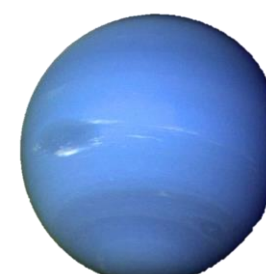
IPPW2019 Short Course: Ice Giants

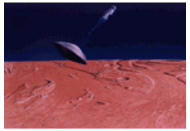
Instrumentation – Atmospheric Structure Instrument (ASI) for *in situ* measurements by an entry probe

Francesca Ferri
Università degli Studi di Padova
Center for Space Activities and Studies "Giuseppe Colombo" (CISAS)



Atmospheric entry probes

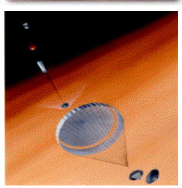
Viking



Pioneer Venus

Galileo

Mars Pathfinder



Huygens

Entry probes allow for sounding atmospheric regions not reachable by remote sensing.
In situ measurements over a wide altitude range and with spatial resolution not achievable by remote sensing observations

- Few robotic probes have successfully entered the atmosphere (and landed) on planetary bodies:
  - **Mars** (USSR Mars 6, NASA Viking 1&2, Pathfinder, MER1&2, Phoenix, MSL, ExoMars2016 Schiaparelli EDM, InSight)
  - **Venus** (NASA Pioneer Venus, USSR Venera probes & Vega lander/balloons)
  - **Jupiter** (NASA Galileo probe)
  - **Titan** (ESA/NASA Huygens probe)

Experience *and* ***lessons*** *learned with* ***Huygens*** *in perspectives for* ***Ice Giants*** *in situ exploration.*

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

Entry

Descent

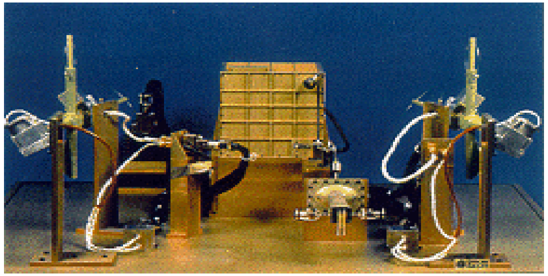
Landing

14th January 2005
Cassini-Huygens probe at Titan

- 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 can determine **density**, **pressure** and **temperature** as function of height from the upper atmosphere down to the troposphere and surface.
- The **atmospheric vertical profiles** allow resolving **vertical gradients** in order to investigate the **atmospheric structure and dynamics**

- ASI is a multi-sensor package for *in situ* measurements by an atmospheric entry probe or lander.
- *Historical 'father' of ASI instrument Dr. Alvin Seiff of NASA AMES (e.g. Viking landers, Pioneer Venus probes, Mars Pathfinder, Galileo).*

Huygens Atmospheric Structure Instrument (HASI)

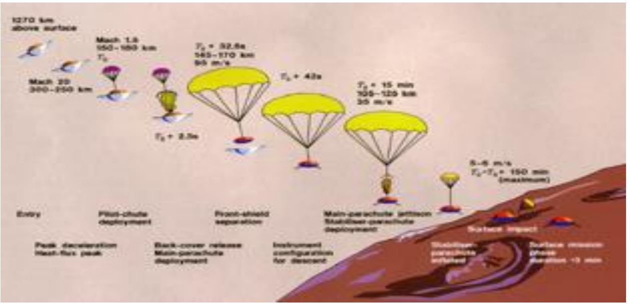


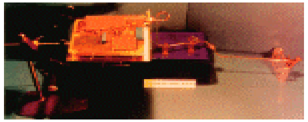
Principal Investigator: M. Fulchignoni

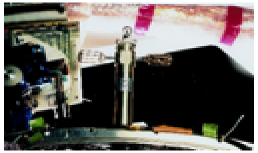
Study of Titan's atmosphere and surface by measuring:

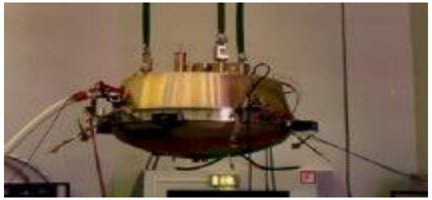
- **acceleration** (ACC)
- **pressure** (PPI)
- **temperature** (TEM)
- **electrical properties** (PWA, RAU)

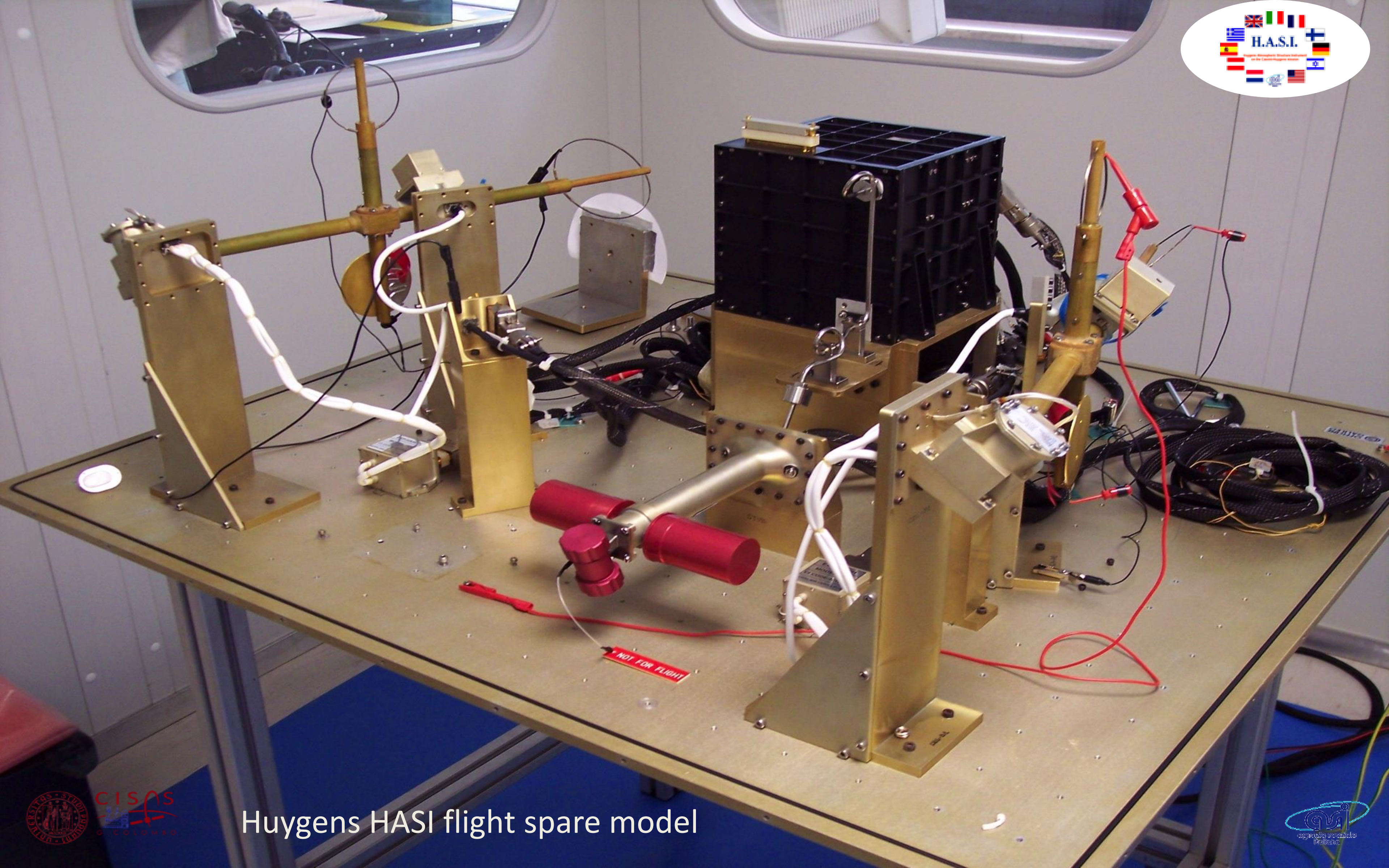
Heritage: Pioneer Venus, Venera, Galileo, and Viking probes







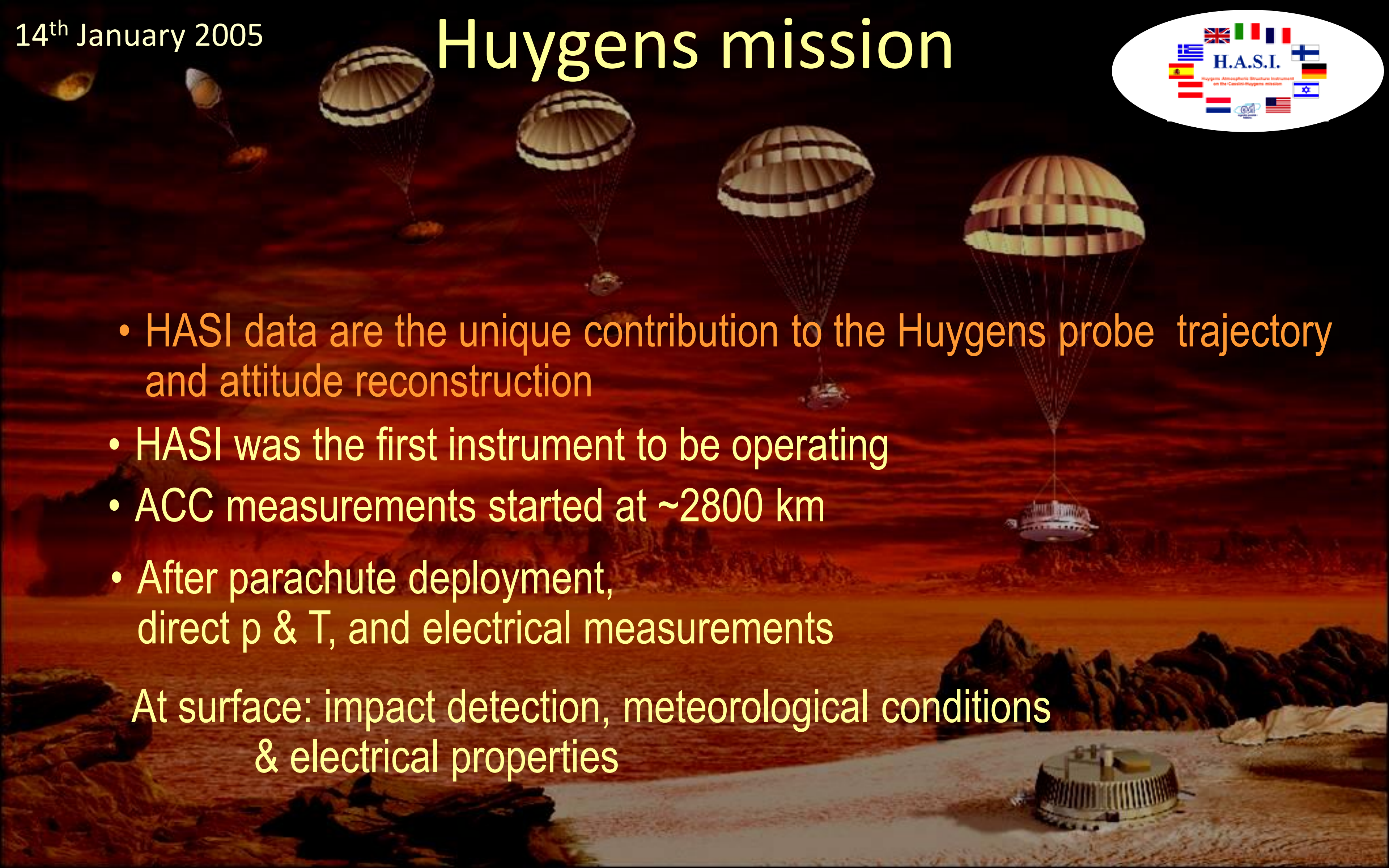




Huygens HASI flight spare model

14th January 2005

Huygens mission



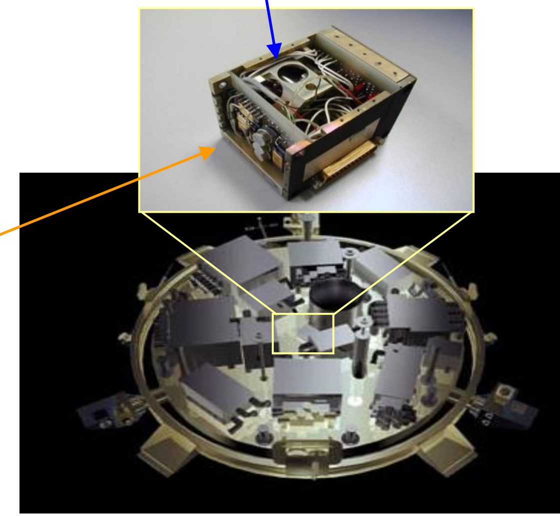
- HASI data are the unique contribution to the Huygens probe trajectory and attitude reconstruction
- HASI was the first instrument to be operating
- ACC measurements started at ~2800 km
- After parachute deployment, direct p & T, and electrical measurements

At surface: impact detection, meteorological conditions & electrical properties

HASI ACC subsystem

- **1 servo accelerometer** (SUNDTRAND, now Honeywell QA 2000-30) on X axis (the Probe spin axis) with switchable range

Mode	Range		Resolution	
	High Gain	Low Gain	High Gain	Low Gain
High resolution	±2 mg	±20 mg	0.3 µg	3 µg
Low resolution	±1.85 g	±18.5 g	0.3 mg	3 mg

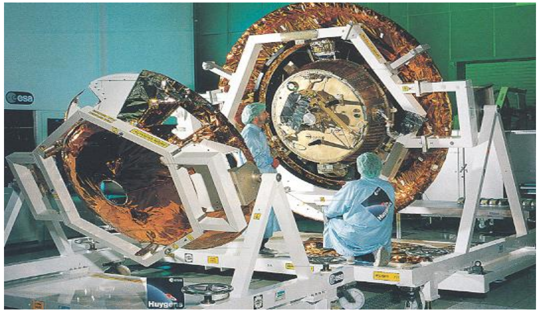


- **3 piezo-resistive accelerometers** (ENDEVCO 7264A-2000T) on the X, Y or Z axes of the Probe
- **2 AD 590 temperature sensors**, one inside the servo accelerometer case (Temp 1) and one attached to the aluminium alloy accelerometer mounting block (Temp 2) for compensation

Main objective: to measure the Huygens probe's **acceleration** and thus to derive **Titan's atmospheric density** profile and for **impact detection**.

HASI ACC testing and calibration

- Sensors have been characterized, tested and calibrated at ACC subsystem, HASI instrument and Huygens probe level.



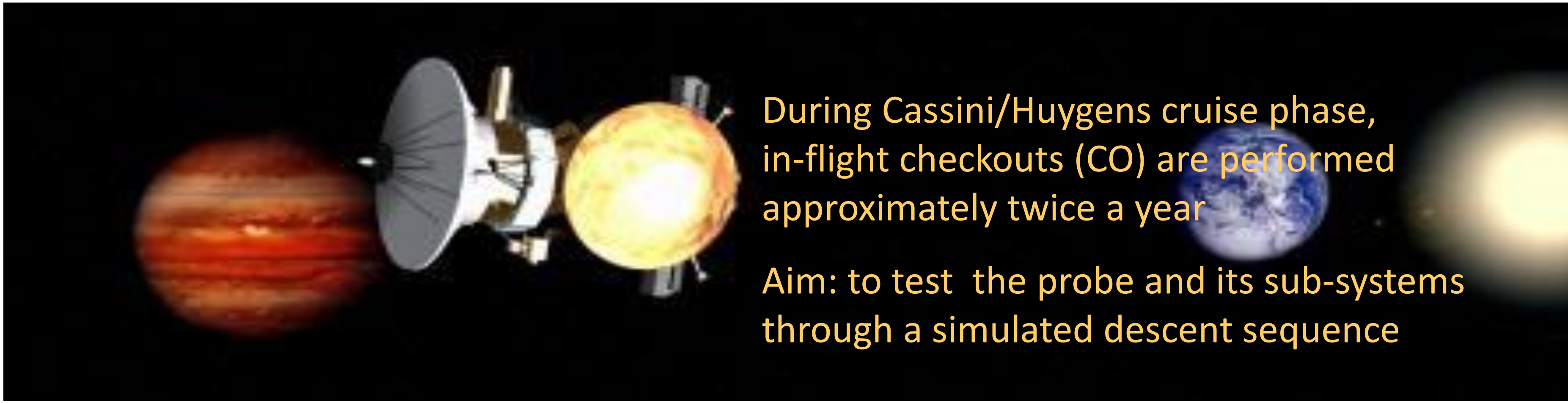
- Beside AIV campaign, a specific special test to characterise the alignment of HASI ACC Servo-to-probe axes has been performed by rotating the probe on a frame in 1-degree steps and recording Servo outputs at each step.

$$a\,(m.s^{-2}) = \left(\frac{1}{sf\,(A/m.s^{-2})} \cdot \frac{a(V)}{R_L(\Omega)} \right) - offset\,(m.s^{-2})$$

$$where:\ sf = scale\ factor,\ R_L = load\ resistor.$$

- Conversion from raw units (*Volts*) to scientific units (*acceleration* in *ms*$^{-2}$)

Huygens In-Flight checkouts

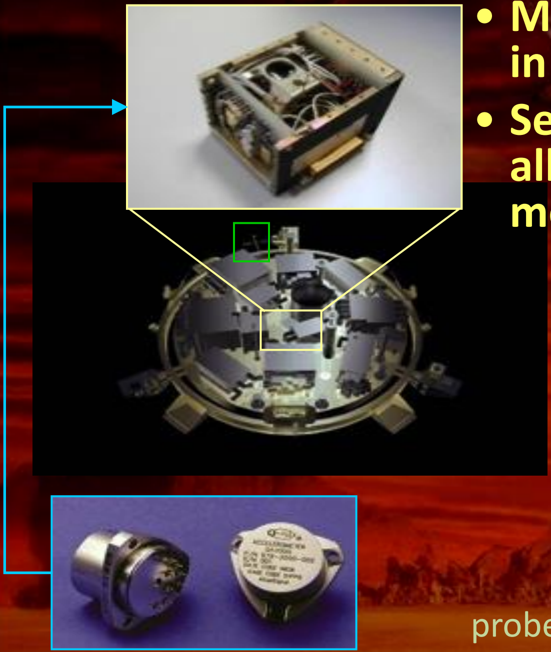


For the HASI-Servo ACC, in-flight checkouts provide an opportunity to monitor the accelerometer's **offset** in a zero g environment and to characterise the **noise** performance.

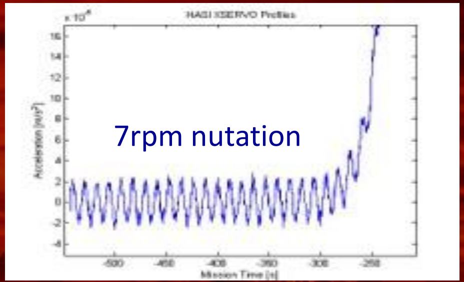
Huygens HASI at Titan

HASI ACC

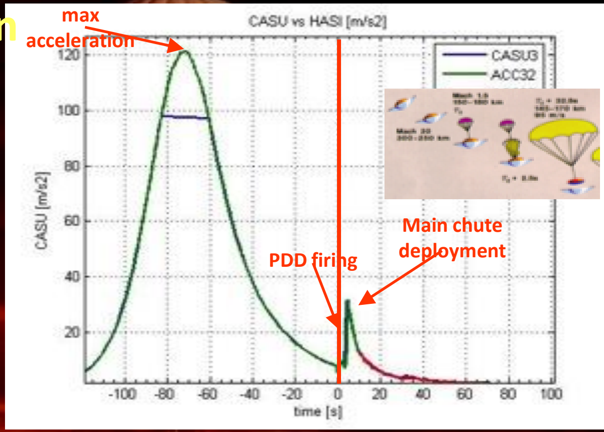
- **Most accurate accelerometer ever flown in a planetary probe**
- **Sensitivity threshold (3E-06 m/s2) allowed measurement of Probe coning motion before atmospheric entry.**



HASI ACC X-Servo *Sundstrand (now Honeywell) QA2000*



Entry & Descent



- **During entry, atmospheric physical properties from acceleration data.**

probe mass (kg)

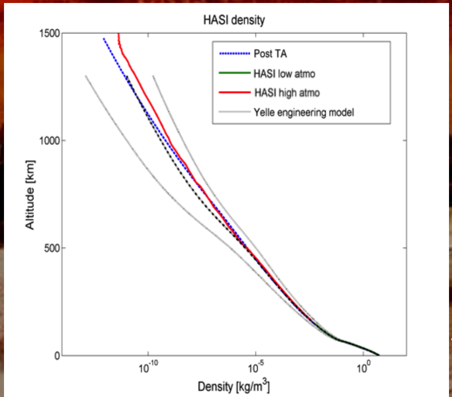
acceleration component in the direction of descent (m/s^2)

$$\rho = \frac{2 m a}{v^2 C_d A}$$

velocity relative to atmosphere in the direction of descent (m/ s)

aerodynamic drag coefficient

probe cross-sectional area (m^2)



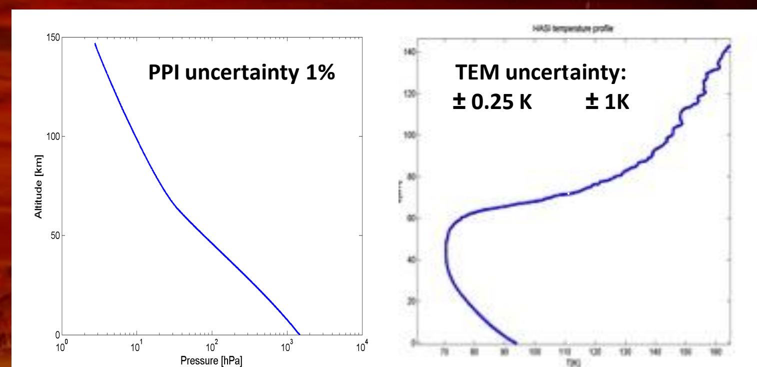
Huygens HASI heritage

Descent

HASI TEM & PPI

Direct pressure and temperature measurements during descent phase under parachute.

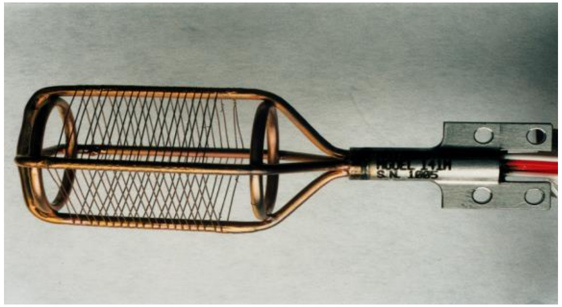
TEM: Pt resistance thermometer
PPI transducers: Vaisala Barocap

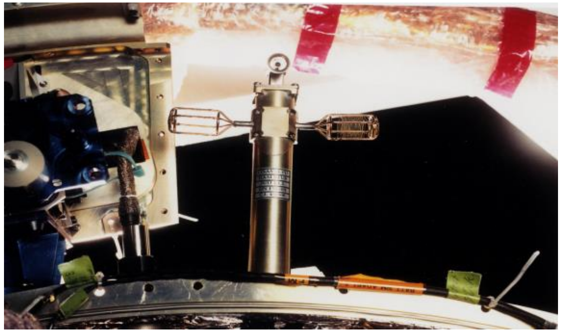


Huygens TEM

HASI PWA booms deployed: direct measurements of **electrical properties** & **acoustic recording**, radar altimetry

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 and for checking its calibration.
- Temperature measurement by monitoring resistance (wrt reference resistor; I=25 mA, pulsed 100ms)

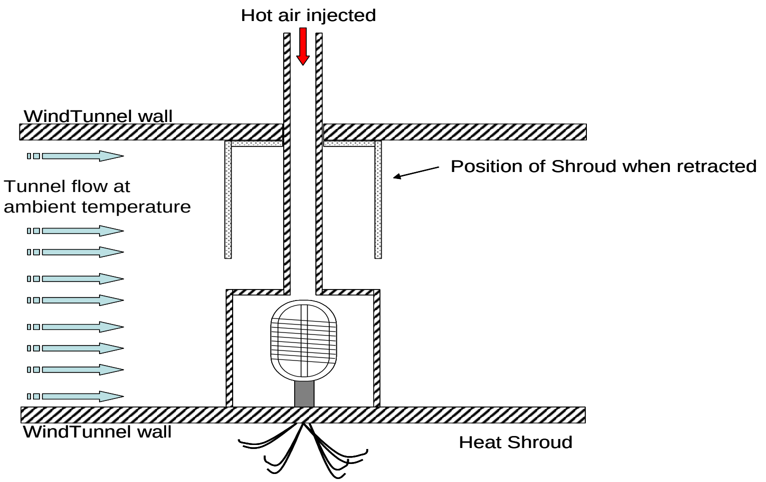
range	Resolution	Accuracy
Low T (60-110K)	0.02K	0.02K
High T (100-330K)	0.06K	0.2K

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

Heritage: NASA Pioner Venus [Seiff et al. 1980], Galileo ASI [Seiff & Knight 1992]
USSR Venera and VeGa lander/aerostats

HASI TEM calibration and characterization

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



- Sensor model: 2[nd] order instrument

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

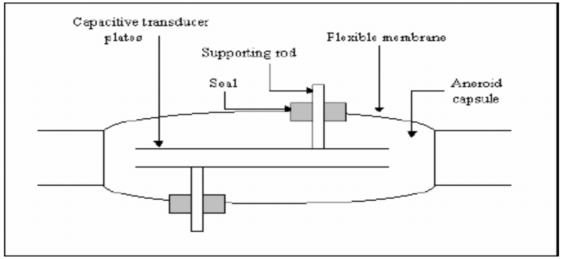
where T_w= sensing wire temperature, T_a= atmospheric fluid temperature
τ response time: τ_1 wire response time, τ_3 supporting frame response time,
τ_2 thermal coupling wire and supporting frame

Pressure sensors

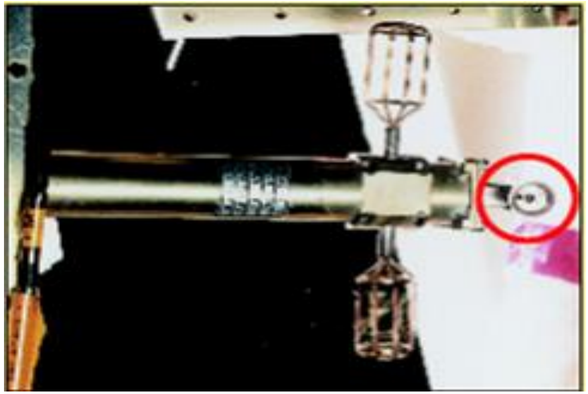
Vaisala Barocap sensors

- Silicon capacitive absolute pressure sensors
- Lightweight and robust
- Sensors commonly used on radiosondes flown on stratospheric balloons
- Used on **Huygens**, **Beagle2**, **Mars-96**, **Mars Polar Lander**, **Phoenix**, **MSL**, **ExoMars2016** EDM, **ExoMars2020** & **Mars2020**

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



HASI PPI Kiel probe



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%

H.A.S.I.
Huygens Atmospheric Structure Instrument on the Cassini-Huygens mission

HASI Pressure Profile Instrument (PPI)

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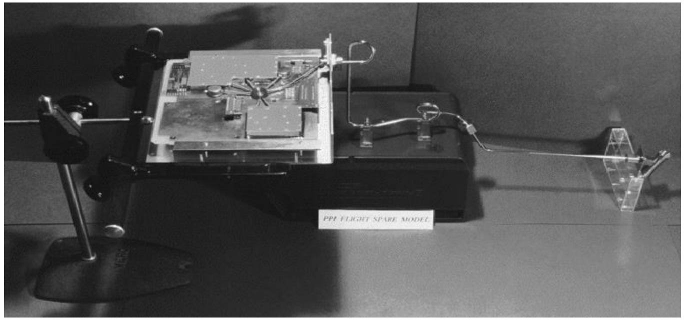
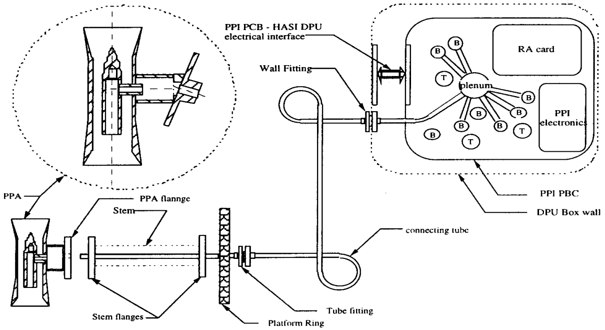
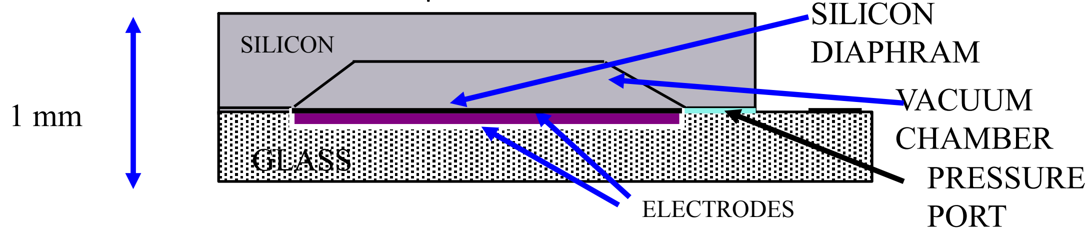
- The atmospheric flow is conveyed through a **Kiel probe** inside the DPU where transducers and electronics are located.
- **PPI** transducers are silicon capacitive absolute pressure sensors (***Vaisala* Barocap**).





HASI PPI schematic

Barocap sensor schematic

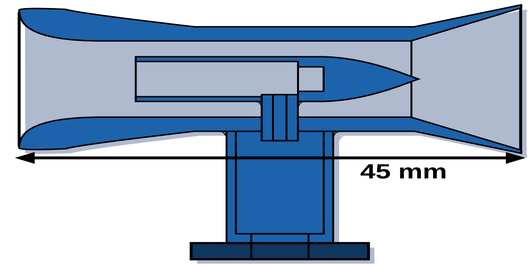


range	Resolution	Accuracy
Low (0-400 hPa)		
Medium (0-1200 hPa)	0.01hPa	1%
High (0-1600 hPa)		

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



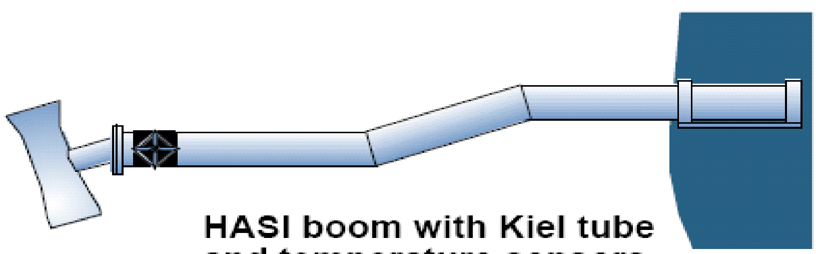
HASI PPI Kiel probe design

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 boom with Kiel tube and temperature sensors

HASI PPI testing and characterization

H.A.S.I.
Huygens Atmospheric Structure Instrument on the Cassini-Huygens mission

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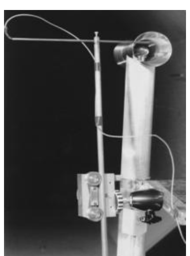
Expected dynamic conditions:

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

Flow field simulation:

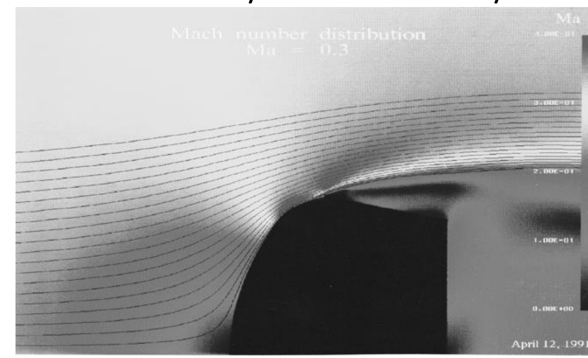
an adaptic-grid for solving 3-D Navier-Stokes equations (developed by Laboratory of Aerodynamics, Helsinki University of Technology, Finland) used to study probe behaviour and for PPI Kiel probe design.

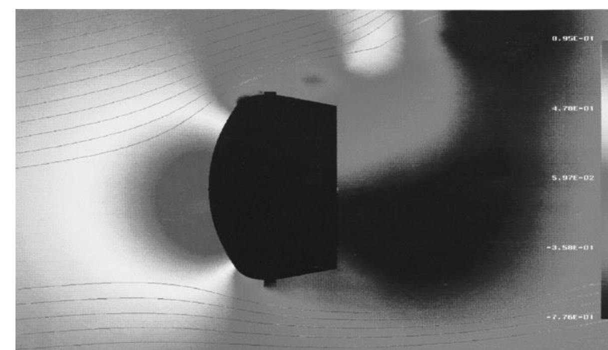


HASI/PPI wind tunnel:

tests with upscaled models to verify Kiel probe design

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



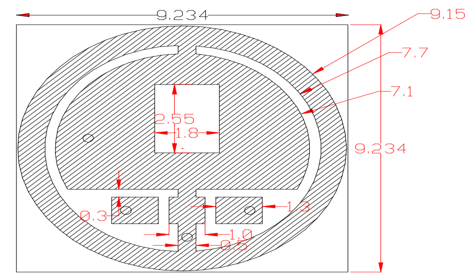


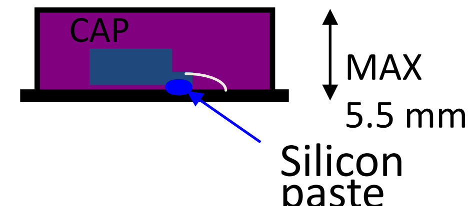
HASI PPI – Vaisala Barocap sensors

PPI sensors (3 Multicaps of 8 frequency output channels)

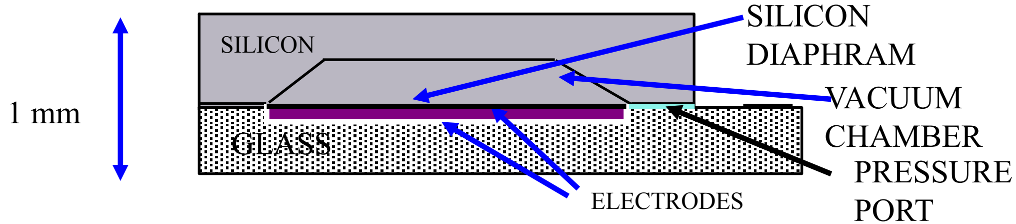
- 8 silicon capacitive absolute pressure sensors (**Barocaps**) in 3 different pressure sensitivity ranges (low, medium, high mode)
- 7 constant and 6 reference sensors (high stability capacitors)
- 3 temperature capacitive sensors (**Thermocap**) for thermal compensation
- Variation of pressure causes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

Sensor housing





HASI PPI Vaisala Barocap

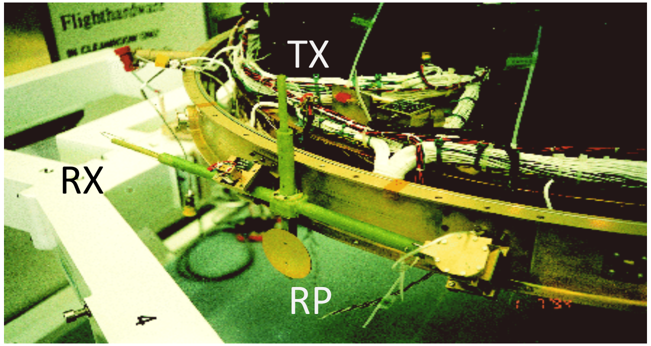


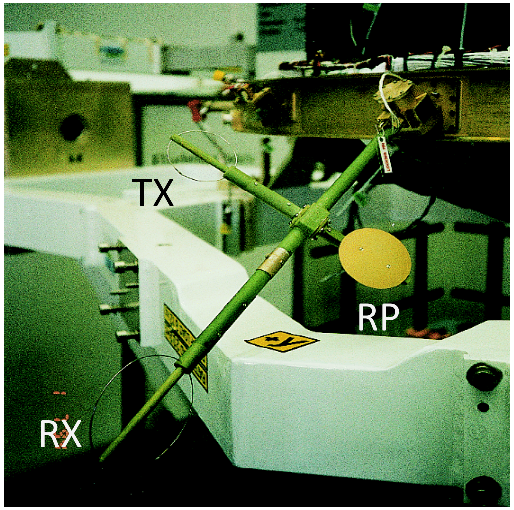
range	Resolution	Accuracy
Low (0-400 hPa)		
Medium (0-1200 hPa)	0.01hPa	1%
High (0-1600 hPa)		

HASI PWA

Permittivity, Wave, and Altimetry package

- **Mutual impedance probe**: 2 couples of MI transmitter (**TX**) and receiver (**RX**) electrodes.
  To measure the **atmospheric electric conductivity** and detect **wave emissions** in atmosphere and relative phenomena i.e. **lightnings**
- **Relaxation probe** (**RP**) to measure the quasi static **DC electric fields** and **ion conductivity** by applying a +/- potentials and monitoring discharge V(t) to equilibrium potential.
- **Acoustic sensor** (**ACU**) to detect **sound waves** to correlate with acoustic noise, turbulence and meteorological events (pressure level threshold 10 mPa)
- **Radar Altimetry** extension (**RAE**) board to process and analyse the return signal of the Huygens Proximity sensor containing info on **surface properties** and **altitude**



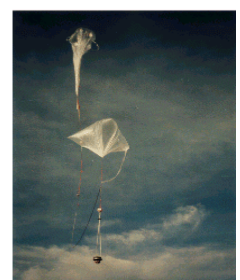


HASI testing and calibration

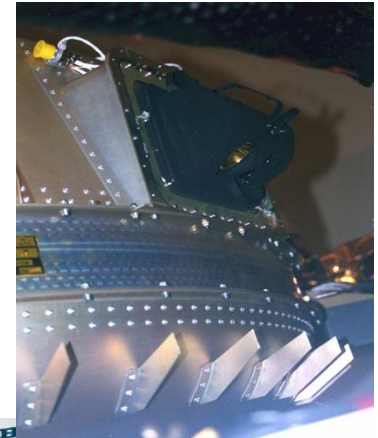
- Sensors have been characterized, tested and calibrated at subsystem, HASI instrument and Huygens probe level.
- **Cruise in-flight check-outs** (every 6 months during 7 years):
  check sensors off-sets and behaviour through mission timeline simulation; eventually monitoring any drift and /or ageing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



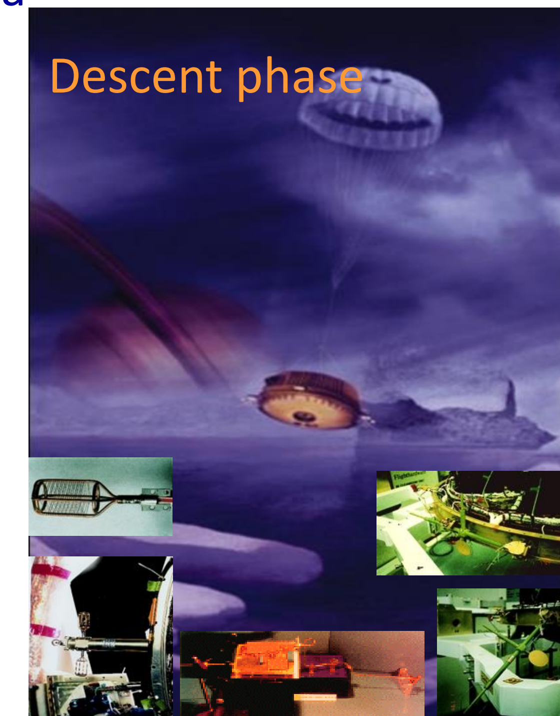




Huygens Assembly, Integration, Verification



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

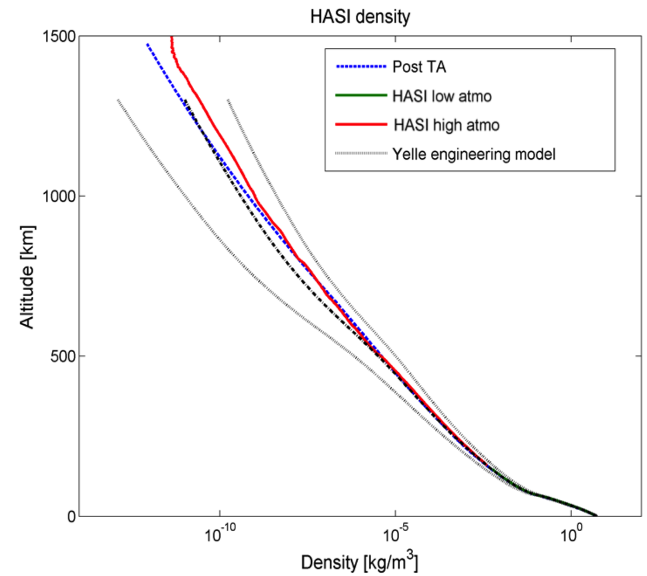
Upper atmospheric profile

From acceleration measurements

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

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

V_r and z from measured acceleration & initial conditions



Credit: ESA / ASI / UPD / OU /

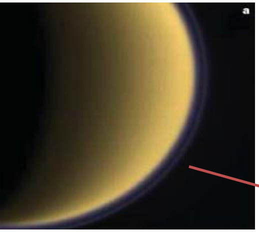
Indirect **temperature** and **pressure** measurements

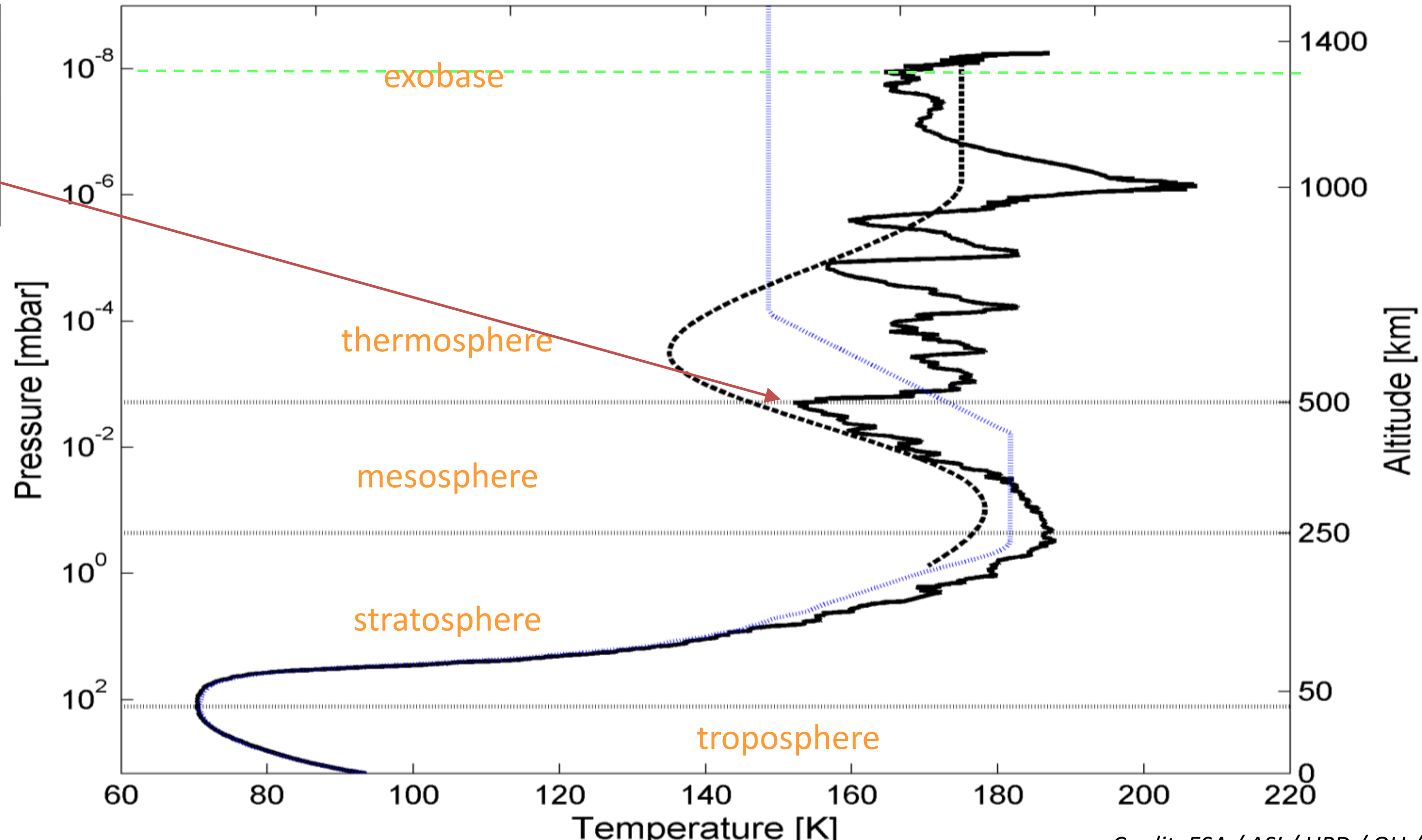
Hydrostatic equilibrium $dp = -g\rho dz$ → $p(z)$

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 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)

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

Dry adiabatic atmosphere

$\boldsymbol{\rho}\mathbf{(z)}$ from equation of state

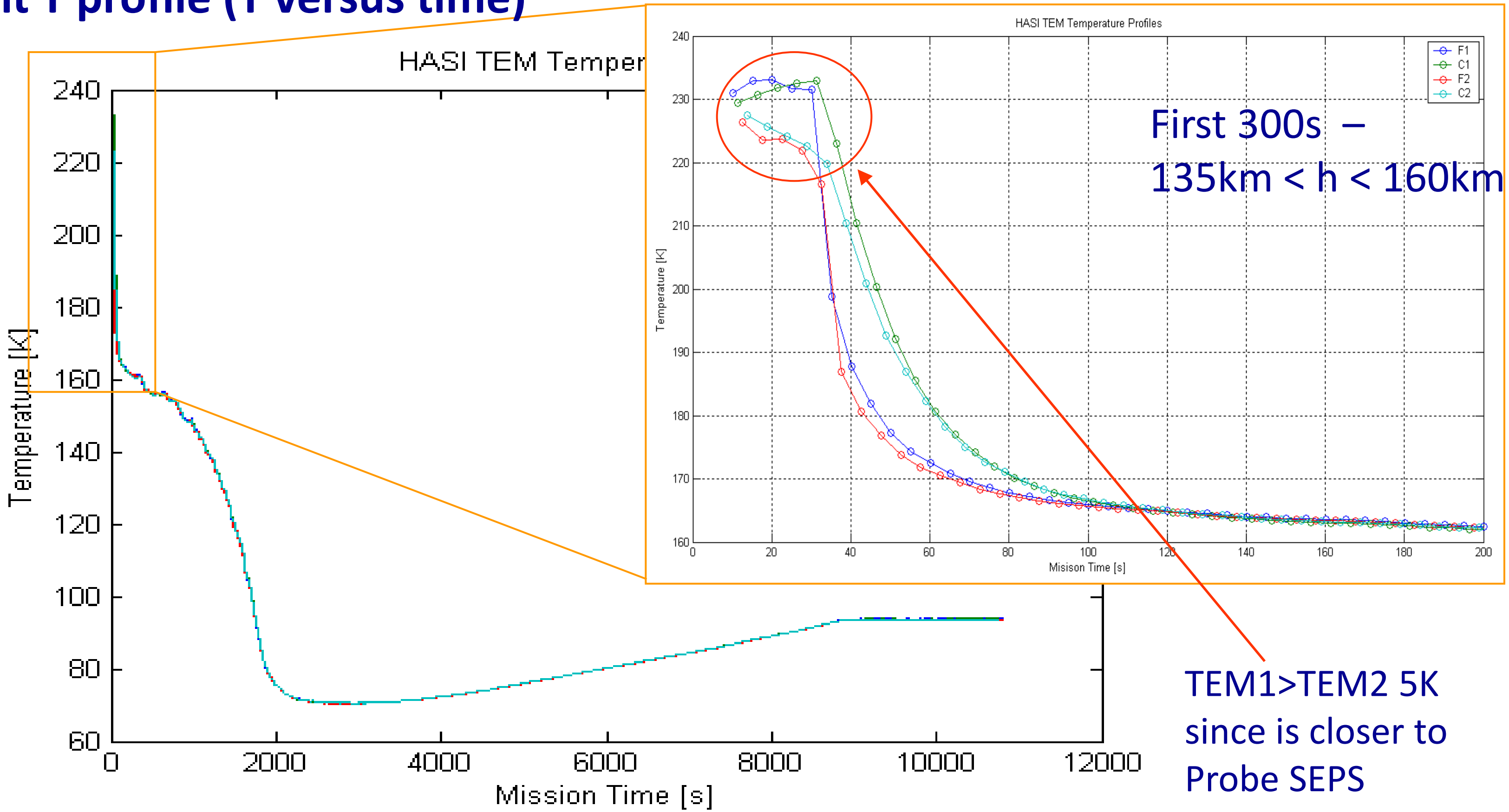
$p = \zeta\rho RT$ ζ compressibility factor

$\mu(p)$ & $R(p)$ μ from GCMS

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

HASI TEM at Titan

Descent T profile (T versus time)

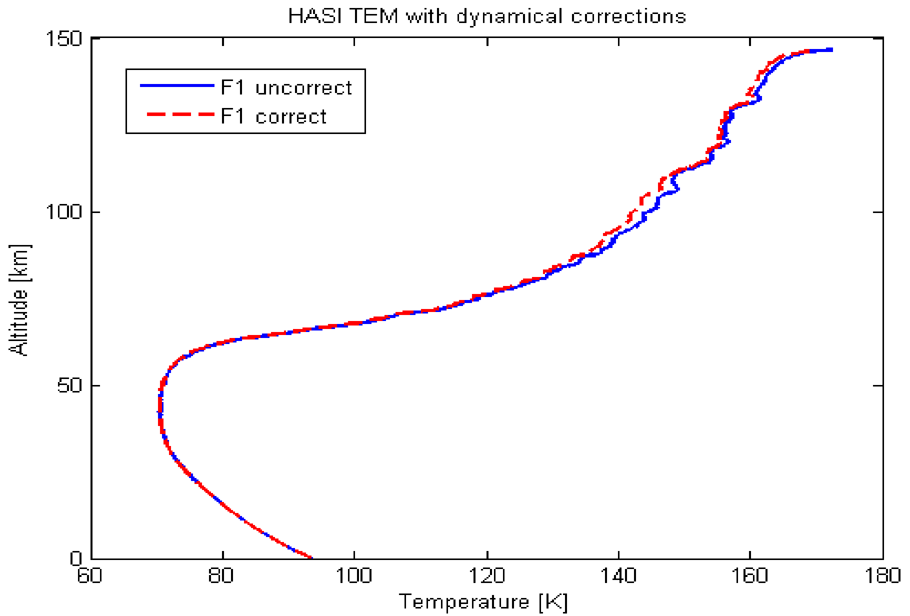


Dynamic corrections

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

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

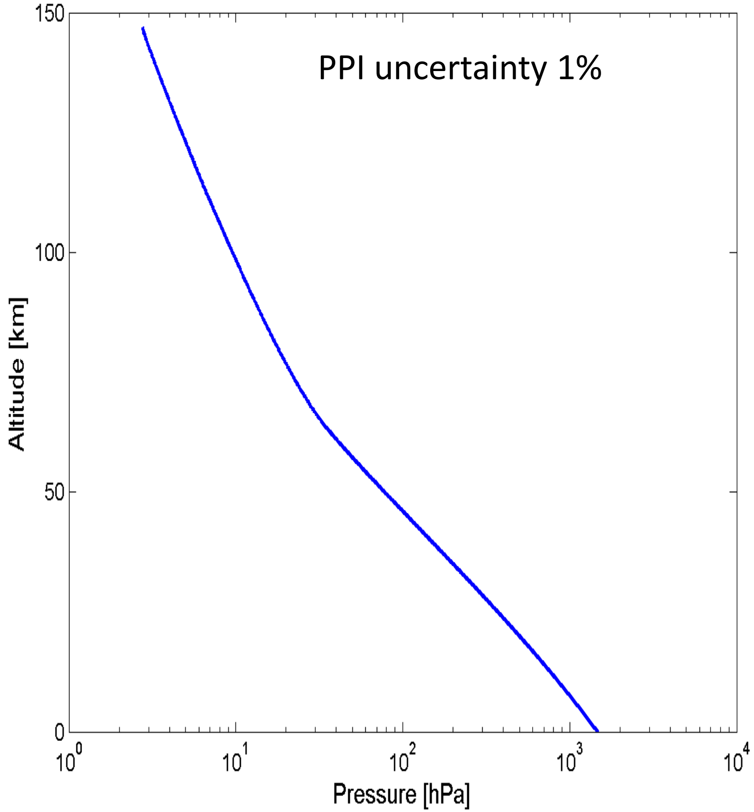
$$p_{stat} = p_{meas}\left(1 + \frac{\gamma - 1}{2} Ma^2\right)^{\frac{\gamma}{1-\gamma}}$$

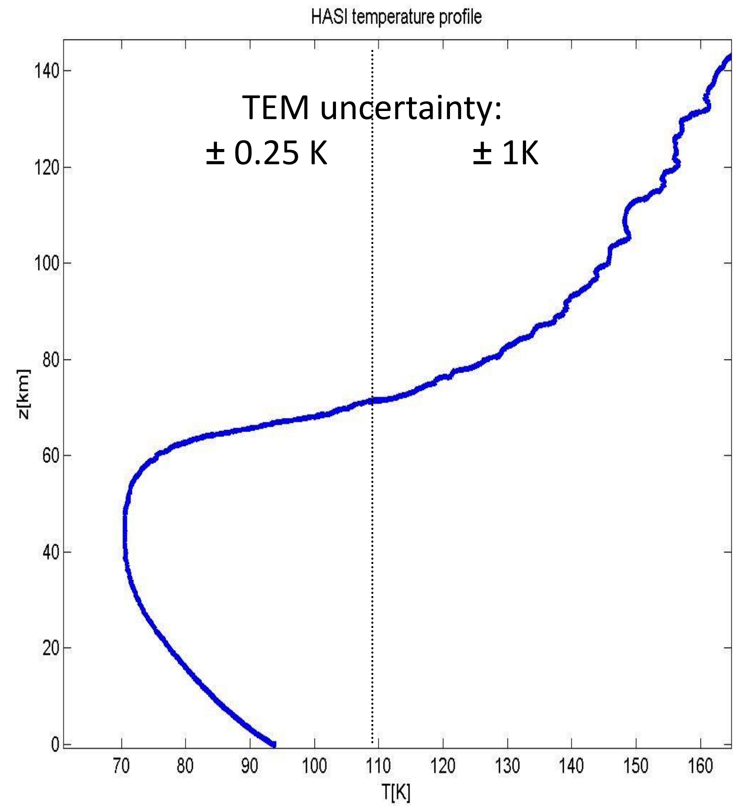


$\gamma = {c_p}/{c_v}$ ratio of the specific heat constants,

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

HASI descent phase





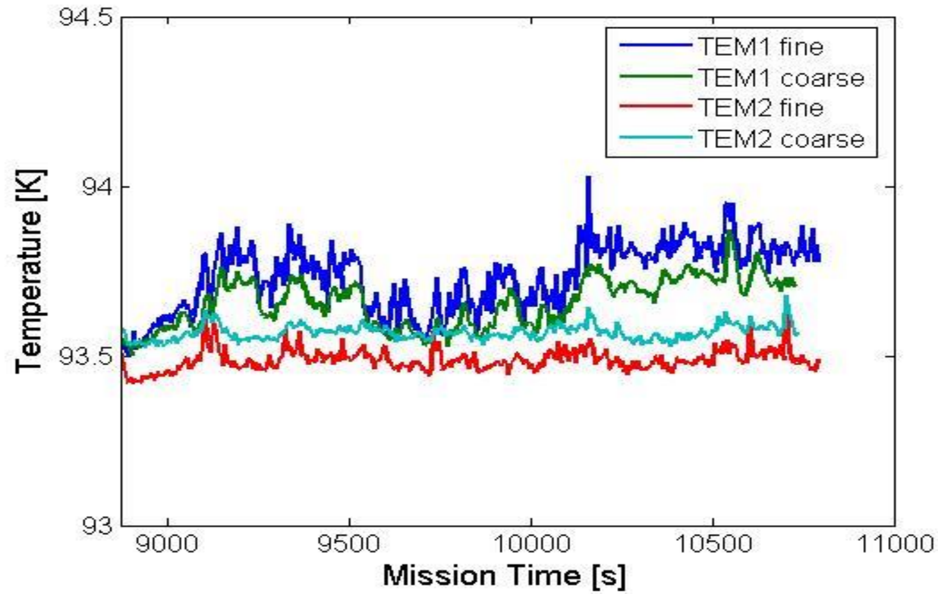
Credit: ESA / ASI / UPD / FMI

HASI surface phase


ESA/NASA/JPL/University of Arizona

Meteo at Titan's surface:

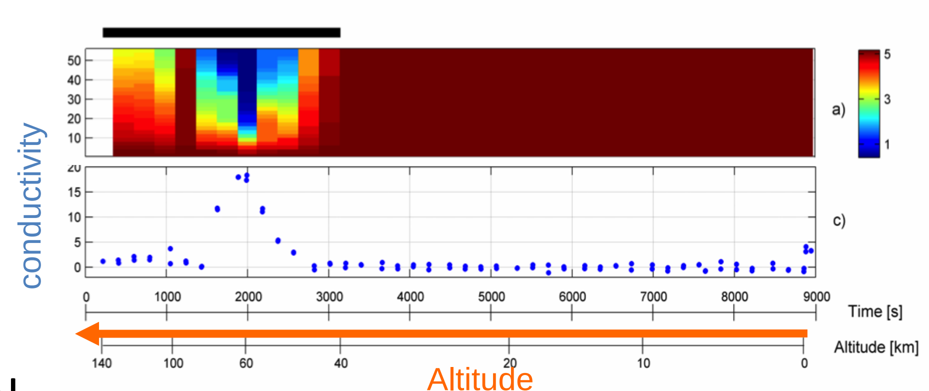
- **Temperature 93.65±0.25 K**



Titan’s atmospheric electricity: HASI PWA results

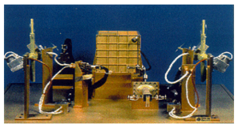
- Presence of charged particle species (electrons, positive and negative ions).
- Lower ionospheric layer between 140 and 40 km induced by cosmic rays with electrical conductivity peaking near 60 km.
- Detection of some events of electrical discharges (potential signature of lightning).

Permittivity Wave Altimetry (PWA)
signature of the ionosphere



Lessons learned

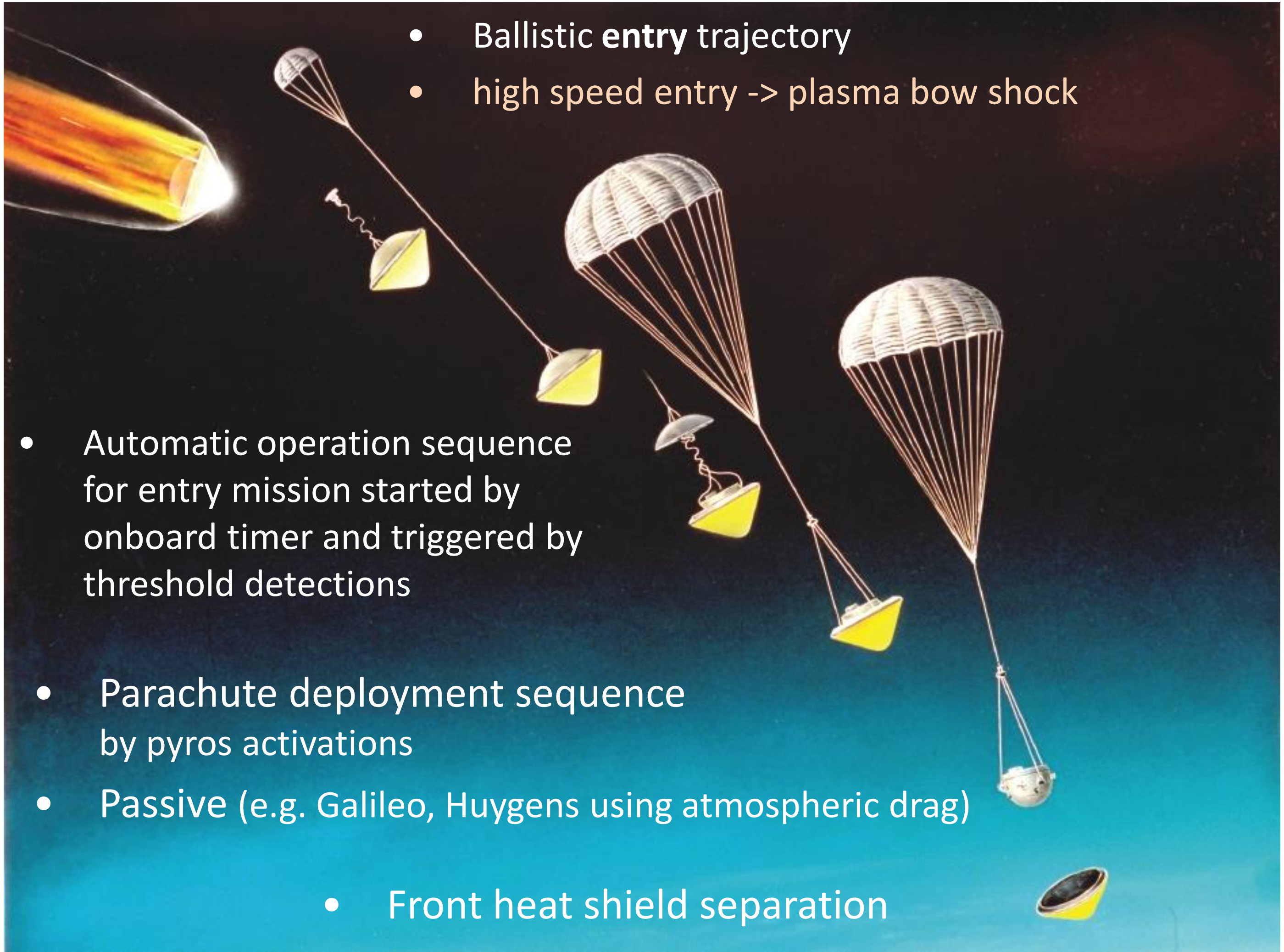
*Experience and lessons learned with **Huygens ASI** in perspective for future in situ exploration:*





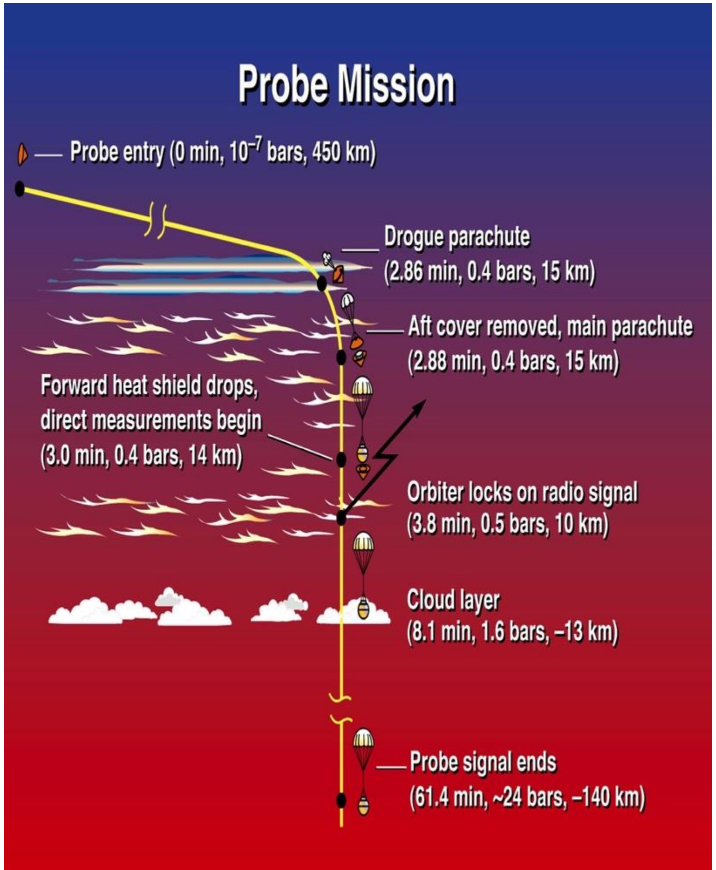

- Good calibration and performance assessment either through ground and in-flight tests are essential for data interpretation.
- On ground tests (like balloon experiments) are very useful for understanding performance of sensors with real data

Operational scenario



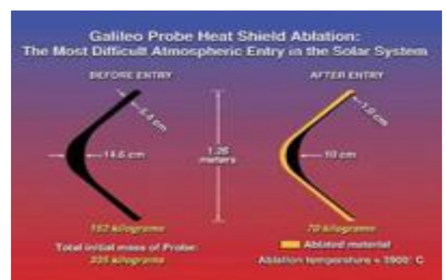
- Ballistic **entry** trajectory
- high speed entry -> plasma bow shock
- Automatic operation sequence for entry mission started by onboard timer and triggered by threshold detections
- Parachute deployment sequence by pyros activations
- Passive (e.g. Galileo, Huygens using atmospheric drag)
- Front heat shield separation

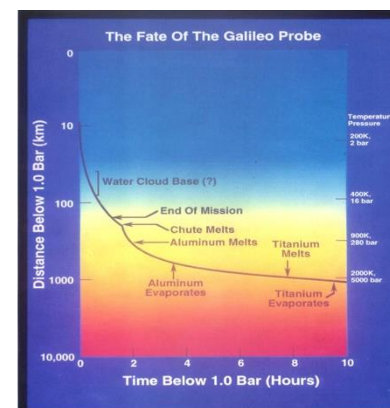
Galileo probe at Jupiter



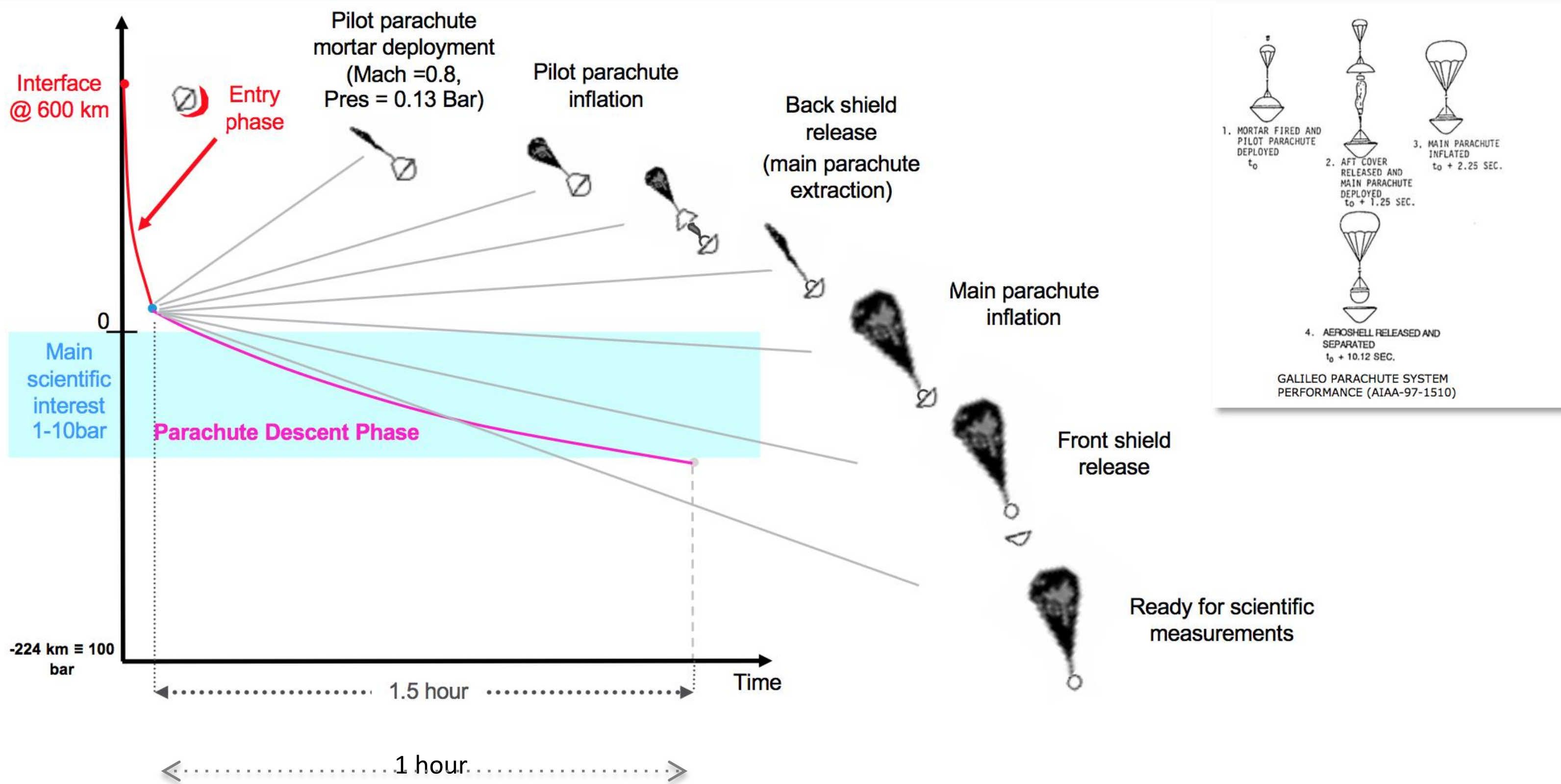
Harsh environment:

- @ high speed entry, a bow-shock wave and a thin shock layer of ionized, luminescent gases at extreme temperature (~15000 K at peak) enveloped the probe
- the intense heat melted and vaporized the frontal heat shield
- high pressure down to 160 km crashed the probe



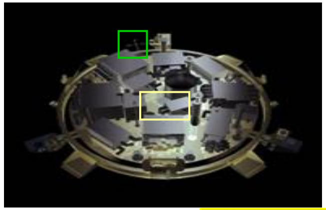


ESA M* Ice Giants CDF study parachute sequence



Ice Giant ASI

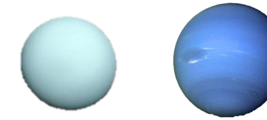
Huygens HASI



ACC X-servo

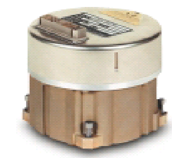
TEM

PWA booms



IG ASI-ACC → X-Servo scientific accelerometer combined also with **GNC inertial measurements**:

GNC sensors → acceleration and angular rate from the 2 IMU units.



IG ASI-TEM → Temperature range 40-300 K
Resolution: 0.05 K   Accuracy: 0.1 K

ASI-PPI → silicon capacitive transducer (Vaisala Barocaps)
range 0.0001-10 hPa, 1% accuracy, resolution 1mPa

IG ASI Atmospheric Electrical Package (AEP)

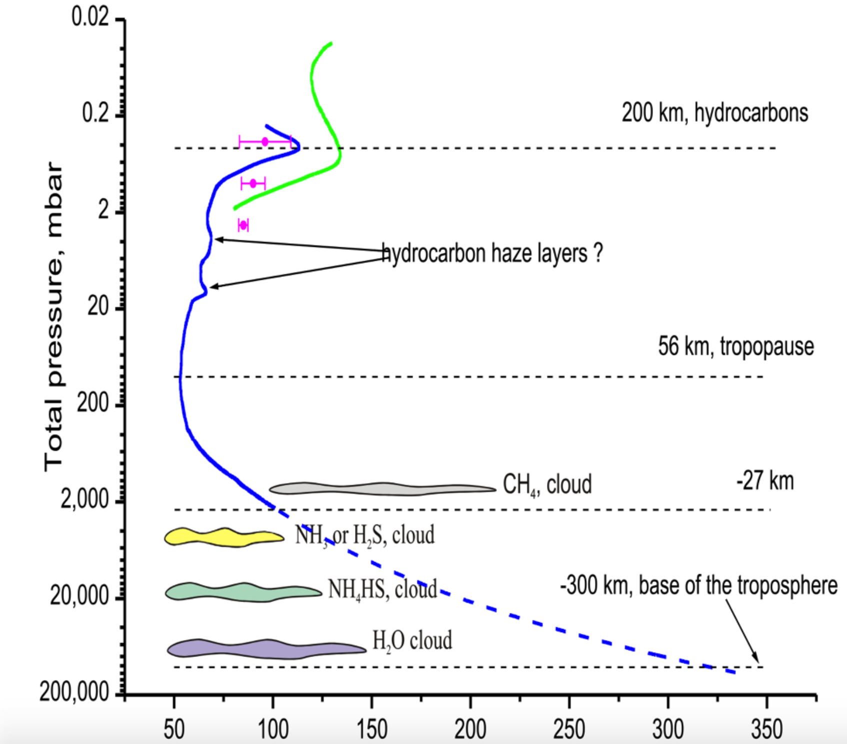
→ mutual impedance probe and relaxation probe for conductivity and DC electric field measurements

µARES antenna of **ExoMars2018 DREAMS**

esa LATMOS

Expected results:
Atmospheric structure and dynamics

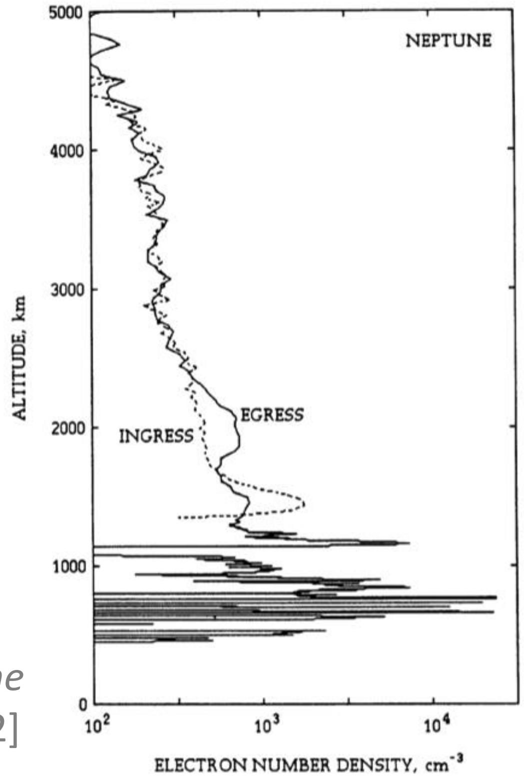
Uranus tropospheric profile



- Vertical structure of the planet's atmospheric temperature and stability
- Atmospheric winds and wave phenomena as function of depth
- Vertical structure of eventual clouds and haze layers
- Vertical distribution of chemical species by convective motions and vertical mixing

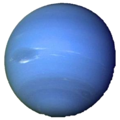
Expected results:
Atmospheric electricity

- Tropospheric electric conductivity profile
- Measurements of natural DC electric field
- Detection of possible electrical discharges, i.e. lightnings
- Spectral analysis in the 1-200 kHz range to determine unknown lightning spectrum and detect potential Schumann resonance



Vertical distribution of free electron in the lower Neptune's ionosphere [Lindal 1992]

Conclusions



ASI instrument at the Ice Giants

- The temperature and density profiles inferred by IG-ASI will provide
  a) an accurate determination of the atmosphere (from the exobase down deep into the troposphere) sounding altitude range never reached
  b) the only new and independent definition of the stratosphere and tropospheric thermal structure
  c) atmospheric parameters for a very precise characterization of the chemical structure
- The characterization of the atmospheric electrical properties and possible detection of lightning
- IG-ASI data will provide a 'ground thruth' for the remote sensing and groundbased observations.

- Information gathered from IG-ASI will pertain to one site along the probe descent trajectory, but combined with measurements from the orbiter will contribute to improve the knowledge of the global atmospheric structure and dynamics.