two pressure sensors inside the Huygens probe, and one constant capacitance are read every 43 s.

Table 3. The approximate transition altitude, pressure and time, when the PPI will change the best fitted sensor

Transition type	Time (t_0+)/min	Altitude/km	Pressure/hPa
Low/medium	75	23 ± 2	400 ± 50
Medium/high	105	10 ± 2	850 ± 100

The PPI measurements scenario includes two health-check sessions taking 6 s each, and performed about every 227 s. Finally, as a part of one health-check session, there is a special mode measurement taking 14 pressure readings in 2 s. This is performed once every 227 s.

The total PPI measurement scheme is carried out at the cruise phase during the six-monthly health-checks of the whole Huygens probe. The channel number parameters of the pressure sensors in the HASI software are designed to be uploadable enabling correcting measures in case of problems with some PPI sensor. If some unexpected deterioration of the performance of any out of the eight PPI sensors is discovered by the six-monthly health-checks during the cruise taking seven years, the sensor can be replaced in the sampling scheme by another PPI sensor.

The maximal temporal resolution of the PPI instrument is 0.150 seconds but in the normal mode only the average and variation of five successive readings of a sensor pair are transmitted. Furthermore, because every fourth sensor pair reading is devoted to temperature compensation and housekeeping service, and the best fitted sensor pair is sampled every second turn, the effective temporal resolution is between 2.4 and 4.8 s. This can be converted to spatial resolution by assuming the temporal resolution of 4.8 s, and by using the estimated Huygens descent profile data (Lebreton *et al.*, 1994). The result is compared to the pressure scale height as calculated from (Lellouch, 1990) as depicted in Fig. 7.

The spatial resolution of the burst mode is superior to the normal mode, but the time slice of the burst is narrow, 2 s at a time every 227 s, amounting to about 1% of the total measurements. This reflects the fact that PPI's main mission is to provide the atmospheric pressure profile. The spatial resolution of the burst mode is depicted in Fig. 7. The burst mode will be most effective when probing the near surface atmosphere for turbulence and other boundary layer phenomena.

The total amount of data will be 24–32 kilobytes, depending on the total operation time.

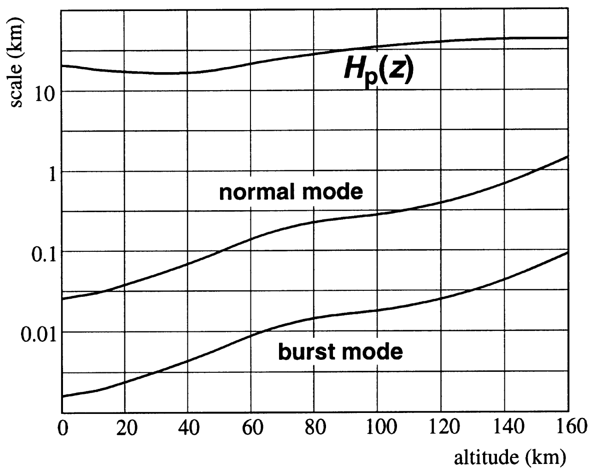

Fig. 7. The spatial resolution of the PPI measurement modes compared to the pressure scale height in the atmosphere of Titan

6. Discussion and conclusions

The PPI measurement concept of utilising Barocap® sensors and a Kiel type pitot tube is a result of a proven sensor design and extensive aerodynamical simulations. The Kiel type pitot tube for measuring the Titan atmospheric pressure was designed by means of simulations performed for the airflow around the Huygens probe and in the vicinity of the tip of the sensor boom, and wind tunnel tests.

The sensors based on the Barocap® pressure sensors with three different sensitivities cover the pressure range of 0–180 kPa. The sensor technology is a heritage from a concept that has been applied in earlier space and terrestrial applications.

The PPI measurements commence at an altitude of 160 km, producing 28 bits of data per second. Measurements are designed to continue beyond the time of impact on the surface of Titan until Huygens stops operating. The total amount of data will be from 24–32 kilobytes depending on the descent time.

The total mass of PPI is 412 g, and the operational power consumption is 130 mW linearly regulated from a 15 V power line.

The PPI is expected to provide the vertical ambient pressure profile of the atmosphere of Titan during the Huygens descent with the accuracy of better than one percent. The pressure profile will be provided from the altitude of about 170 km down to the surface of Titan. Thorough amalgamation of the data from HASI, the altimeter, the wind experiment, and the surface science package is needed to generate the atmospheric vertical profiles of the pressure, density, temperature and the mean molecular weight.

As its secondary objective, the PPI is anticipated to detect gravity waves in the upper part of the measuring region, and shed some light on the boundary layer effects.

The development of PPI included the fabrication of mechanical, engineering, flight and flight spare models. Each of them were integrated to the HASI and submitted to functional and environmental tests to meet the ESA requirements. Currently the PPI flight unit has been integrated to the Huygens entry probe and the integration tests have been successful. As a part of the test activities, a special balloon test session of PPI and other HASI instruments simulating the actual mission of Huygens was carried out successfully in November 1995.

The final tests and verification of launch readiness of the PPI/HASI and all the Huygens payload were completed during the spring 1997 and it was shipped to the launch pad in Cape Canaveral for integration to the Cassini spacecraft in April 1997. Preparations aiming for launch in October 1997 are currently under way.

During the cruise phase to Saturn the PPI/HASI, as well as the whole Huygens payload, will be awakened every six months for a special health check test. These test data will help understand the condition of the PPI, and also the other Huygens instruments. In case of some unexpected behaviour revealed by the health check tests, the PPI sensor sampling scheme can still be modified during the cruise phase.

Three weeks prior to the arrival to Titan the Huygens probe will be separated from Cassini spacecraft. Thereafter Huygens starts its autonomous journey towards the Titan atmosphere in pursuit of shedding light on some of the scientific puzzles of the Saturnian moon.

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