

## PLANETARY PROBE ENTRY AND DESCENT INSTRUMENTATION - A REVIEW

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### ABSTRACT

Planetary entry probes may carry a variety of 'simple' instrumentation to characterize the profiles of basic atmospheric physical properties and composition, in addition to sophisticated chemical analyses and imagers. I survey these 'simple' sensors, noting technological improvements in conventional atmospheric structure instruments as well as a number of less well-known instruments such as shock-layer radiometers, acoustic and electric instruments.

### 1. INTRODUCTION

Following the first planetary entry probes (an excellent review is by Wilson [1]) it has become more or less standard to incorporate a basic atmospheric structure instrument to characterize a planetary atmosphere. During a steady, usually subsonic descent (often under a parachute) the atmosphere is profiled with a pressure and temperature sensor. The upper atmospheric density profile (from which a temperature structure can be derived, with assumptions) is obtained during the hypersonic entry from an accelerometer.

I review the sensors used in these measurements, and their technological evolution. I additionally discuss some other simple sensing techniques. Sophisticated gas and condensate chemical analyzers present a whole range of other issues and are beyond the scope of this paper. Doppler measurements are also not discussed.

### 2. TEMPERATURE SENSING

Temperature is notionally one of the simplest atmospheric measurements to make, but in fact is not trivial. It therefore makes a good starting point for this review.

An old adage in instrumentation engineering is that a temperature sensor measures the temperature of the sensor. The sensor may or may not be at the same temperature as the medium of which a measurement is desired, namely the atmosphere. Two significant error sources must be noted - one due to extraneous heat fluxes, the other due to dynamic response.

In the first, the temperature sensor immersed in the static atmosphere may have a constant temperature, but if the sensor must conduct heat into the atmosphere to balance sunlight absorbed by the sensor, or electrical power used to drive it, then the sensor will be superheated relative to the atmosphere. Appropriate corrections must be applied - usually derived through empirical testing. Low power operation and shading of the sensor can help.

The second correction relates to the sensor's dynamic response. If the environmental temperature changes, as for example if descending through an atmosphere with a temperature gradient, then the sensor must absorb or reject heat to change its temperature. This heat flux will depend on the surface area of the sensor, on the thermal conductivity of it, and on the heat transfer properties of the atmosphere, including its density and the flow speed. The sensor will behave roughly as a first-order dynamic system, with the error from a step change in temperature having an exponential decay characterized by a time constant. Such a system, when presented with a constantly-changing temperature, will have a constant error.

The sensing techniques themselves deserve some comment. On internal equipment, thermistors are occasionally used, but these are typically nonlinear. Mechanical shock can lead to calibration changes. More robust and linear are semiconductor devices (e.g. the LM335 with 10mV/K or the AD590 at 1 mA/K.) The temperature range of these devices is somewhat limited. Ordinary silicon diodes can be used over a wider range, having a typical sensitivity of 1mV/K (although precautions must be taken to eliminate e.g. photovoltaic effects.) More typically, however, platinum resistance thermometers are used (e.g. on Pioneer Venus, Huygens etc.) due to their wide temperature range and strong calibration - usually a long platinum wire is wound on a frame immersed in the flow (e.g. [2,3,4]). Thermocouples are finding wider application now (e.g. [5]) that their small voltage output can be more reliably handled with modern electronics. Speed-of-sound measurements can also be used to infer atmospheric temperature (see later section.)

### 3. PRESSURE SENSING

Almost exclusively, pressure is sensed with diaphragm-type sensors (e.g. 3,4). An important consideration, especially where the diaphragm displacement is sensed with a strain gauge, is that such sensors need accurate temperature compensation. Often such compensation is built into the transducer itself, although that has not always been the case.

Accordingly, the sensors are often mounted well inside the body of a descent probe, such that they experience minimal temperature disturbances. The pressure they sense is brought to them via a small pipe from the outside.

Note that the usual approach for descent probes is to sense the total (i.e. pitot) pressure. This is the sum of the ambient ('static') pressure and the dynamic pressure of the relative flow. The reason for this somewhat indirect approach is that a true static measurement is quite difficult to obtain, especially in the presence of angle-of-attack excursions.

A flow-straightening Kiel tube (e.g. [4]) can be used to collimate the flow around the pitot orifice - this further reduces the sensitivity of the measurement to changes in angle-of-attack.

To derive the static pressure requires knowledge of the dynamic pressure, which is half the product of density and velocity squared (although a compressibility factor may also have to be applied for high Mach number flows.) This in turn requires other data. However, a fair approximation of the dynamic pressure on a body falling at terminal velocity is its ballistic coefficient multiplied by gravity - and this is roughly constant with altitude. Caution must be taken if there is substantial attitude motion or other variation in ballistic coefficient (e.g. parachute behaviours).

One notable technique devised for the Martian surface was an ion current pressure sensor, using the radioactive source from a smoke detector [6]. A potential of ~5V was applied between the centre and wall of a small metal can, and the ion current measured with a current amplifier. For a given gas composition, this device had a current proportional to pressure. A significant advantage of this technique (devised for the DS-2 Mars Microprobes, but not, in fact, selected for flight) is that the design could be made insensitive to the large delivery shocks associated with surface penetration - such shocks might produce calibration offsets in diaphragm-type sensors : see also [7].

### 4. ACCELEROMETERS

The most primitive type of accelerometer (the 'g-switch') holds a mass by a spring or magnet, and when a threshold is exceeded, the mass closes a microswitch. These devices, while primitive, are reliable and are often used to trigger parachute deployment.

The entry deceleration yields a profile of atmospheric density (if the velocity, mass and aerodynamic coefficients are known). The most sensitive accelerometers (with micro-g resolution) use an electromagnetically-levitated proof mass. These devices are somewhat massive (~60g) but well-proven. Some specific modifications are sometimes made e.g. redesign of the suspension magnet for Pioneer Venus to save weight [2]

Domestic applications, and in particular automobile airbag actuation, have stimulated low-cost miniature accelerometer development. Very small (<1g) devices with ranges of up to ~50g are widely available, e.g. the Analog Devices ADXL250, flown on the DS-2 Mars Microprobes [8] However, such devices may lack the very high sensitivity of the larger units used in the past.

In addition to the conventional entry deceleration profile and the recovery of density, such measurements can also be applied during descent to infer wind motions (e.g. [9,10] and rapid oscillations which may be characteristic of self-excited aerodynamic motions, or of atmospheric turbulence [e.g. (11).] Finally, at the end of the descent, accelerometers can be used to characterize the mechanical properties of the planetary surface [12], assuming that the vehicle itself is not deformed too substantially by the impact. Derived scientific quantities might be bearing strength of a porous solid surface [13], or the density of a liquid in the case of Titan [14].

The Viking landers [15] included full inertial platforms, with gyros and sensitive accelerometers. Sadly, few probes today are so well-instrumented, although the availability of compact and low-power fiber-optic and piezoelectric rotation sensors (usually, if not correctly, termed 'gyros') may help redeem this situation.

### 5. OPTICAL INSTRUMENTATION

Improving communications bandwidth, and the remarkable miniaturization of digital cameras for consumer applications make downward-looking descent cameras a possibility. As well as scientific observation of an unknown surface (e.g. the Huygens Descent Imager and Spectral Radiometer DISR [16]) such cameras can be used for precision landing-site

determination and characterization on spatial scales intermediate between those of landed cameras and those in orbit – e.g. the MARDI instrument on Mars Polar Lander [17].)

### 5.1 Radiometers & Spectrometers

The upward- and downward optical and infrared heat fluxes are of key importance in controlling the temperature structure of the atmosphere. Furthermore, the residuals between these quantities is the vertical convective heat transport, which is a central atmospheric parameter. Historically, Net Flux Radiometers (e.g. [18]) have used windowed and/or rotating photodiodes and pyroelectric detectors to monitor the fluxes. Again, developments in photodiodes and filter miniaturization make such measurements rather straightforward (with the exception of where corrosive and hot atmospheres must be kept away from the detectors). A recent example of a sensor of this type is the Ultraviolet flux monitor on the Beagle 2 Mars lander [19].

Another approach is to measure the entire spectrum of the light, as in DISR [16]. This is particularly useful since atmospheric absorptions due to e.g. methane or water can be measured, and the abundance profiles of these species inferred. Such measurements were made on the Venera probes for example [20]. Visible/Near-IR spectrometers are now rather compact – we may expect more instrumentation of this type. One convenient technique may be to isolate the detector from the environment using a fiber optic cable (e.g. [21].)

Simple photodiode measurements with high-pass filtering may permit the detection of lightning.

### 5.2 Nephelometer

In addition to characterizing the clouds or haze in an atmosphere from the absorption and scattering of light above and below the descending probe, optical measurements can be used in-situ to measure sufficiently abundant particles. Usually a laser beam is projected from the side of the probe : in simple sensors, the backscattered light is simply measured with a photodiode, e.g. [22]. More typically [23,24] the light is reflected from a mirror held at a short distance from the probe – measurement of the light scattered at various angles can constrain (typically via Mie theory) the size, shape and composition of the particles. 3 distinct types of cloud particle were identified on Venus, for example.

### 5.3 Infrared Absorption Spectrometer

In conceptual and structural terms this instrument (proposed for Huygens, flown on terrestrial balloons [25]) is similar to a nephelometer, but only one raypath (conceivably a multiple pass between two mirrors) is used. The wavelength of the light beam is swept, usually by using a tunable diode laser whose wavelength is modulated by the applied current, across a narrow spectral region containing an absorption line of a gas species of interest. Usually a separate diode is required for each species. Such a technique offers the possibility of very high spatial resolution profiling (just as the speed of sound can do for temperature) of even moderately low-abundance (ppm) species. TDL sensors were flown on DS-2 and on the Mars Polar Lander.

### 5.4 . Shock Layer Radiometer

An experiment that has sadly not been repeated since PAET [26] is an entry flux radiometer. Essentially, photodiodes with interference filters are mounted behind a small window in the front shield, to allow the flux from the shock layer at specific wavelengths to be monitored. That experiment demonstrated the consistency of the flux profile with the terrestrial N:O ratio and CO<sub>2</sub> abundance e.g. [27].

Calibration of such a measurement is challenging, and the atmospheric data is on only a handful of species, but it does probe a region of the atmosphere that is generally difficult to access by other means. Of particular interest is the CN emission in Titan's atmosphere [28] which may even be observable from Earth [29] during the Huygens probe entry.

## 6. ENTRY SHIELD EROSION GAUGE

It is worth noting that some purely engineering measurements are of importance. Among these, the recession of the heat shield by aerothermodynamic ablation is notable. Although conceivably some scientific information might be derived from a measurement per se, the reduction of safety margins by improved knowledge of the entry process and materials performance ultimately may permit higher payload mass fractions on entry probes. Pioneer Venus [30] and Galileo had recession gauges to monitor the thickness of the heat shield during entry.

## 7. SOLID-STATE CHEMICALLY-SPECIFIC SENSORS

The most obvious example of this type of sensor is the humidity gauge. A rather large example (~1kg) was

flown on Venera 13 and 14, using phosphorus pentoxide [31]. Modern sensors can weigh well under a gram - usually they take the form of a capacitor, with a moisture-sensitive polymer as the dielectric. However, such sensors would only be able to usefully measure water abundance over a modest altitude range due to sensitivity and temperature range restrictions.

Other solid state sensors might include sensors for O<sub>2</sub>, ammonia, CO or sulphur compounds. A challenge for this type of device (some of which are used in auto engine-management, or in domestic CO alarms) is cross-sensitivity - combinations of such sensors ('e-nose') may be more useful. While lacking the sensitivity and wide-spectrum capability of GC and MS, such compact sensors may be useful in profiling a handful of variable species. An amperometric O<sub>2</sub> sensor was flown on Mars Polar Lander as part of the Thermal and Evolved Gas Analyzer package [32].

## 8. ELECTROMAGNETIC INSTRUMENTS

The Galileo probe incorporated a Lightning and Radio Emissions Detector (LRD) to detect the electrical and magnetic components of lightning signals. This sensor was also able to measure the spin rate of the probe [33]

Conventional, sensitive magnetometers such as those flown on orbiters are not very applicable to entry probes, not least because spacecraft fields are problematic - a boom is difficult to accommodate on an atmospheric vehicle. However, development of miniature (few g) fluxgate and other magnetometers has been stimulated by game controller/virtual reality helmet and mobile robotics applications.

Since geomagnetic fields (such as the magnetic 'stripes' on Mars) fall off as distance cubed, an entry/descent probe (or other aerial or even surface vehicle [34]) can be an ideal platform for revealing smaller anomalies and smaller-scale structures. A magnetometer on an entry probe might also yield interesting information on the plasma sheath during entry.

Electric field measurements, as well as detecting lightning, may be of more general interest in atmospheric electricity. Relaxation probe measurement of electrical conductivity (to identify the density of negative and positive charge carriers) are also rather compact. Such measurements are planned, for the first time in a planetary atmosphere [35] on the Huygens probe to Titan - arguably a demonstration of the utility of engaging new investigations rather than simply cloning previous atmospheric structure instruments. It is important to note that these measurements may be strongly affected by the descent airflow, and much remains to be understood about these measurements -

field/balloon experiments will be important in this regard e.g. [36].

## 9. ACOUSTIC INSTRUMENTATION

Three types of acoustic instrumentation can be considered. First is a simple passive microphone. Secondly, active instrumentation may simply record time-of-flight of acoustic pulses, to determine either the speed of sound, or as an anemometer. Finally, active SODARs (i.e. atmospheric sonar) may be used.

The Venera landers included passive microphones in order to search for thunder on Venus (inconclusively - low-frequency sound signals detected can be attributed to aeroacoustic noise during the descent - an endemic problem. [37] Note that acoustic emission will be dominated by a frequency of the order of  $L/V$ , where  $L$  is the characteristic length scale of the vehicle, and  $V$  the descent speed. Aeroacoustic noise was also detected on the surface (when the vehicle was stationary) and used to infer surface windspeeds [38].

The Mars Polar Lander incorporated a passive microphone as a low-cost 'piggyback' experiment [39]. The low power, mass and data volume requirements were met by components (e.g. DSP chips) whose performance has increased dramatically in recent years with the explosive popularity of mobile phones.

Speed of sound sensors have been proposed [40] as early as 1966 - speed of sound is a useful measure of temperature if the composition is known (and temperature measurements can be made more rapidly (~20 Hz) than is possible with sensors with a characteristic time constant. Thus speed of sound sensors may recover vertical temperature profiles during a descent with higher spatial resolution than is possible with other sensors.

If, on the other hand, temperature is known, the speed of sound places a constraint on composition - useful in characterizing variable abundances such as those of condensibles like methane on Titan [41]. Speed of sound in hydrogen-rich atmospheres is also influenced by the ortho:para hydrogen ratio [42], which is a tracer of convection. This parameter is otherwise rather difficult to measure.

One approach to measure the speed of sound is to use phase-sensitive detection in a waveguide [40]. More usually one measures the transit time of an ultrasound pulse across a gap (higher frequencies permit smaller transducers, more accurate time measurement and suppress ambient noise, which is attenuated more strongly at high frequencies.) This is the technique

used in the first of these instruments to actually fly to another planetary body, the Surface Science Package on the Huygens probe [43].

The combination of multiple pulse-transit time sensors allows wind speeds to be recovered – see the paper by Cuerva et al in these proceedings.

Finally, sodars are widely used to characterize the lower atmosphere - detecting turbulence, temperature contrasts and precipitation. The Huygens probe Surface Science Package (SSP) incorporates both a speed of sound sensor and an acoustic sounder - while these were included initially to characterize liquids on Titan's surface, it was recognized that these sensors would return valuable data during descent.

## **10. SOME REMARKS ON INTEGRATION, PRESSURE VESSELS AND A NOTE ON DYNAMIC RANGE**

The architecture of many space projects, with the need for parallel development of many instruments and the probe system to carry them, has tended to put individual instruments in boxes. This approach has advantage, and early- and well-defined interfaces make the job of the project manager and everyone else easier. It is, however, of limited utility for probe instruments that must access the environment, often in several directions, such that there are many sub-elements, penetrations and connections.

It may be, especially for small vehicles, rather more productive to consider the entire vehicle as part of the instrument, or vice versa – the system must be considered as an integrated whole. A modern digital wristwatch can incorporate temperature, pressure and magnetic sensors, together with its power source and display – but only because all the elements are packaged in an integrated fashion. The DS-2 Mars microprobes arguably came closest to this ideal [8], although the VEGA balloons presented similar miniaturization challenges [44]

Venus probes and outer planet probes may encounter very large atmospheric pressures, up to 100 bar (conceivably more, although the probability of successful communication from such depths seems slim.) Two approaches have been used in the past – Russian landers and the Pioneer Venus probes used pressure vessels. The technical challenges in the development of such structures, and testing them, and the various windows and cable feedthroughs that are needed are formidable (e.g. [45].) Another approach, used on the Galileo probe, which was designed for more modest pressures and temperatures, was to have

an unsealed probe, but sealed experiment boxes. This approach may be judged in one sense to have been unsuccessful, in that convective heat transfer was higher than expected and led to elevated operating temperatures.

However, it is the author's belief that a distinction needs to be drawn between the requirement to exclude a hot, corrosive atmosphere, and a requirement for a pressure vessel. Few components, it will be found, actually have pressure-induced failure mechanisms (large components like electrolytic capacitors or batteries are most likely.) It may be that the functional requirement of delivering operating instrumentation to depth can be met by a thin-walled vessel, filled with an incompressible fluid such as an oil – as the oil expands as it warms up, it seeps out, while no atmosphere is ingested. Oil-filled housings are sometimes used instead of pressure vessels in ocean-bottom instrumentation.

Several of the measurements discussed here, such as pressure and in particular accelerometry, require large dynamic ranges – from micro-g to hundreds of g. It is difficult to accommodate such large ranges with adequate accuracy, and thus adjustable-gain circuits are often used.

The gain-switching logic must be designed with care. However, an alternative approach is to simply record all the various channels simultaneously (since atmospheric structure data is rarely a strong driver on data rates and volume, and the power requirements are trivial). The improvement in electronics capabilities may make this sort of (admittedly extravagant with 1970s technology) approach attractive.

## **11. INSTRUMENTATION PHILOSOPHY**

A personal impression is that more can and ought to be done with simple sensors : a shift of emphasis from exquisite construction to testing and analysis.

Such an approach may offer significant cost savings, as recognized for many years by the 'small satellite' community. Not only can overall costs be substantially lower (even allowing for a much larger initial parts count, and the labor costs of testing and downselection, choosing the best 5 out of 50 parts, for example) but the performance of such parts is generally superior to that of established space-rated parts. One notable example is the Digital Signal Processor in the Mars Microphone lost on MPL, whose design was driven by cellular telephone requirements.

Since the spacecraft market is inadequate to drive electronic component development, the use of commercial parts is often mandated. Care must of course be taken to ensure that the components will function in the anticipated environment, but this is more reliably determined by testing than by analysis. The former ought (but sometimes is not) adequately performed for space-qual parts anyway. I would argue that an off-the-shelf commercial part, manufactured by the million for a demanding consumer-electronics market, given careful and comprehensive performance testing, is preferable to a bespoke space-qual part made in small batches, which may not have received substantial testing.

A broad testing campaign can pay dividends in the event of unforeseen circumstances. The entire Galileo probe payload had to be recalibrated (or at least the engineering models still on the ground) to understand its performance under the elevated and rapidly-changing temperatures experienced during the probe's descent.

The two highest-sensitivity ranges of the Pioneer Venus accelerometer profile were lost due to the servo-loop acquisition time of the accelerometer being too slow in its highest-gain setting. This problem was not uncovered in ground testing because the schedule became too tight for thorough end-to-end testing of sensors and electronics from different suppliers. The 'inadequate schedule for testing' cause of failure is seen all-too-often.

Another anomaly was the failure of the external sensors on all four of the Pioneer Venus probes. Originally this was attributed to some mysterious electrical discharge (with one consequence that the Galileo probe was therefore protected against such discharge). However [46] testing showed that certain Kynar insulation broke down at around 650K and produced hydrogen fluoride, which led to the failure of the electrical connections to the sensors.

## 6. CLOSING REMARKS

Various interesting measurements can be made during a planetary entry and descent. I have argued for more numerous, but potentially simpler, measurements, subject to appropriate caution.

It is inevitable in an endeavour like planetary exploration that unforeseen circumstances transpire, and failures may occur. It is our responsibility not only to attempt to minimize the opportunities for failure, but to document them well when they do occur, such that they can be understood and avoided in the future. The

pioneers in this area (e.g. [3]) have set us a good example.

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(note – many of the journal issues cited here are 'special issues' with many papers devoted to other aspects of the same mission – the interested reader is urged to browse adjacent pages of the journals for details on other instruments and the spacecraft themselves)

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*Figure 1. A playful reminder that planetary probes are venturing into the unknown. Simple-minded interpretation of isolated datasets (such as the accelerometer record of a probe hitting a tree's canopy) is likely to fail to yield the true and complete story – datatypes from many sensors need to be combined to understand the environment completely. Artwork by J.R.C. Garry – see [www.fastlight.demon.co.uk](http://www.fastlight.demon.co.uk)*