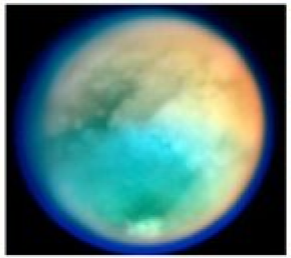
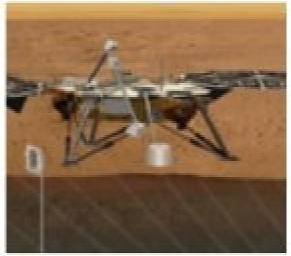




IPPW9 Short Course
Probe Science Instrumentation

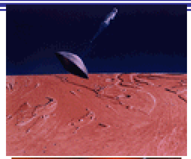
Entry / Descent (*in situ* probe science)

Atmospheric Structure Instrument / Meteorological sensors (ASI/MET)

Francesca Ferri
Università degli Studi di Padova,
CISAS “G. Colombo”

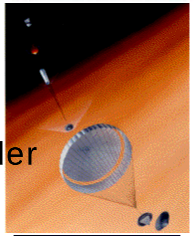
Planetary entry probes

Viking

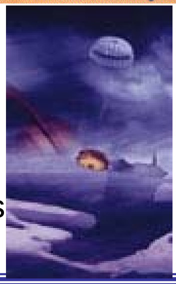


Pioneer
Venus

Galileo



Mars
Pathfinder



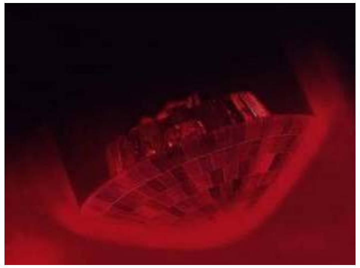
Huygens

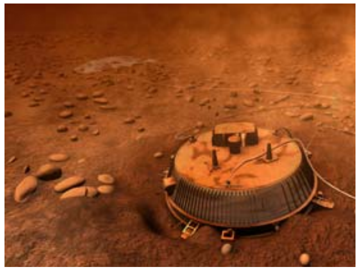
- Few robotic probes have successfully entered the atmosphere and landed on planetary body:
  - Mars (USSR Mars 6, NASA Viking 1&2, Pathfinder, MERs, Phoenix)
  - Venus (NASA Pioneer Venus probes)
  - Jupiter (NASA Galileo probe)
  - Titan (ESA/NASA Huygens probe)

  and re-entry vehicle in Earth's atmosphere (e.g. Stardust, Gemini)

Only Viking, Venus Pioneer and Titan Huygens probes made direct in situ p & T measurements during descent!

EDL *in situ* probe science: Atmospheric Structure Instrument (ASI-MET)

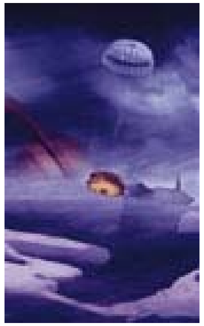


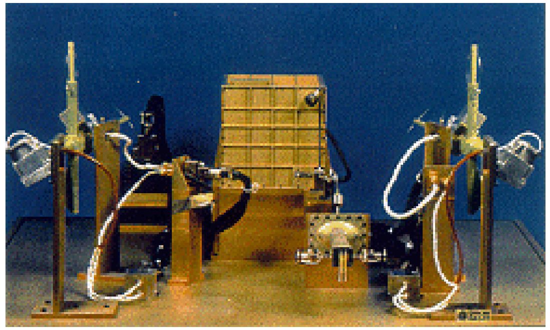


- Atmospheric probes and landers could provide key measurements for planetary atmosphere investigation, specifically by deriving **atmospheric structure** from ***in situ* measurements** during the entry, descent and landing of the probe.
- Relaying on accelerometric data and also to sensors (p & T) directly exposed to the atmospheric flow during the descent phase.
- ASI-MET can determine **density**, **pressure** and **temperature** as function of height from the upper atmosphere down to the surface.
- The **atmospheric vertical profiles** allow resolving **vertical gradients** in order to investigate the **atmospheric structure and dynamics**

- ASI/MET flown in every atmospheric entry probe and lander
- *Historical 'father' of ASI instrument Dr. Alvin Seiff of NASA AMES*.

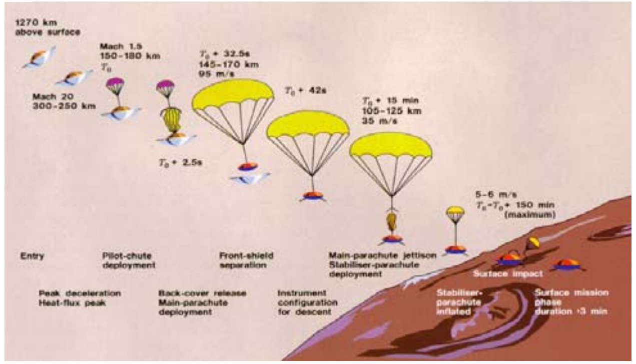
Huygens Atmospheric Structure Instrument (HASI)

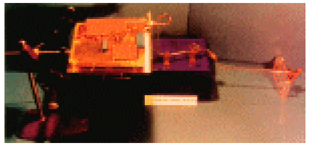



- **Study of Titan's atmosphere and surface**

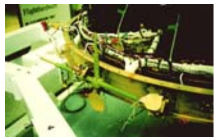
by measuring

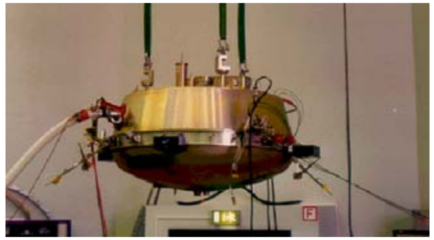




- **acceleration** (ACC)
- **pressure** (PPI)


- **temperature** (TEM)
- **electrical properties** (PWA, RAU)





- ***Heritage: Pioneer Venus, Venera, Galileo, and Viking probes***

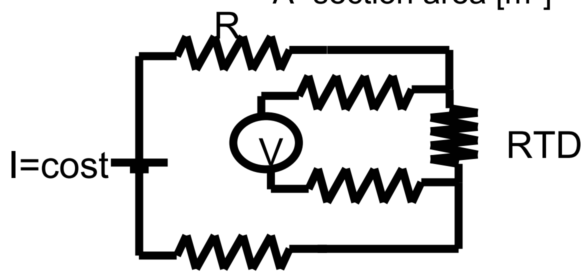
Temperature sensors

Resistance Temperature Detector (RTD)

- Pt RTD used as standard for ITS90
- High precision
- Stable and linear
- Wide measurements range

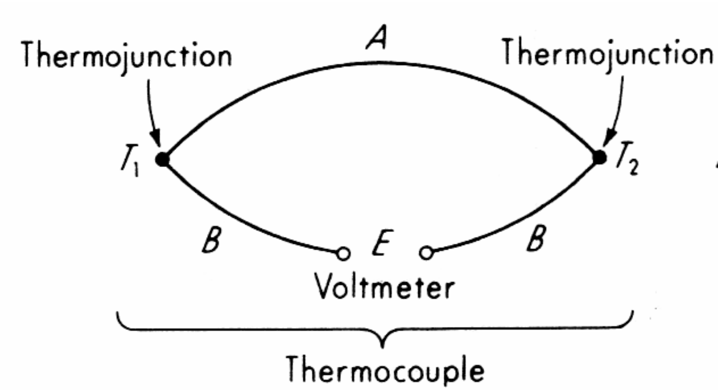
$$R = \frac{\rho\, l}{A}$$

R = resistance [Ω]
ρ=resistivity [Ωm]
l=length [m]
A=section area [m^2]



Themocouples (TC)

- (Ni-Cr10%) / (Cu-Ni) T -200°C +350°C [chromel/constantana] (type E)
- Need T reference
- Poorly stable and accurate
- Low V output



Temperature-measuring problems in flowing fluids

- Conduction error
- Radiation error
- Velocity effects: free-stream static (T_{stat}) rises to stagnation of total temperature (T_{stag})
  r recovery factor determined by experimental calibration

$$r = \frac{T_{stag,ind} - T_{stat}}{T_{stag} - T_{stat}}$$

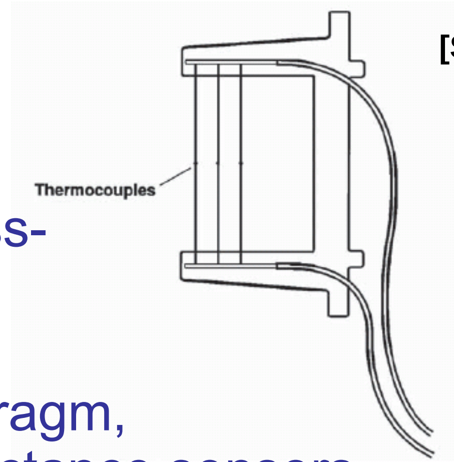
Probe measuring T_{stag}, r=1

Probe measuring T_{stat}, r=0

$$T_{stat} = \frac{T_{stag,ind}}{1 + r[(\gamma - 1)/2]N_{mach}^{2}}$$

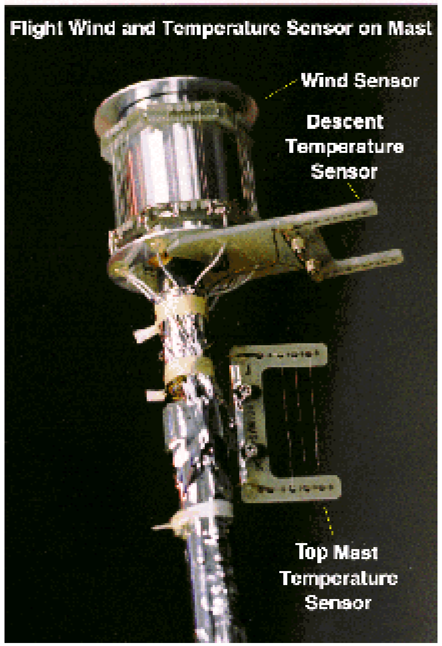
- Dynamic response -> time constant τ

Mars PathFinder ASI/MET



[Seiff et al. JGR 1997]

Temperature sensor:
Three redundant thin-wire (75μm) chromel-constantan (E type) thermocouples suspended on fiberglass-epoxy bracket.



Pressure sensor:
Tavis deflecting diaphragm, variable magnetic reluctance sensors.

Wind sensor:
6 hot wires (0.9Pt/0.1Ir) anemometers

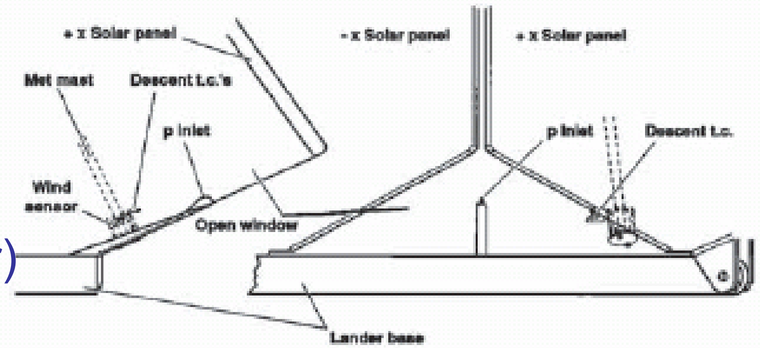
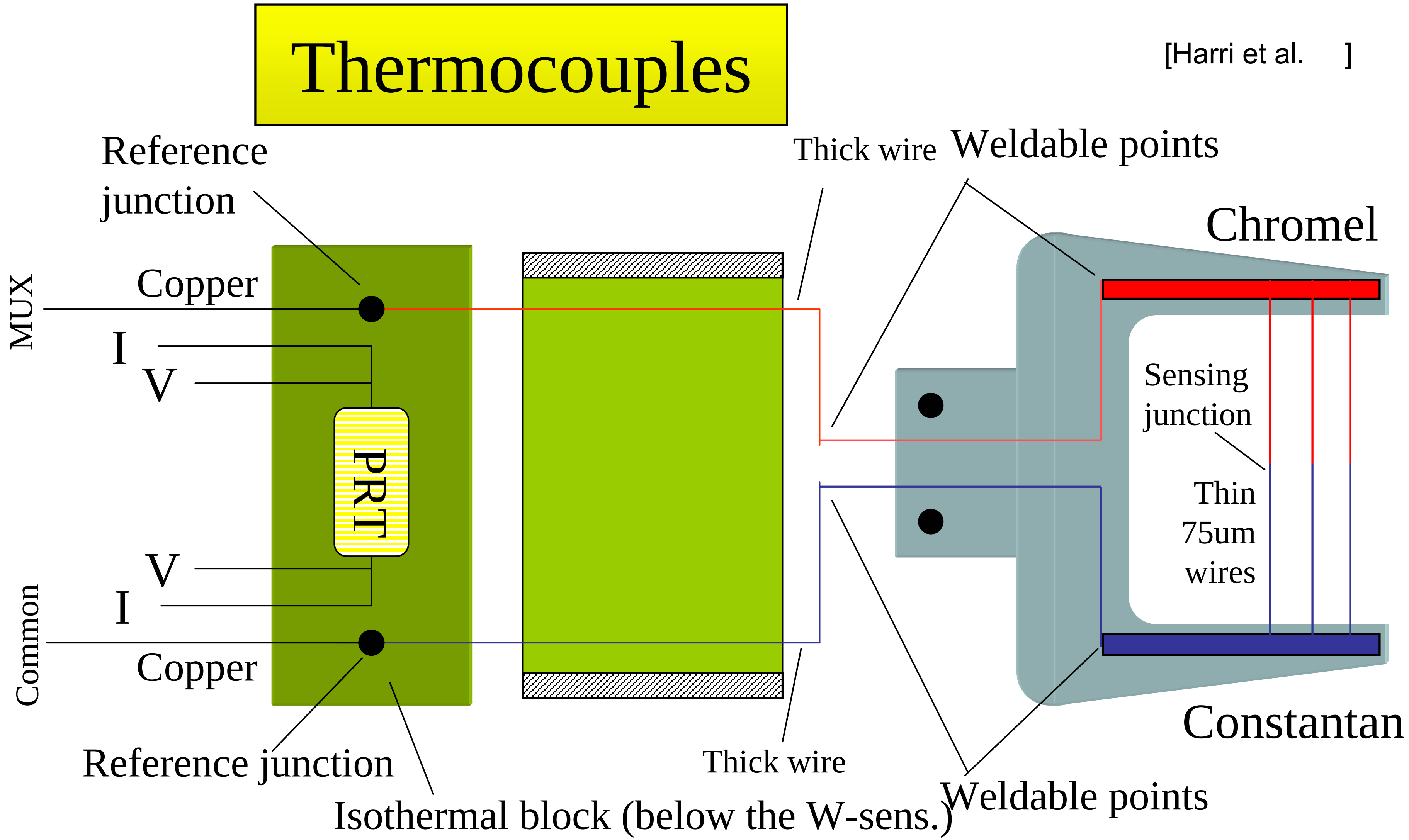


Figure 5. Sketch of pressure inlet and descent thermocouple locations during parachute descent. The pressure inlet lies in the plane of the triangular window opening at one corner of the lander. (The sensor itself is on the lander base near the integrated electronics unit box.) The descent temperature sensor is just below the wind sensor on the stowed meteorology mast, oriented approximately parallel to the window opening.

Descent measurements not possible since sensors mounted inside the lander

Mars NetLander ATMIS

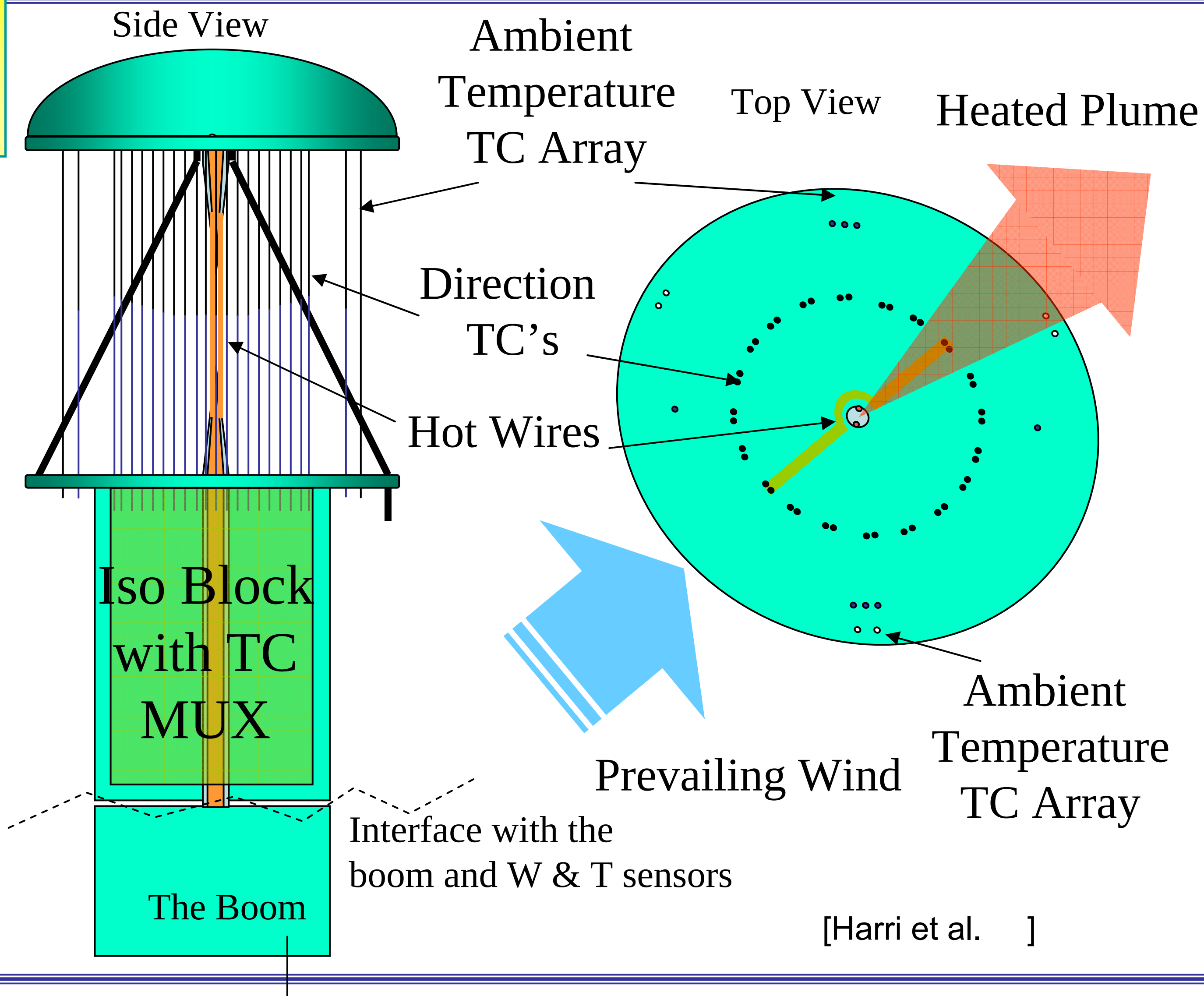


Mars NetLander ATMIS

Wind sensor & thermocouples

Thermoanemometer

- 100 C over temperature central hot wire senses wind speed
- 20 differential thermo-couples sense wind direction
- Reference temperature from absolute thermo-couple around the wind sensor
- Thermocouple mux on the isothermal block
- Heritage from **Mars Polar Lander**



[Harri et al.]

Pioneer Venus ASI

- **Platinum Resistance Thermometer** (PRT) directly exposed to the atmospheric flow (e.g. sensor located outside the lander boundary layer).

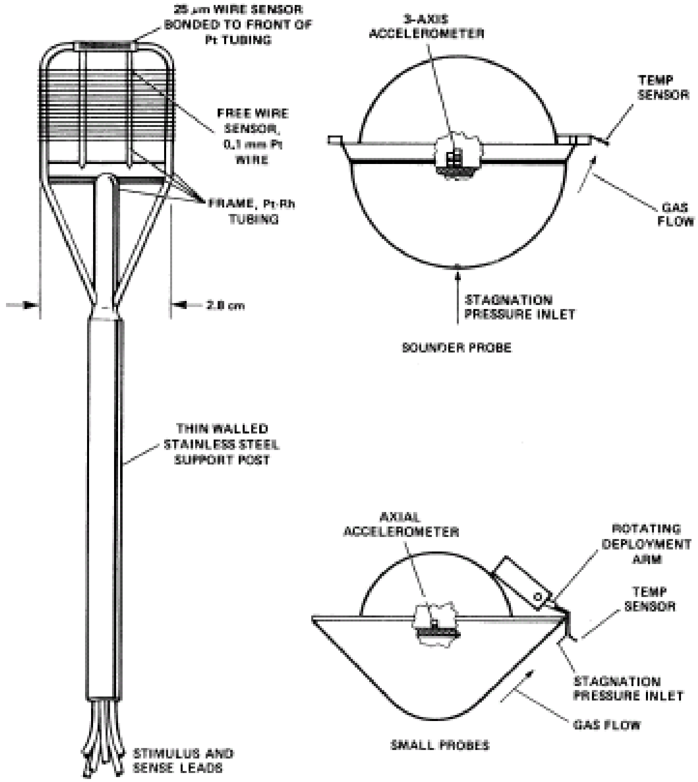
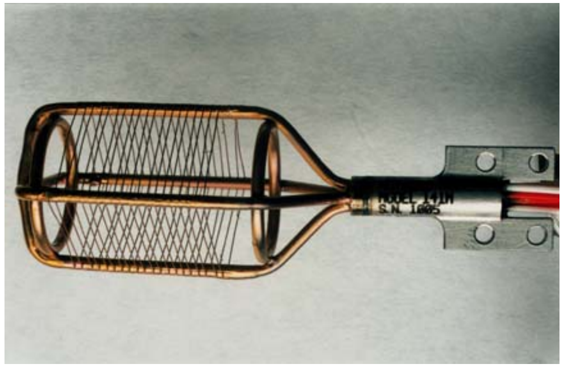
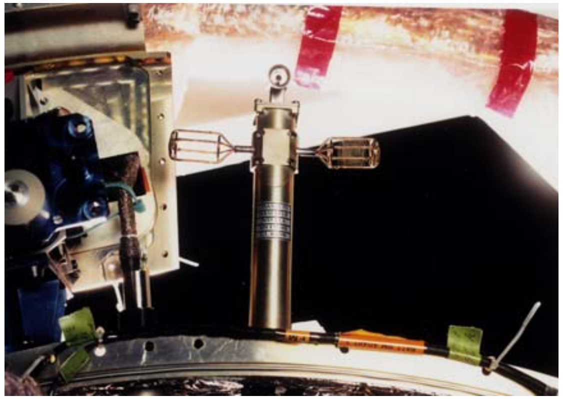


Fig. 1. Temperature sensor configuration, and its installation on the probes. Also shown are the acceleration sensors and pressure inlets.

[Seiff et al. 1980]

HASI TEMperature sensors





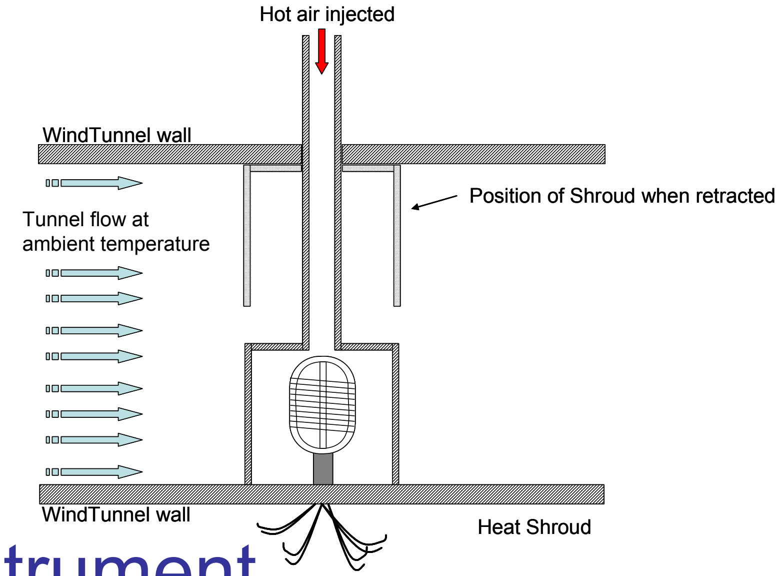
- Two redundant dual element platinum resistance thermometers (TEM).
- The primary sensor (FINE) directly exposed to the air flow (double wire 0.1mm - faster time response)
- The secondary sensor (COARSE) is embedded in the structure and designed as spare unit in case of damage of the primary sensor.
- Temperature measurement by monitoring resistance (wrt reference resistor; I=25 mA, pulsed 100ms)

range	Resolution	Accuracy
Low T (60-110K)	0.02K	0.02K
High T (100-330K)	0.06K	0.2K

Main objective: to measure **Titan's atmospheric temperature profile**.

HASI TEM calibration and characterization

- **Static calibration**
  by ITS-90 procedures
- **Dynamic calibration**
  by tests in wind tunnel
  to derive response time



- Sensor model: 2nd order instrument

$$\tau_1\tau_2\frac{d^2T_w}{dt^2}+(\tau_1+\tau_2)\frac{dT_w}{dt}+T_w=\tau_3\frac{dT_a}{dt}+T_a$$

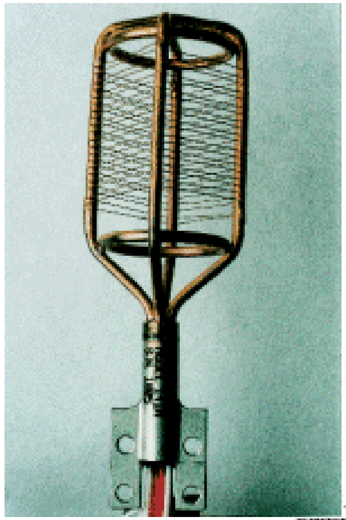
where T_w= sensing wire temperature, T_a= atmospheric fluid temperature
τ response time: τ_1 wire response time, τ_3 supporting frame response time,
τ_2 thermal coupling wire and supporting frame

HASI testing and calibration

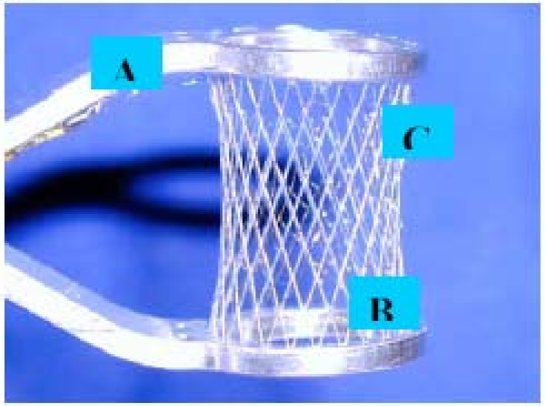
- Sensors have been characterized, tested and calibrated at subsystem, HASI instrument and Huygens probe level.
- **Cruise in-flight check-outs** (every 6 months during 7 years): check sensors off-sets and behaviour through mission timeline simulation; eventually monitoring any drift and /or ageing effects.

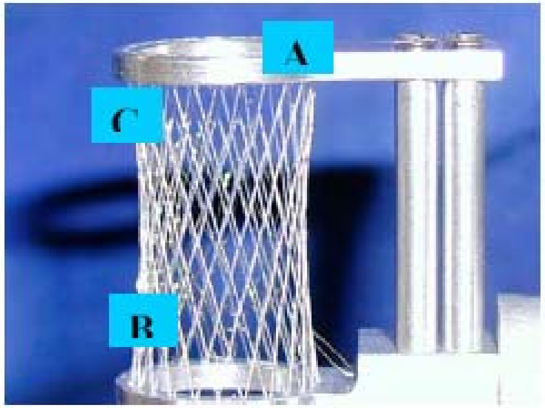
- Beside Huygens AIV campaign, **HASI stratospheric balloon flight experiments** have been performed to **simulate Huygens descent** at Titan, and to test and verify HASI sensors performance
- Huygens/HASI balloon drop tests

MarsTEM



A prototype of PRT for Mars descent measurements

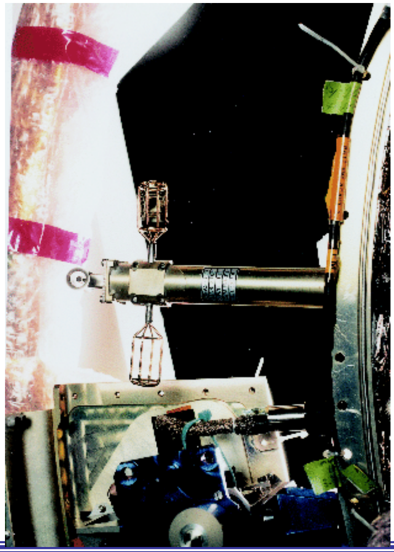


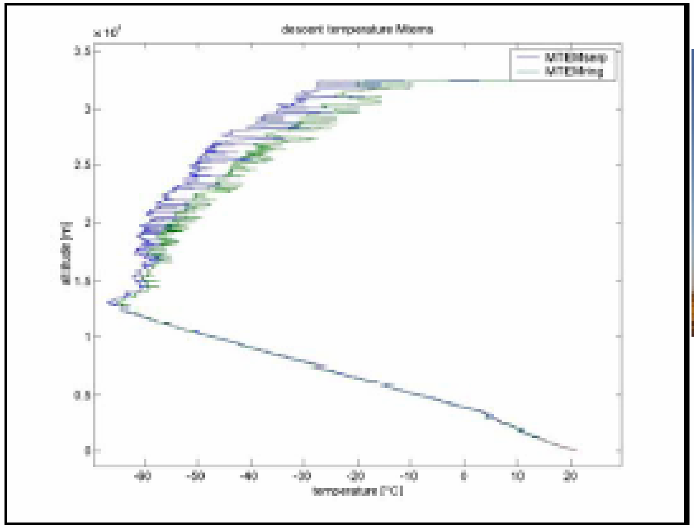


[Colombatti & HASI team]

. MARSTEM sensors: serp (left) and ring (right) configurations (A. supporting aluminium structure; B. suspending PTFE fibres; C. platinum wire)

developed and tested in the Huygens/HASI balloon campaigns





Proposed for ESA ExoMars DREAMS surface package

Pressure sensors

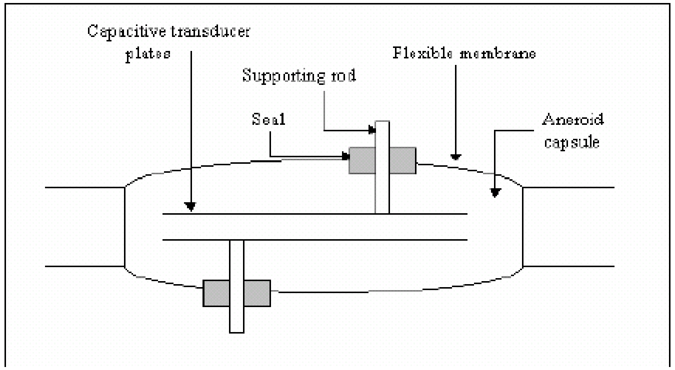
Vaisala Barocap sensors

- Silicon capacitive absolute pressure sensors
- Lightweight and robust
- Sensors commonly used on radiosondes flown on stratospherici balloons
- Used on Huygens, Beagle2, Mars-96, Mars Polar Lander, Phoenix, MSL

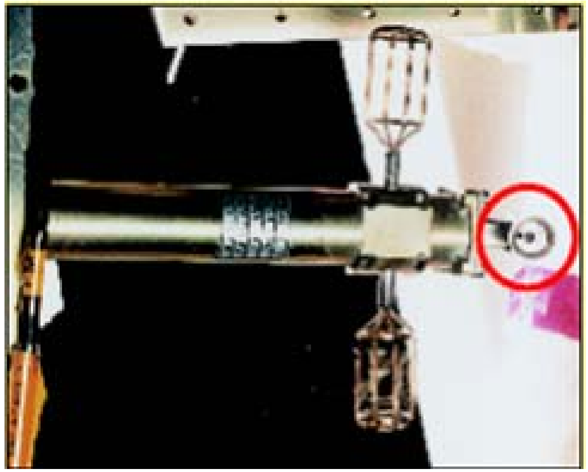
Example: Huygens HASI PPI

PPI Sensor / total mass	~ 15g / ca. 411 g, 1 PCB 16x16 cm
Range	0-2000 mbar (8 sensors)
Resolution	5 ubar
Accuracy	1%

Barocap principle (Δp->ΔC-> $\Delta\nu$)



HASI PPI Kiel probe



Viking & Mars Pathfinder ASI/MET pressure sensors

Tavis deflecting diaphragm, variable magnetic reluctance sensors

- Relatively massive, but
- reliable
- excellent repeatibility
  (0.07% between 2 Mars' years)
- Thermal compensation by PRT sensor

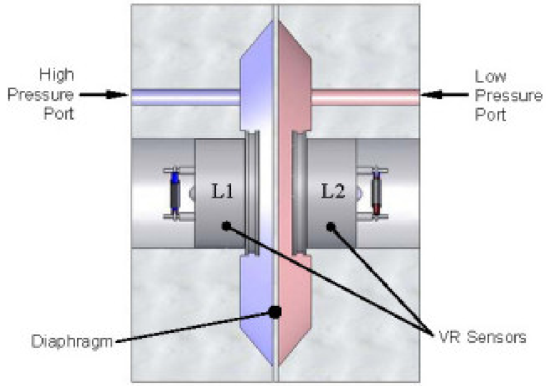


Figure 1

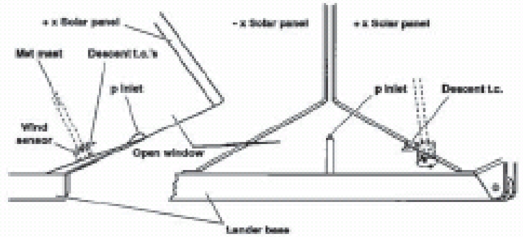
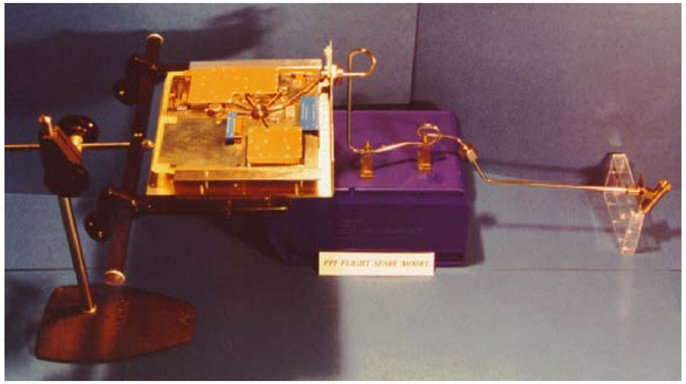
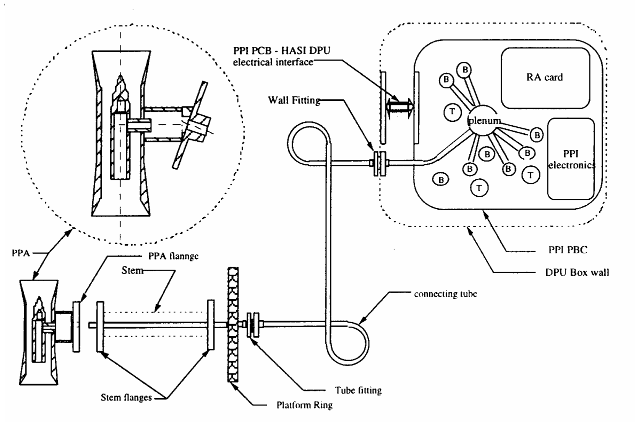


Figure 5. Sketch of pressure inlet and descent thermocouple locations during parachute descent. The pressure inlet lies in the plane of the triangular window opening at one corner of the lander. (The sensor itself is on the lander base near the integrated electronics unit box.) The descent temperature sensor is just below the wind sensor on the stowed meteorology mast, oriented approximately parallel to the window opening.

HASI Pressure Profile Instrument (PPI)

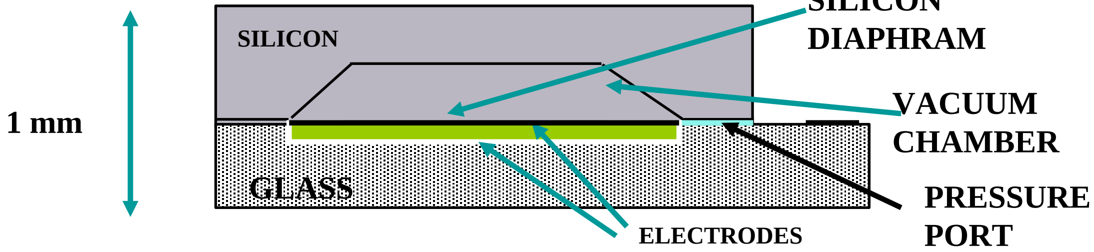
- The atmospheric flow is conveyed through a **Kiel probe** inside the DPU where transducers and electronics are located.
- PPI transducers are silicon capacitive absolute pressure sensors (*Vaisala* Barocap).





HASI PPI schematic

Barocap sensor schematic

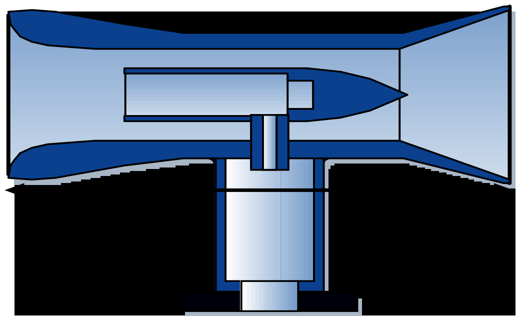


range	Resolution	Accuracy
Low (0-400 hPa)		
Medium (0-1200 hPa)	0.01hPa	1%
High (0-1600 hPa)		

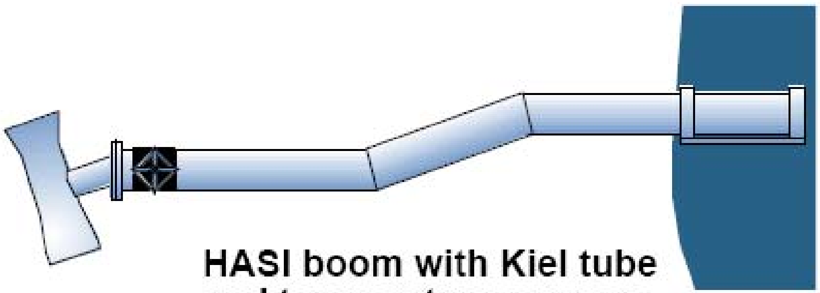
Main objective: to measure **Titan's atmospheric ambient pressure** and 3-axis **wind velocity**

HASI PPI – Kiel probe assembly

- Pitot tube inside Kiel probe measures total pressure i.e. the sum of ambient and kinetic pressures
- Accurate measurements despite change in flow inclination angle up to 45°
- Gas inlet into the electronic box insiede the probe (warm compartment)



HASI PPI Kiel probe design



HASI boom with Kiel tube and temperature sensors

Total pressure is related to the ambient pressure through

$$p_{tot} = p\left(1 + \frac{\gamma - 1}{2} M^2\right)^{\gamma / (\gamma - 1)}$$

γ is the adiabatic constant

M is the MAch number in free stream

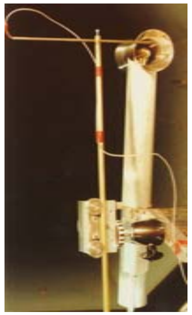
HASI PPI testing and characterization

Expected dynamic conditions:

- Wide range of Mach and Reynolds numbers
  - Supersonic flow during entry
  - Turbulent flow at lower atmosphere (below 90 km)

Flow field simulation:

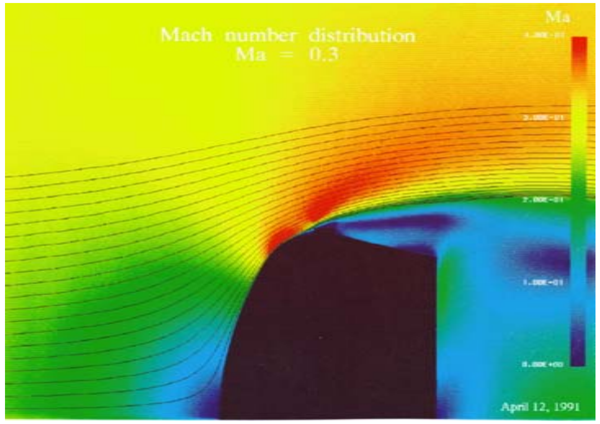
an adaptic-grid for solving 3-D Navier-Stokes equations (developed by Laboratory of Aerodynamics, Helsinki University f Technology, Finland) used to study probe behaviour and for PPI Kiel probe design.

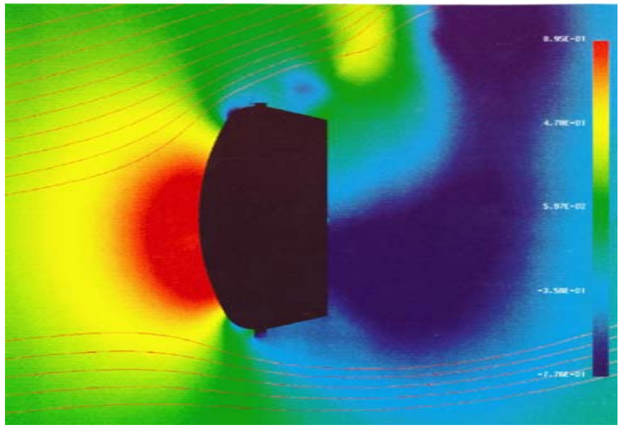


HASI/PPI wind tunnel:

tests with upscaled models to verify Kiel probe design

Simulated streamlines:
Mach 0.3 / 0° & Mach 0.6 / 10°



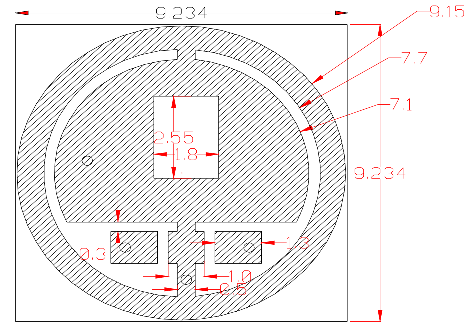


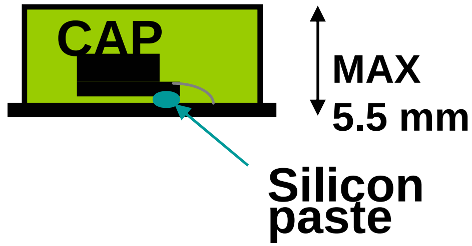
HASI PPI – Vaisala Barocap sensors

PPI sensors (3 Multicaps of 8 frequency output channels)

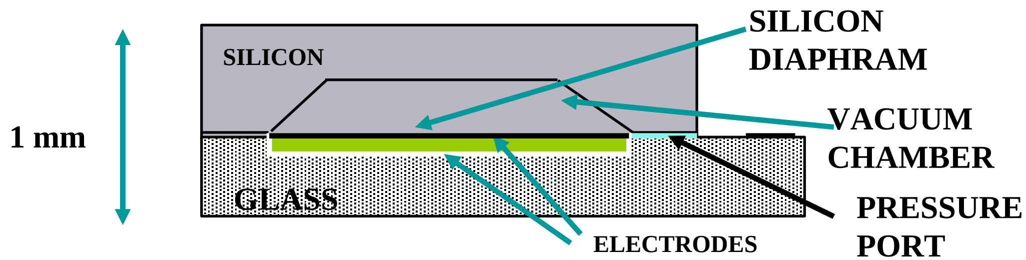
- 8 silicon capacitive absolute pressure sensors (**Barocaps**) in 3 different pressure sensitivity ranges (low, medium, high mode)
- 7 constant and 6 reference sensors (high stability capacitors)
- 3 temperature capacitive sensors (**Thermocap**) for thermal compensation
- Variation of pressure causes changes in the head capacitance that is converted into frequency.

Sensor housing





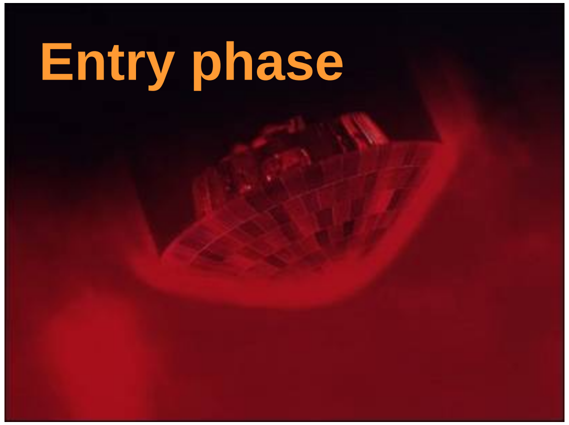
HASI PPI Vaisala Barocap



Barocap sensor schematic

range	Resolution	Accuracy
Low (0-400 hPa)	0.01hPa	1%
Medium (0-1200 hPa)		
High (0-1600 hPa)		

HASI measurements at Titan

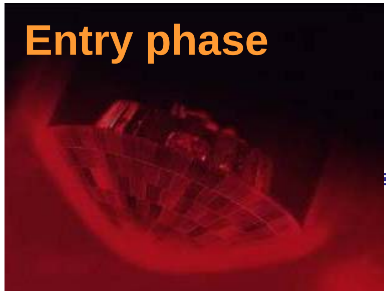


- *From ~ 1500 to 160 km*

  atmospheric physical properties from **accelerometer data**

- *From ~ 160km down to surface descent under parachute*

  T & **p** directly measured by sensors having access to the unperturbed field outside the probe boundary layer.
  PWA booms deployed: direct measurements of **electrical properties** and **acoustic recording**



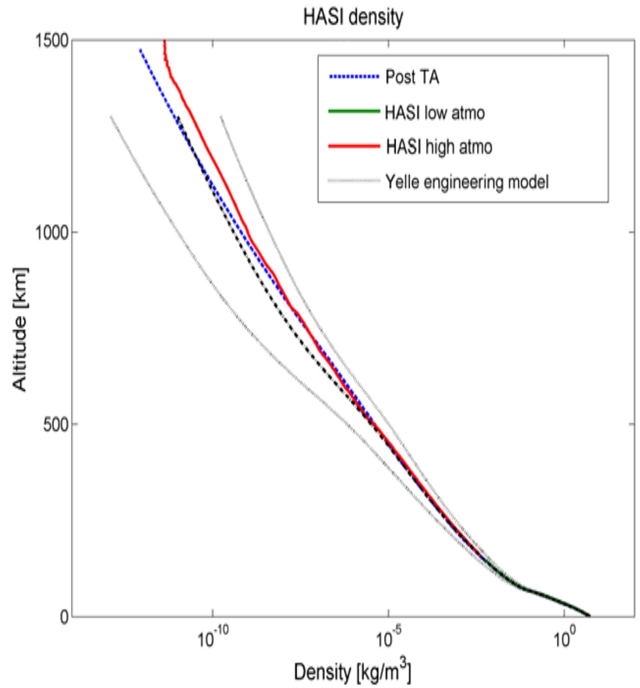
Upper atmospheric profile

From acceleration measurements

density profile from the top of the atmosphere (1570 km) to parachute deployment at ~ 160 km

$$\rho(z)=-2(m/C_DA)(a/V_r^2)$$

V_r and **z** from measured acceleration & initial conditions



Credit: ESA / ASI / UPD / OU /

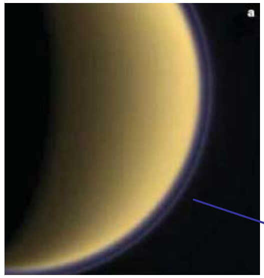
Indirect **temperature** and **pressure** measurements

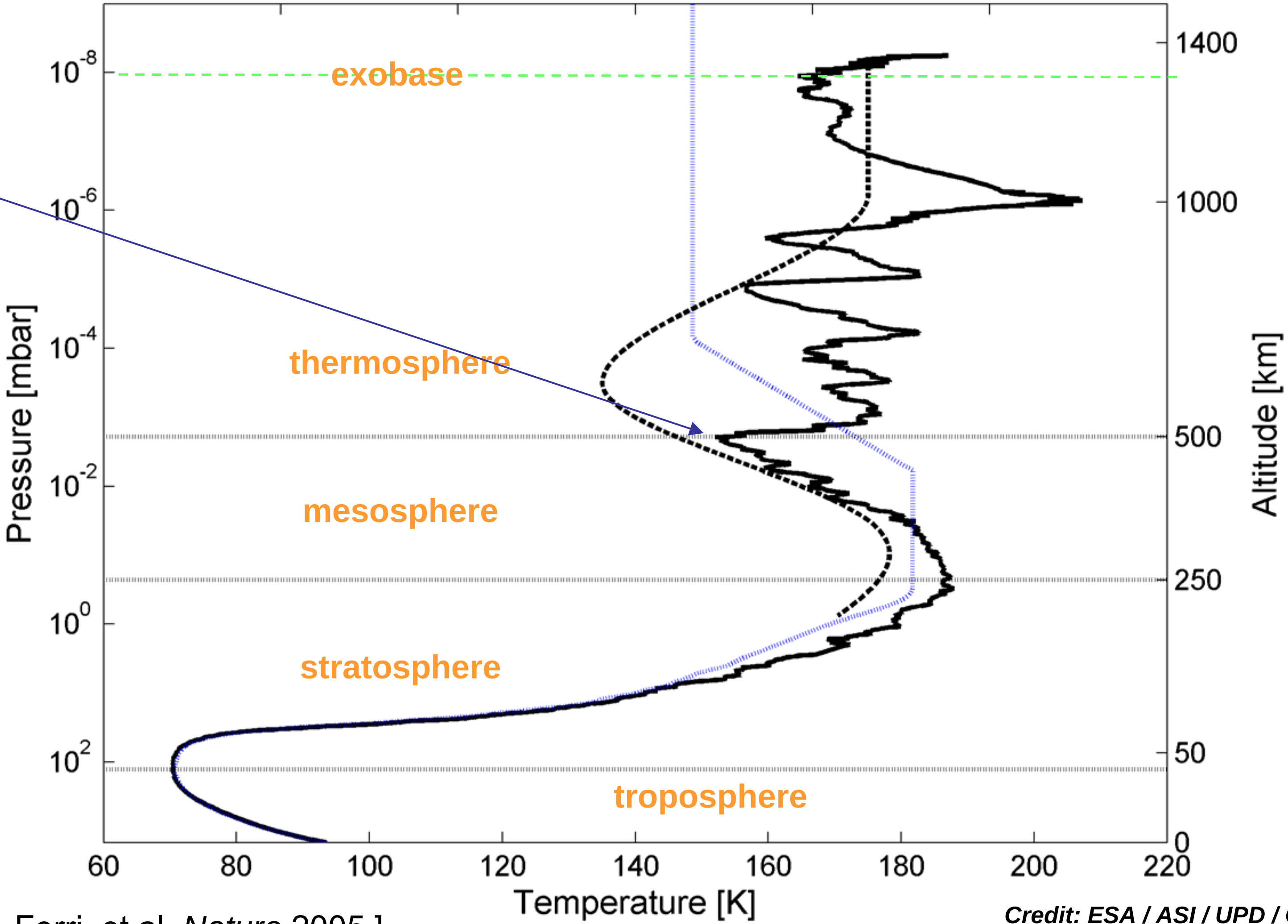
Hydrostatic equilibrium $dp=-g\rho dz$ ➡ $p(z)$

Equation of state of gas $\rho= \mu p/RT$ ➡ $T(z)$, $T=\mu p/\rho R$

[Fulchignoni, Ferri et al. *Nature* 2005]

HASI temperature profile





[Fulchignoni, Ferri et al. *Nature* 2005]

Credit: ESA / ASI / UPD / OU / FMI

HASI Mission Timeline

ENTRY
from higher than 1270 km to 170 km;
Tacc=Probe-ON +21min 30s to T0 (expected at 28 min)

DESCENT
from Tdata=T0+10s to surface
DESCENT 1st state from Tdata to TdataH=T0+2min 30s
DESCENT 2nd state from TdataH to Tradar=T0+32min
DESCENT 3rd state from Tradar to **last km** (~T0+2h12min)
IMPACT state from last km to surface (~T0+2h14min)
SURFACE state from ACC impact detection to link loss

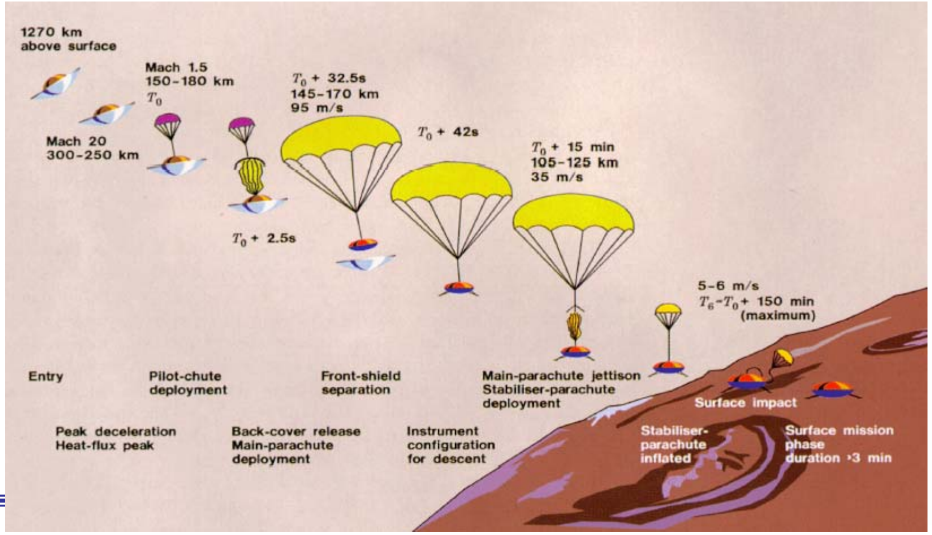


Table I: NOMINAL MISSION TIMELINE

T0-6.5 min

DDBL TIME or ALTITUDE	EVENT NAME	HASI EVENT DESCRIPTION
17:46	Thasi (-5min before Entry)	HASI power-ON START-UP mode start
18:06	----	TITAN DESCENT mode start (ENTRY state)
21:30	TaccSample	ACC sampling start
28:00 00:00	T0 ----	Mortar firing DDBL time reset
00:43	----	2nd HASI Power on
00:49.655	Teon	Protected power on
~~01:00~~ T0-10 s	Tdata Td1	TEM sampling start Low PREssure measurement start 1st BOOM release attempt window start (DESCENT 1st state)
01:40	Td1w	1st BOOM release attempt window end
02:20	Td2	2nd BOOM release attempt widow start
02:30	TdataH	Probe relay data link is OK. PWA sampling (mode A) start (DESCENT 2nd state)
03:20.645	Teoff	2nd BOOM release attempt widow start Protected power off
10:00	Tswitch	Switch HASI TM packet allocation.
32:00	Tradar	Proximity sensor sampling (PWA mode C) start (DESCENT 3rd state)
1:15:00	Tmid	Medium PREssure measurement start
1:45:00	Thigh	High PREssure measurement start
7 Km	----	PWA mode D
1 Km (132 min (*))	----	ACC TM data stop (IMPACT state)
200 m	----	PWA mode D, with RELaxation experiment stopped
Impact detected by ACC servo (134 min (*))	Timpact	ACC impact trace PWA mode G ACC TM data restart (SURFACE state)
+TBD min	Tloss	Loss of Radio Link (END OF MISSION)

HASI during DESCENT phase

Starting from ~162 km, descent under parachute

T & p directly measured by sensors having access to the unperturbed field outside the probe boundary layer.

PWA booms deployed: direct measurements of electrical properties and acoustic recording

<u>Huygens radar altimeter</u> :
HASI-PWA radar return signal elaboration from ~30 km; lock expected at ~20 km

Lower atmosphere: atmospheric structure

Starting from 162 km, descent under parachute

From measured p & T, assuming hydrostatic equilibrium

$$dp = -g\rho dz = -(pg/RT)dz \qquad (1)$$

Altitudes & velocities as fz of time:

$z(t)$ integrating (1)

$v(t) = dz/dt = -(RT/\mu gp)(dp/dt)$

Dry adiabatic atmosphere

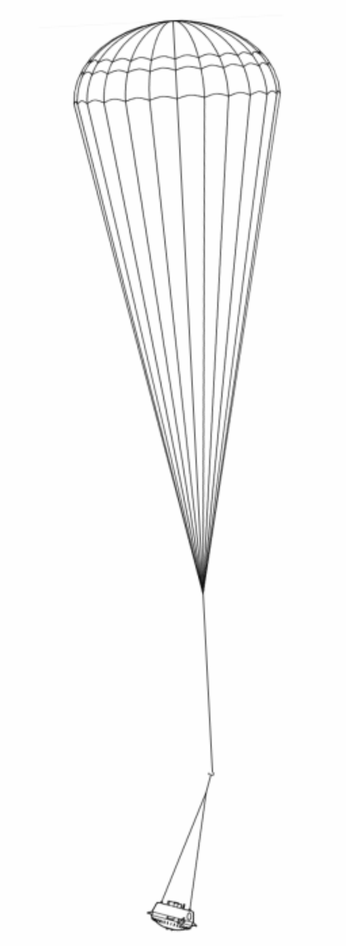
$\rho(z)$ from equation of state

$p = \zeta\rho RT$ — ζ compressibility factor

$\mu(p)$ & $R(p)$ — μ from GCMS

Lapse rate $dT/dz = -(g/R)(d\,ln T/d\,ln p)$

Trajectory determination



DESCENT

– Integration starting from **hydrostatic equilibrium + real gas** (PPI and DTWG approach)

$$-\frac{dp}{p} = \frac{mg}{RT(1+Z)}dz \qquad (1)$$

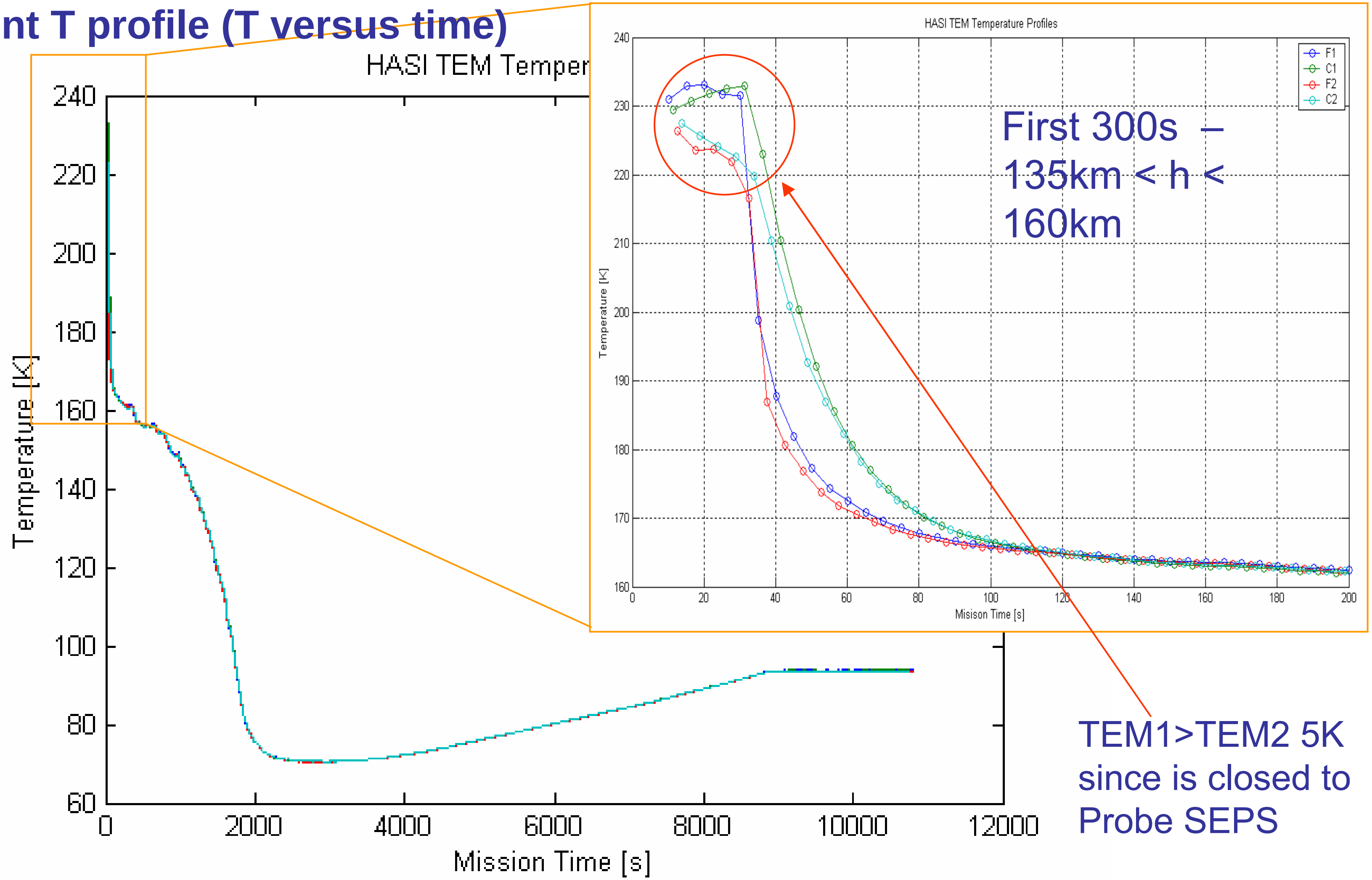
(1) from ground up => rough estimate of descent profile

hence given g(t), iterative integration of (2) from up to down

$$a = -g\hat{e}_r - \rho v v \frac{SC_D}{2M} \qquad (2)$$

HASI TEM at Titan

Descent T profile (T versus time)

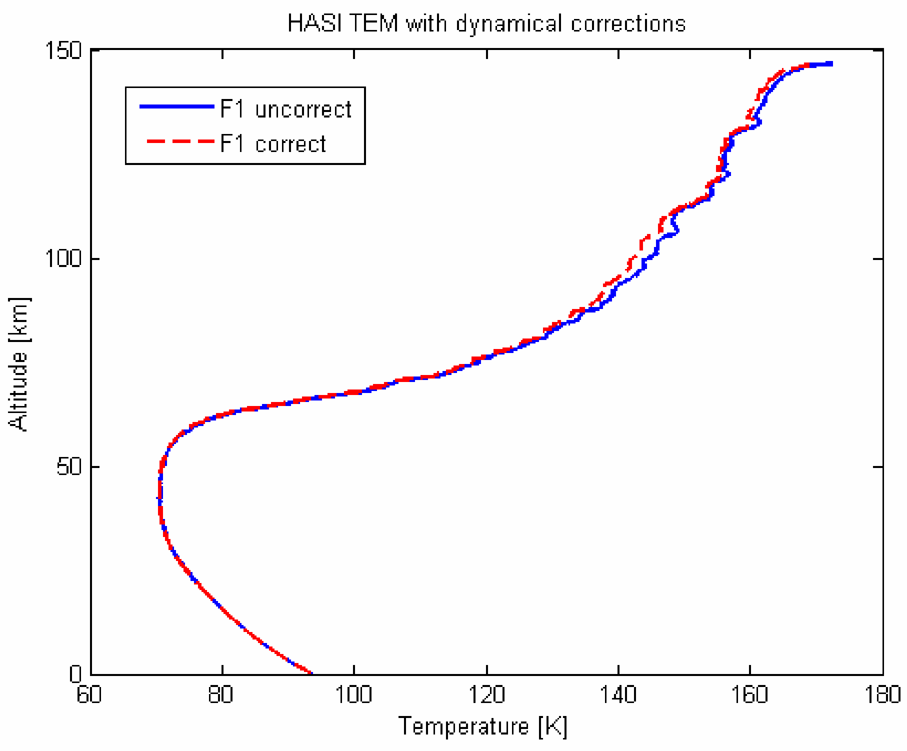


Dynamic corrections

- Dynamic corrections to derive static p & T from total values:

$$T_{stat} = \frac{T_{meas}}{\left(1 + r\frac{\gamma - 1}{2} Ma^2\right)}$$

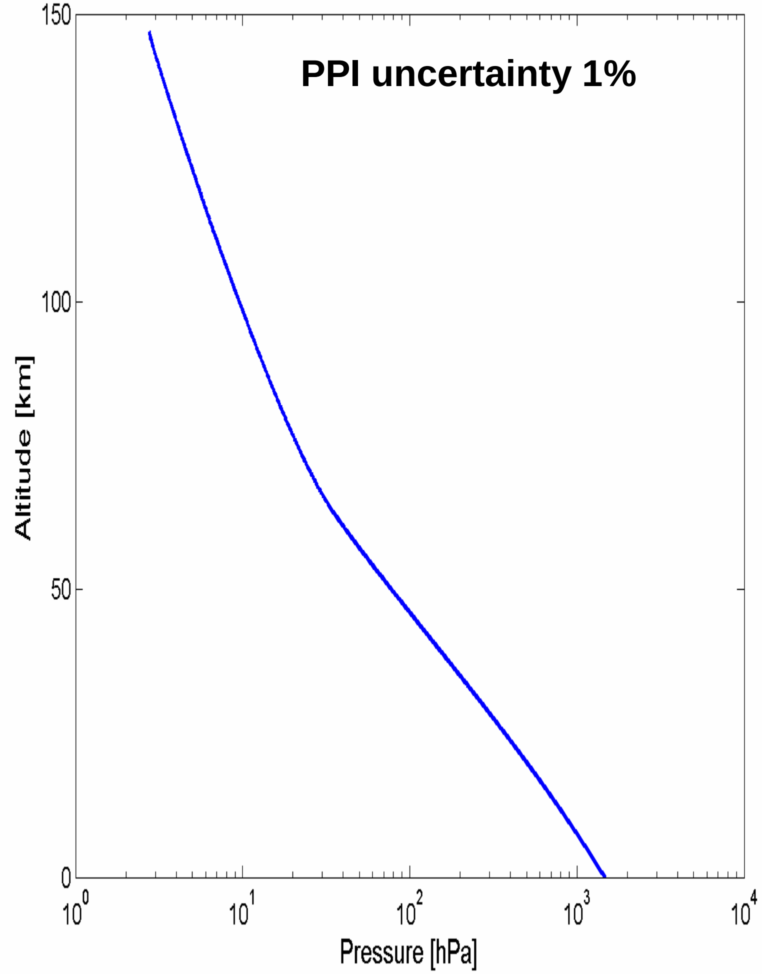
$$p_{stat} = p_{meas}\left(1 + \frac{\gamma - 1}{2} Ma^2\right)^{\frac{\gamma}{1-\gamma}}$$

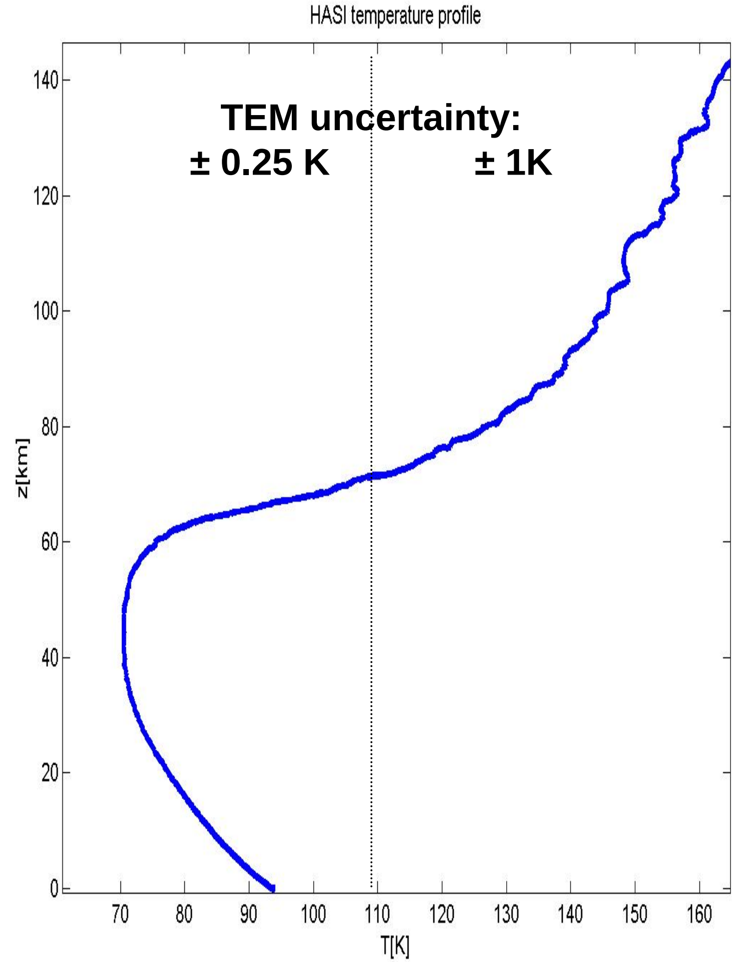


$\gamma = {c_p}/{c_v}$ ratio of the specific heat co

Ma Mach number,
r recovery factor, determine by experimental calibration.

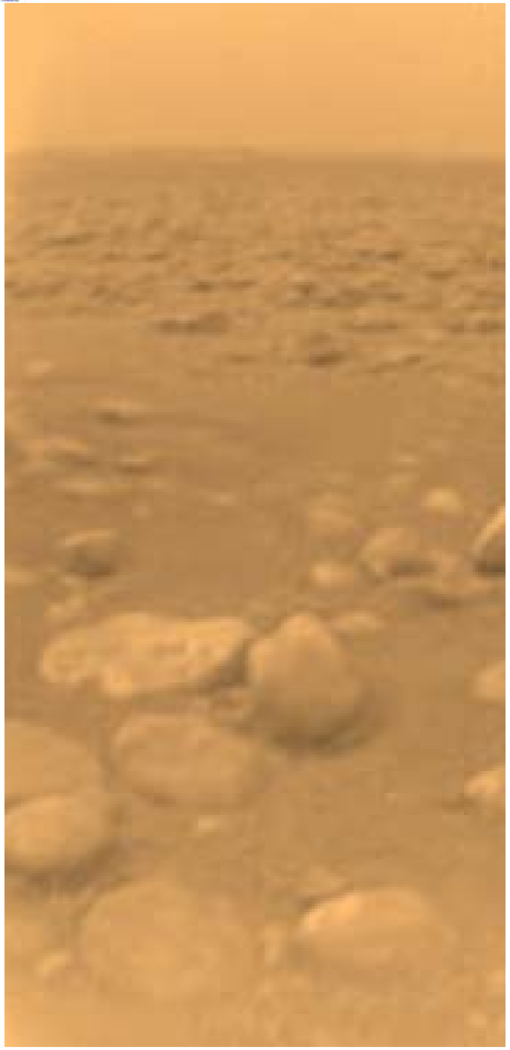
HASI descent phase





Credit: ESA / ASI / UPD / FMI

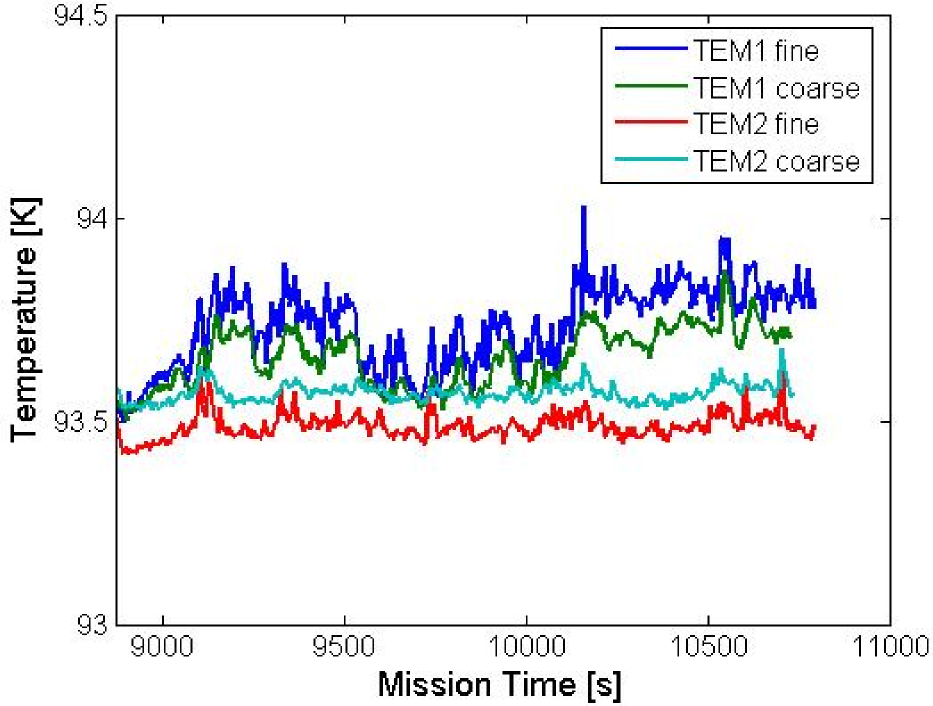
HASI surface phase



ESA/NASA/JPL/University of Arizona

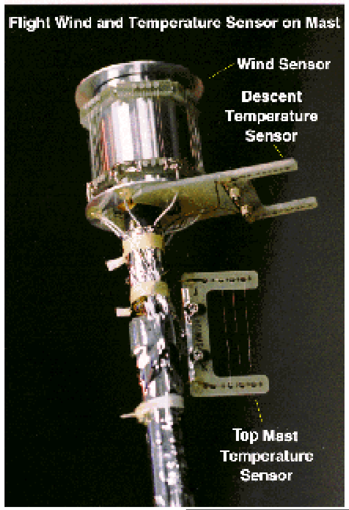
Meteo at Titan's surface:

- **Temperature 93.65±0.25 K**
- **Pressure 1467±1 hPa**



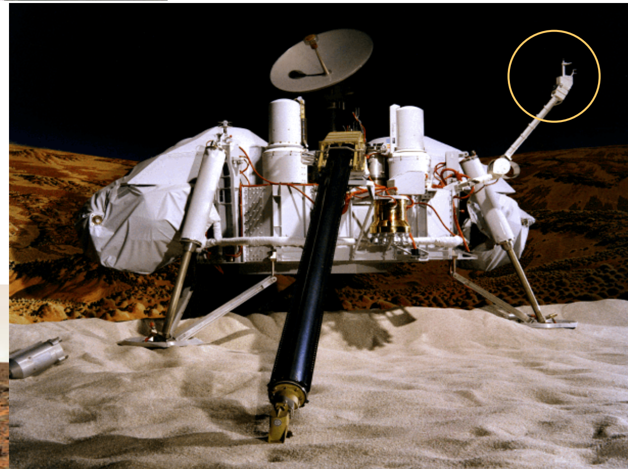
Temperature measurements near Mars surface

- The only existing in situ measurements of the atmospheric temperatures near the surface of Mars by **Viking landers** [Seiff & Kirk, 1977] & by **Pathfinder** [Schofield et al., 1997].
- Simultaneous T measurements from more than one level by Pathfinder ASI/MET
- Temperature in situ measurements together with pressure and wind velocity measurements are fundamental for studying the meteorology and the planetary boundary layer on Mars, and also for the investigation of the Martian atmospheric structure and dynamics.

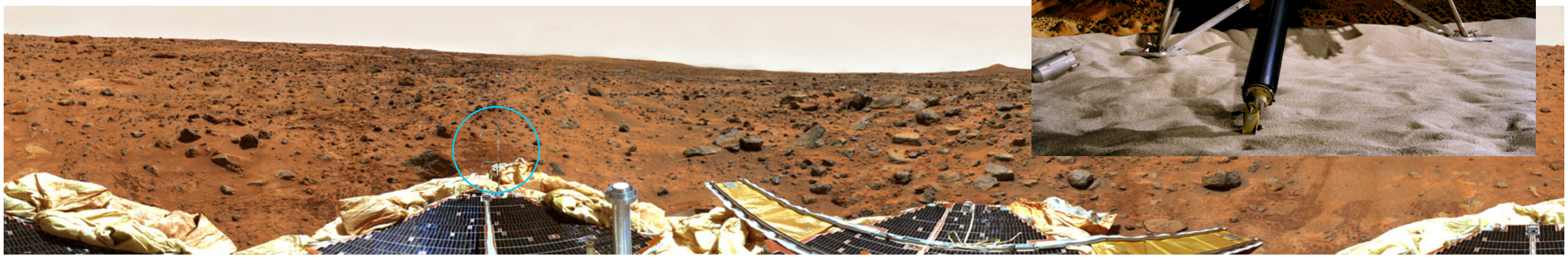


☹ No ASI / environmental sensors on MER

NASA Viking



NASA Pathfinder



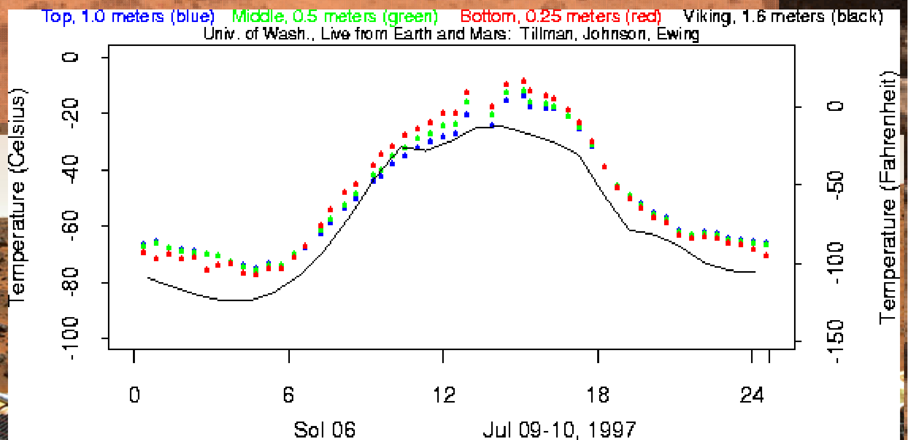
Direct temperature measurements on Mars

Problems

- **Mars' atmosphere is thin (ρ~0.02 kg/m3) and has a low heat capability =>**
  - **weak thermal coupling between T sensors & atmosphere**
  - **sources of thermal contamination (e.g. conduction to the support frame, solar and radiative heating of the sensing elements) affect T measurements (many conventional temperature sensors for terrestrial meteorology could operate as bolometers than kinetic temperature sensors)**
- **Sandblast, dust abrasion can stretch, deform sensing element compromising mechanical hardness and calibration.**

Surface T range at Mars: **~140-300 K**
263-197 K [Pathfinder ASI/MET]

Proposed for ESA ExoMars 2016
Accuracy: 0.1 K Resolution: 0.04 K



Temperature measurements

Requirements for T sensors

- Durability
- Accuracy
- Fast response time

<u>Suggested sensor types</u>

Commercial

–Unsheathed fine gage thermocouples (TC)

or

–Platinum-wire resistance temperature thermometer (PRT)

Both have a thin wire as sensing element (subject to breackage). TC more fragile than Pt wires.

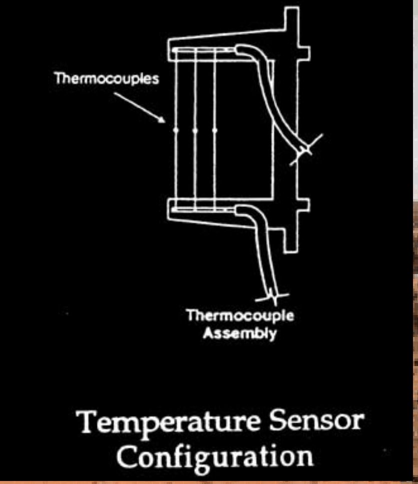
Short response time <-> very fine wire => more vulnerable to breackage

VK & MPF: thin-wire (75μm) chromel-constantan (E-type) TC;

3 sensing elements per sensor <-> triply redundant to insure against breakage

Commercial PRT exists with Pt wire wound around a ceramic or glass core, hermetically sealed in glass capsule (to resiste contamination and insuring mechanical & electrical stability) => thermal coupling with atmosphere is weaker than with free wires.

Mars Pathfinder ASI



Temperature measurements

TC vs PRT

TC

- **TC more fragile than Pt wires. Redundancy to insure against breakage.**
- **TC are differential sensors => to perform T measurements, a reference junction with absolute T sensor (PRT) is needed.**

PRT

- **Standard thermometer: International Practical Temperature Scale (ITS) is based on Pt resistance.**
- **if stretched, Pt wire could change calibration.**
  Wire stretching could be evaluated by intercomparing two sensing elements units (primary & secondary elements of a double resistance sensor)
- **Glass encapsulated probes => no contamination, mechanical & electrical stability, but weaker thermal coupling with atmosphere than free wires**
- **Pt-resistance thermometers operate on the principle of change of electrical resistance as a function of T**

Temperature measurements

TC vs PRT

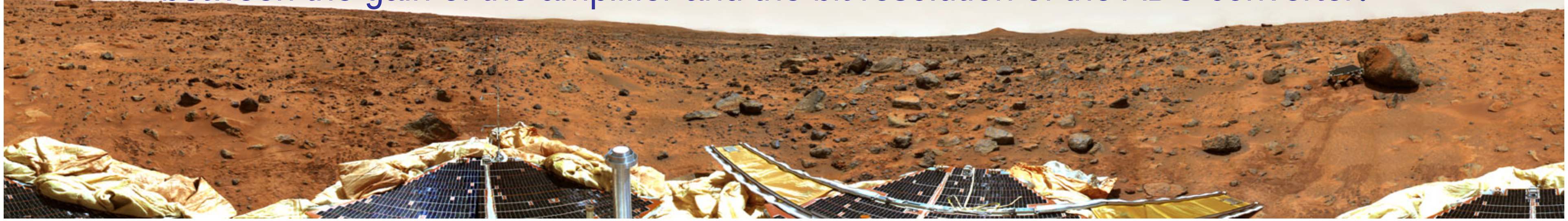
Electronics

TC need a reference junction with absolute T sensor.

PRT: T measurements through 4-wires measurements at the ends of the thermoresistance and of a reference R or inserting the thermoresistance in a leg of the Wheastone bridge circuit.

A multiplex could allow to sample different sensors with mainly the same electronics.

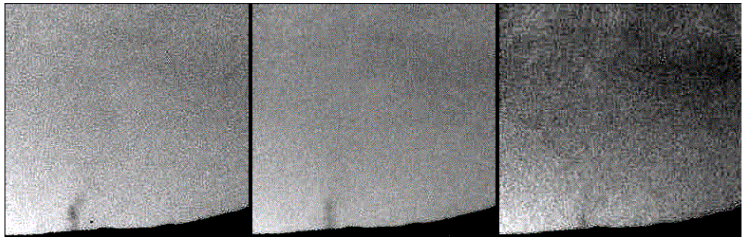
Accuracy of 0.1 K and resolution of 0.04 K in the Martian surface temperature range can be achieved with both the sensor types, trading between the gain of the amplifier and the bit resolution of the ADC converter.

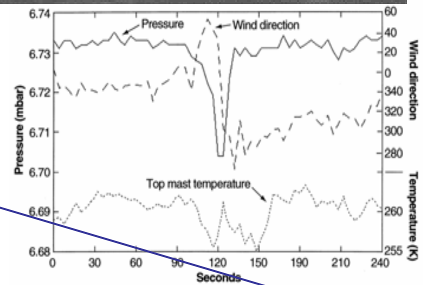


Dust devil detection by in situ measurements

Dust devils (low-pressure, warm core convective vortex that loft dust from surface) are common events on Mars

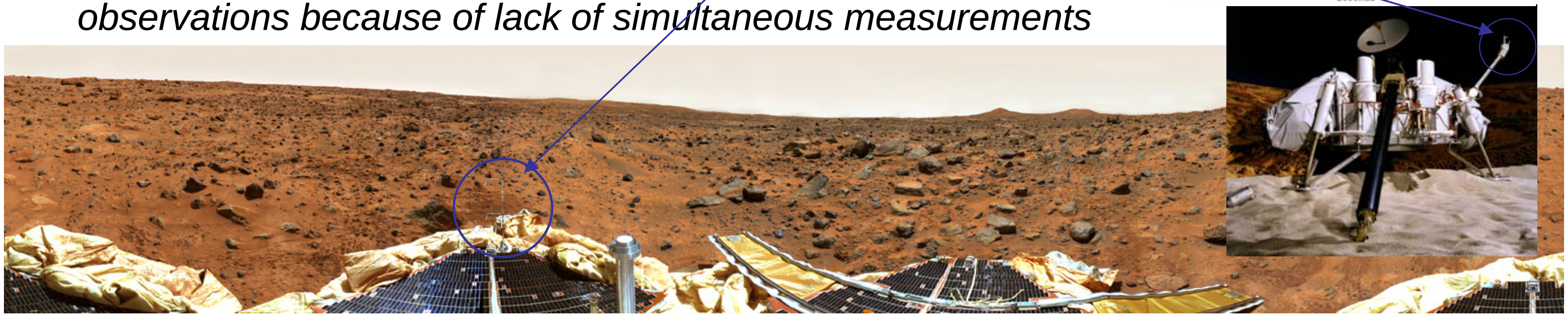
Dust plumes in the images of the Pathfinder and MER



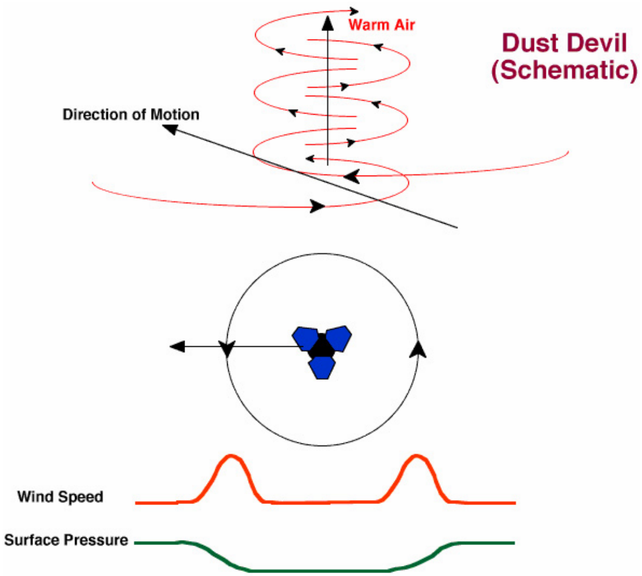


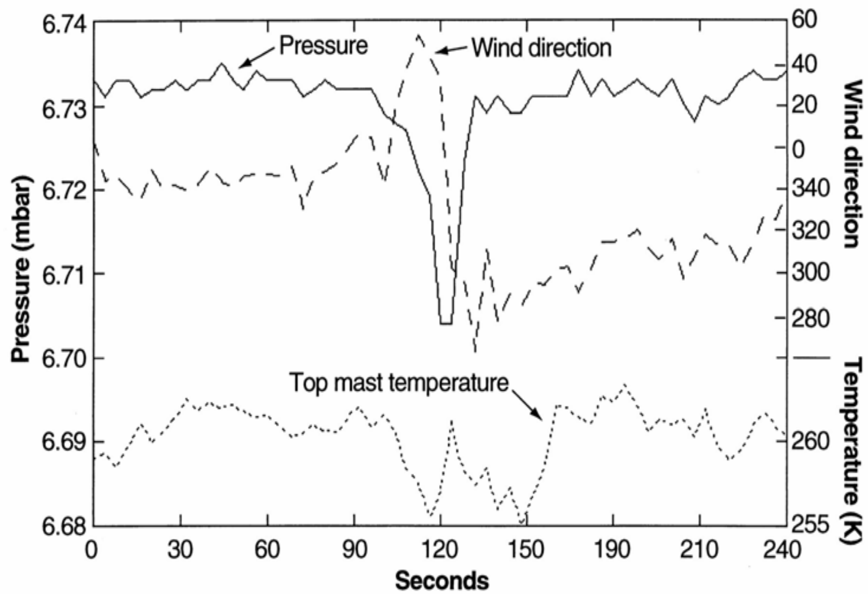
Several **events in meteorological records** by ASI/MET of Viking 1&2 and Pathfinder

None of these events could be put in relation with visual observations because of lack of simultaneous measurements



Dust devil signature on meteorological data





The rapid pressure minimum accompanied by shifts in wind direction recorded during the passage of a dust devil on the Pathfinder ASI/MET Pathfinder ASI/MET [Schofield *et al.*, 1999]

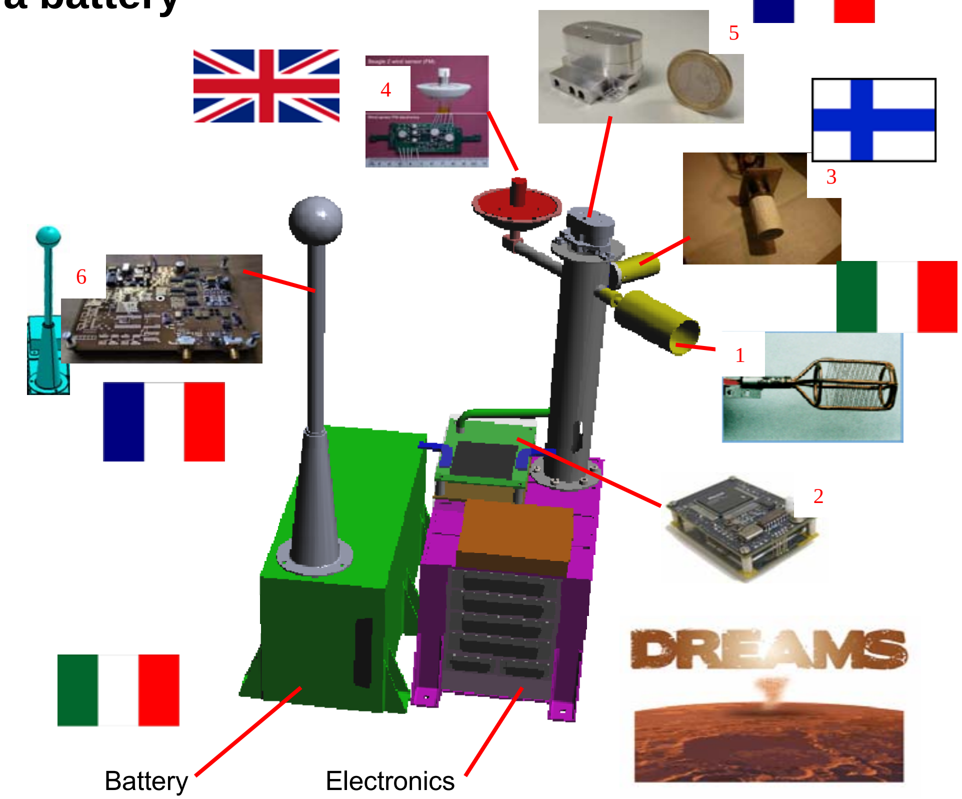
The passage of a convective vortex leaves a typical signature on pressure and wind measurements: a drop in atmospheric pressure associated with rotating wind vector. Short term variations in measured surface pressure, wind direction and air temperature over periods of tens of seconds

EXoMars EDM 2016
DREAMS Surface Package

The DREAMS Surface Payload is a complete meteorological station comprising six sensors, a battery and electronics.

- **MarsTEM**– atmospheric temperature sensor (I)
- **MetBaro** – atmospheric pressure sensor (Fin)
- **MetHumi** – atmospheric humidity sensor (Fin)
- **MetWind** – wind sensor (UK)
- **ODS** – optical depth sensor (F)
- **MicroARES** – atmospheric electricity sensor (F)

☹ *no direct atmospheric measurements during descent*



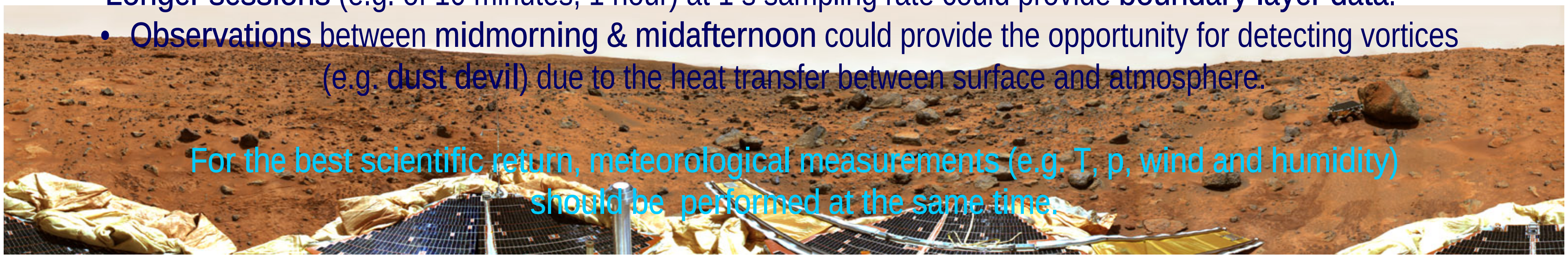
DREAMS can demonstrate high technology readiness, based on existing European heritage from Huygens, Beagle 2, Humboldt and Phoenix

Meteo/environmental sensors for ExoMars

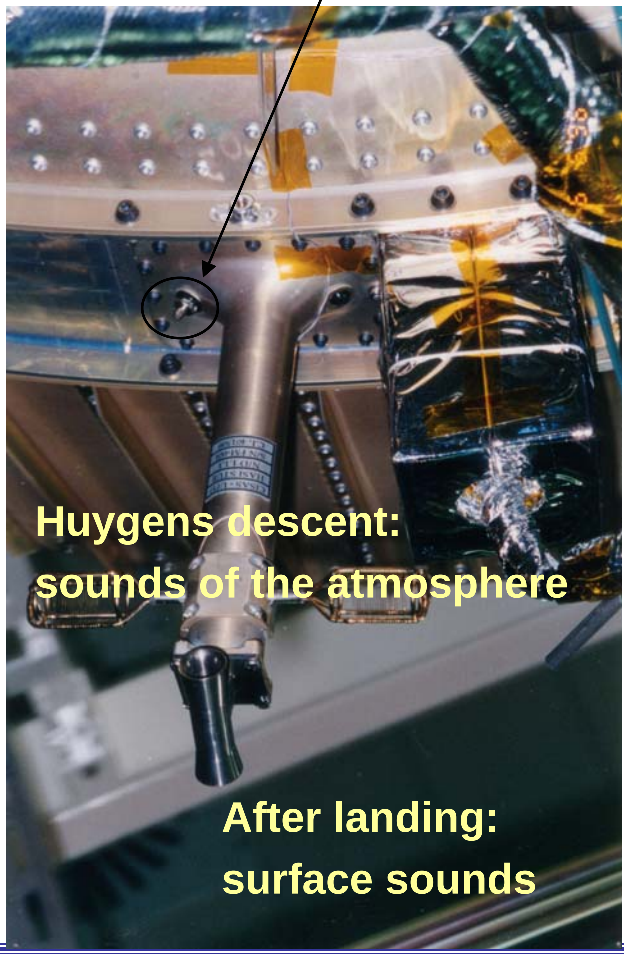
Sampling rate and observational strategy

- Locating **sensors at different heights** on the rover (e.g. by mean of a mast, or under, at middle height and on the top of the rover) -> simultaneous temperature measurements from more than one level, in order to resolve **vertical gradients** in the near-surface temperatures.
- The surface measurements (e.g. T, pressure, & wind velocity) aimed to
  (1) record Martian meteorology &
  (2) get data for the study of the surface boundary layer.
- Meteorological record requires measurements on different timescales with a good coverage on local time, whereas the boundary layer measurements require periods of continuous rapid sampling.
- In order to detect temperature fluctuations and atmospheric phenomena, such as vortices, a sampling rate of 5 s or less is requested.
- **Observation strategy** organised in **sessions**, and sampling the sensors only at special sols or time (data rate and power limitations surely prevent continuous rapid sampling).
- For **meteorological record short session** (few minutes) of 5 s sampling rate equally spaced during a sol can be performed.
- **Longer sessions** (e.g. of 10 minutes, 1 hour) at 1 s sampling rate could provide **boundary layer data.**
  - **Observations** between **midmorning & midafternoon** could provide the opportunity for detecting vortices (e.g. **dust devil**) due to the heat transfer between surface and atmosphere.

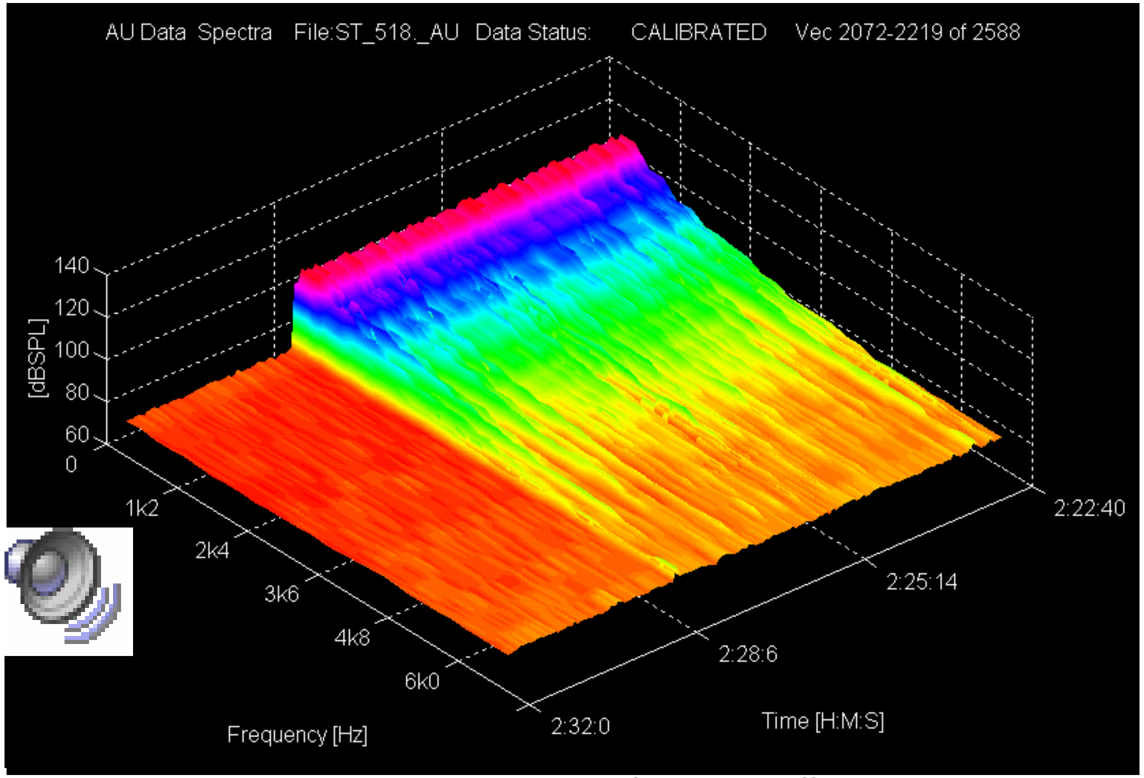
For the best scientific return, meteorological measurements (e.g. T, p, wind and humidity) should be performed at the same time.



Acoustic sensor / microphone



HASI – ACU Acoustic pressure transducer
to detect acoustic noise, turbulence and meteorological events (e.g. thunderstorm, hail, rain)



Dynamic spectrum of acoustic differential pressure.
Sound pressure level of 0 dB corresponds to 20 μPa

Credits: ESA / ASI / UPD / RSSD / IWF / CNRS / IAA