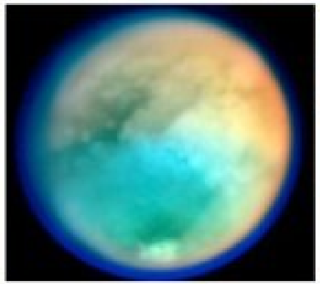
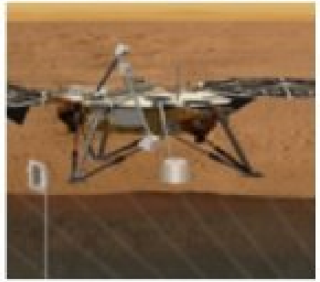
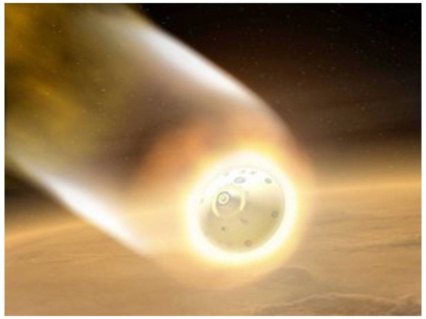
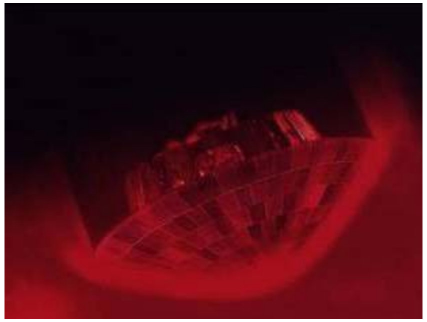




IPPW9 Short Course
Probe Science Instrumentation
Entry / Descent (*in situ* probe science)

Accelerometers / Gyros

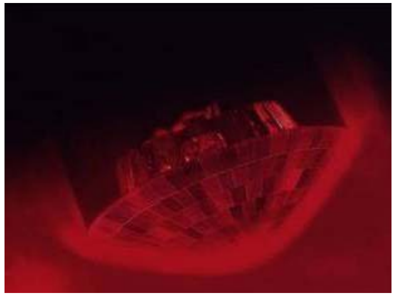
Francesca Ferri
Università degli Studi di Padova,
CISAS "G. Colombo"

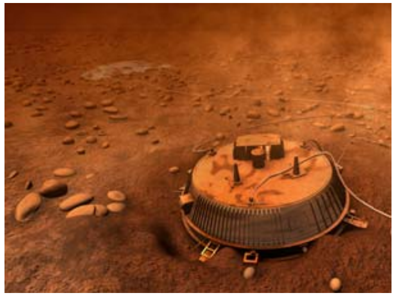
EDLS measurements


- **Entry, Descent, Landing System** (EDLS) of an atmospheric probe or lander requires mesurements in order to trigger and control autonomously the events of the descent sequence; to guarantee a safe landing
- These measurements could provide
  - the engineering assessment of the EDLS and
  - essential data for an accurate trajectory and attitude reconstruction
  - and atmospheric scientific investigations
- EDLS phases are critical wrt mission achievement and imply development and validation of technologies linked to the environmental and aerodynamical conditions the vehicle will face.

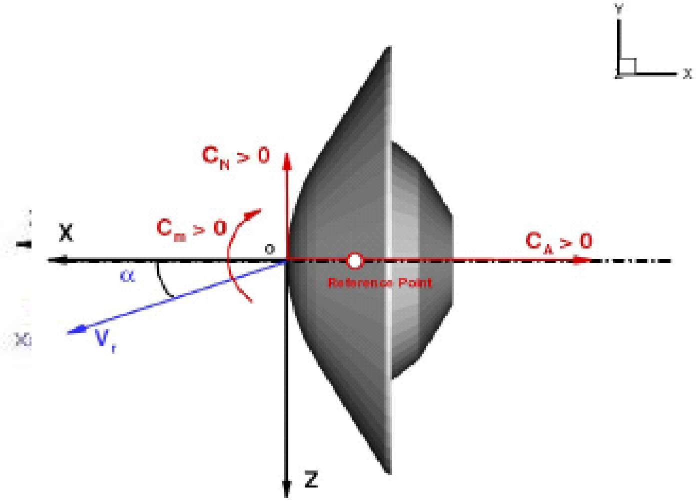
EDL *in situ* probe science: Accelerometers & Gyros





- Inertial measurements during ballistic entry and descent phases allow for passive navigation control and triggering events of mission sequence.
- Accurate trajectory and attitude reconstruction
- Retrieval of atmospheric vertical profiles along the probe trajectory
- Impact detection

Inertial navigation of an entry probe



Reference frames

Velocity fixed frame coefficients

C_D drag force

C_L lift force

Body fixed frame coefficients

C_A axial force

C_N normal force

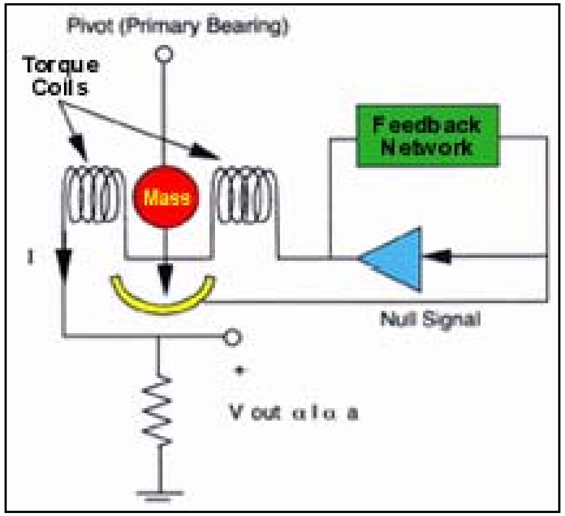
C_p pitching moment

- **Inertial reference frame** (IRF)
- **Acceleration** =>change in velocity and position
- **Gyroscopic sensors** => Rotational motion of the body and orientation of accelerometers wrt IRF
- Acc+gyros data are combined together in order to define translational motion of the vehicle within IRF and to calculate the position.
- Inertial systems are self-contained within the vehicle (e.g.strap-down sensors, rigidily fixed to the vehicle) and provide estimate of **changes of position.**
- Need for accurate knowledge of starting vehicle position (e.g. entry state)

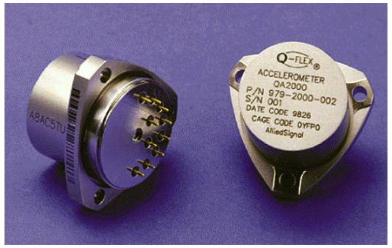
- Knowledge of **aerodynamics / environment conditions** the vehicle will face.

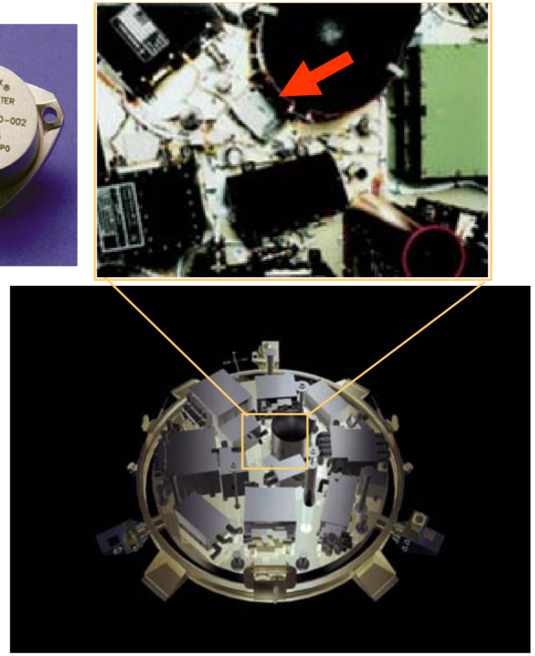
High Accuracy Accelerometers

Force-balance (Servo) Accelerometers



HASI ACC principle, performance and accomodation





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

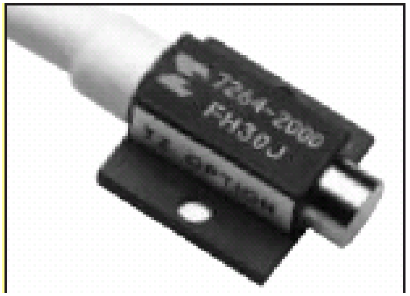
- Allow very high accuracy
- Comparatively complex & heavy
- Comparatively sensitive to mechanical loads
- A typical science instrument for entry and descent: the most accurate ever flown in a planetary probe.

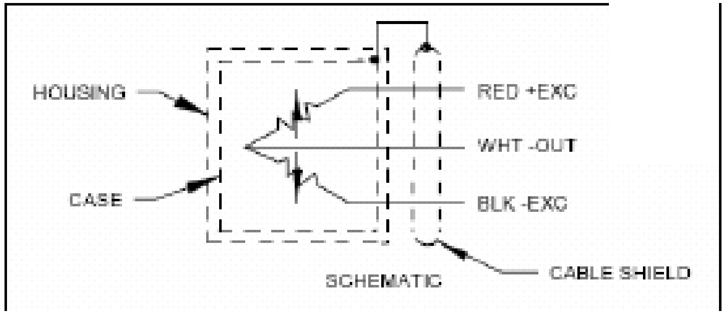
Example: Huygens HASI x-axis servo accelerometer

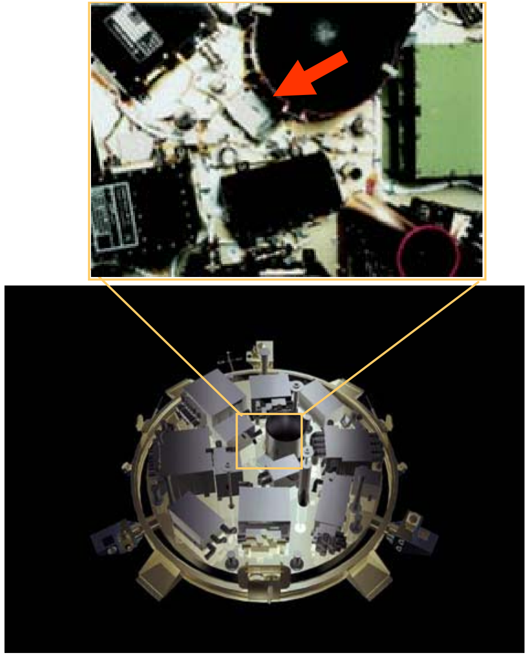
Type	Honeywell QA 2000
Mass (servo sensor / total)	71g / 300g
Power	~1.7 Watts
Accuracy	1% full scale

'Standard' Accelerometers

Piezoresistive Accelerometers







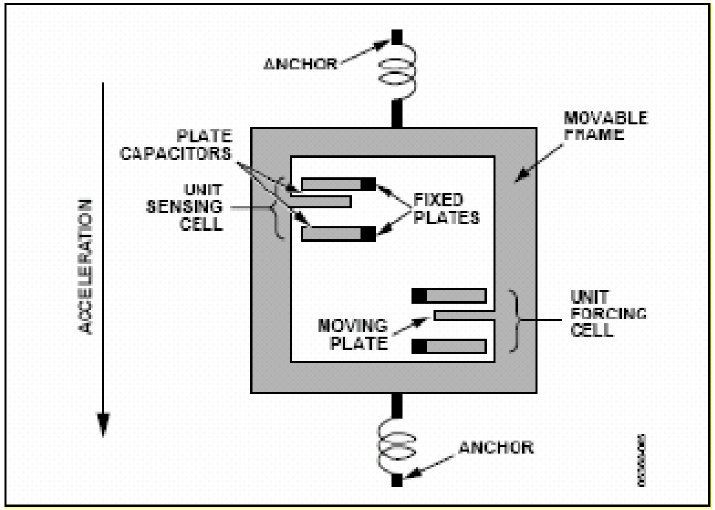
Example: Huygens HASI X / Y / Z accelerometers

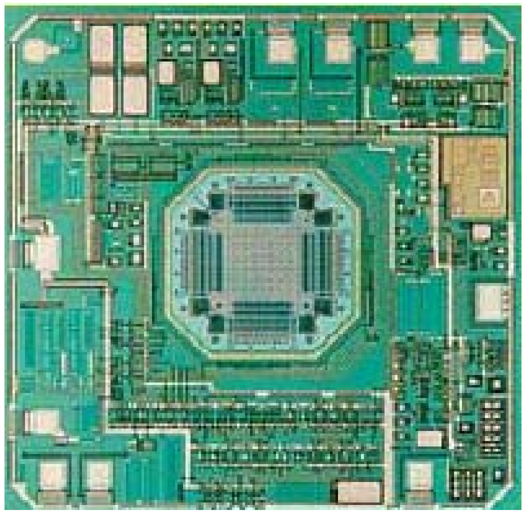
- Very lightweight and robust
- Moderate accuracy
- Low power, simple electronics
- Used on Huygens, Deep Space 2, ...

Type	Endevco 7264A-2000T
Frequency range	0 – 1000 Hz (5%)
Range / Resolution	+/- 20g / +/- 50 mg
Nonlinearity / Hysteresis	+/- 3%
Mass	1g (sensor)

MEMS Accelerometers

- Based on Micro-ElectroMechanical Systems
  - Very lightweight and robust
  - Good accuracy
  - Low power, simple electronics
  - Often used in automotive applications
  - Very high EMI/RF tolerance
  - Qualification for space required





Example: AD ADXL78 1-axis MEMS accelerometer sensor

Mass / size	< 1 g, 5 x 5 x 2 mm
Acceleration range	+/- 35 g to +/- 70 g
Temp range	-40 to +105 deg C
Accuracy	Linearity 0.2%
Power @ Supply voltage	6.5 mW @ +5 V

Gyroscopes ('Gyros')

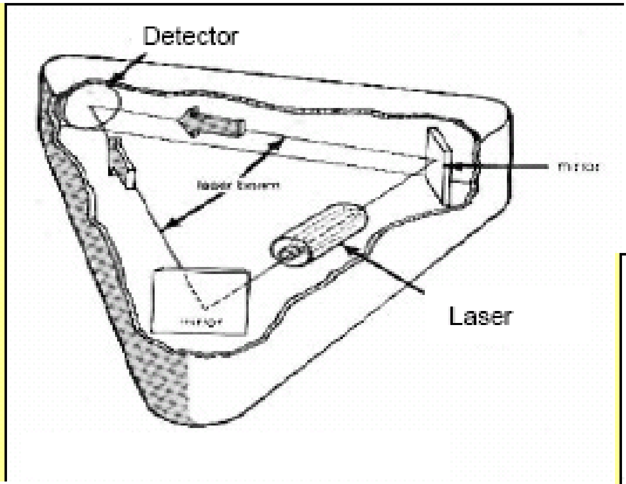
Gyroscope

- Devices for measuring orientation, based on the princicle of conservation of angular momentum
- Conventional: mechanical gyros

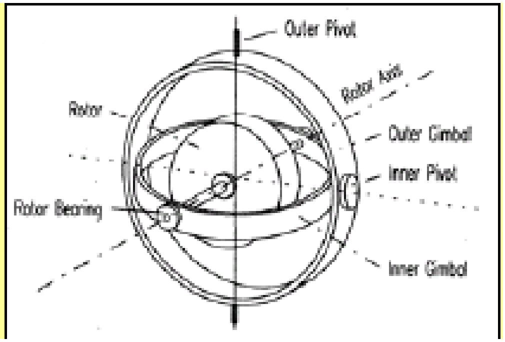
Optical Gyros (laser gyros)
- Use interferometric methods to sense angular motion (Sagnac interferometer)
- No moving parts
- No gravity effects
- High bandwidth
- Very reliable
- Low power

Laser ring gyro + electronic unit

Fiber Optic Gyros (FOG)
- Use optical fibre as propagation path
- Measure angular motion by detecting phase difference
- Very robust



Laser- (left) and mechanical gyro (below)



Example: high performance fiber optic gyro performance for space

Type	FOG 2500, Northrop Grumman
Drift rate	0.001 deg / hr
Max rate	100 deg / sec
Power	5W
Size	170 mm dia x 54 mm
Mass	~2 kg

Inertial Measurement Units (IMUs)

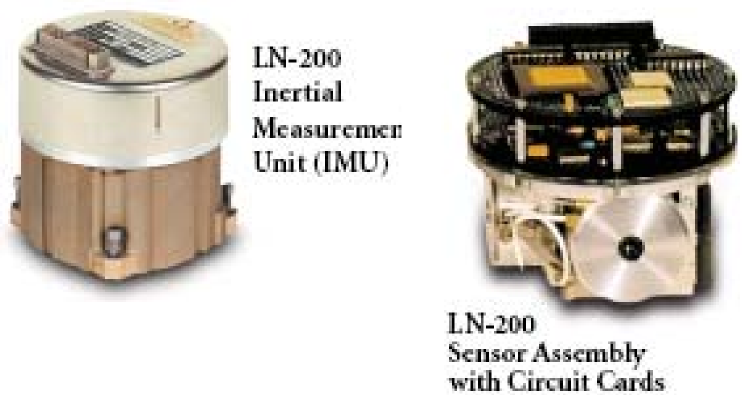
IMU combines multiple sensors plus data processing electronics in one unit

- **Accelerometers**
- **Gyros**
- ➢ Acceleration (and derived velocity)
- ➢ Rotation (and rotation rate)

Typical parameters (Honeywell IMU)

I/F / rad-hardness	RS422 / MIL1553, 100 krad
Mass	4.44 kg typ.
Size	~233mm dia x 169mm
Power	22W typ.
Gyro bias (1-sigma)	< 0.005 deg /hr
Scale fator	< 1 ppm

Example: NASA MER IMU Litton LN-200S

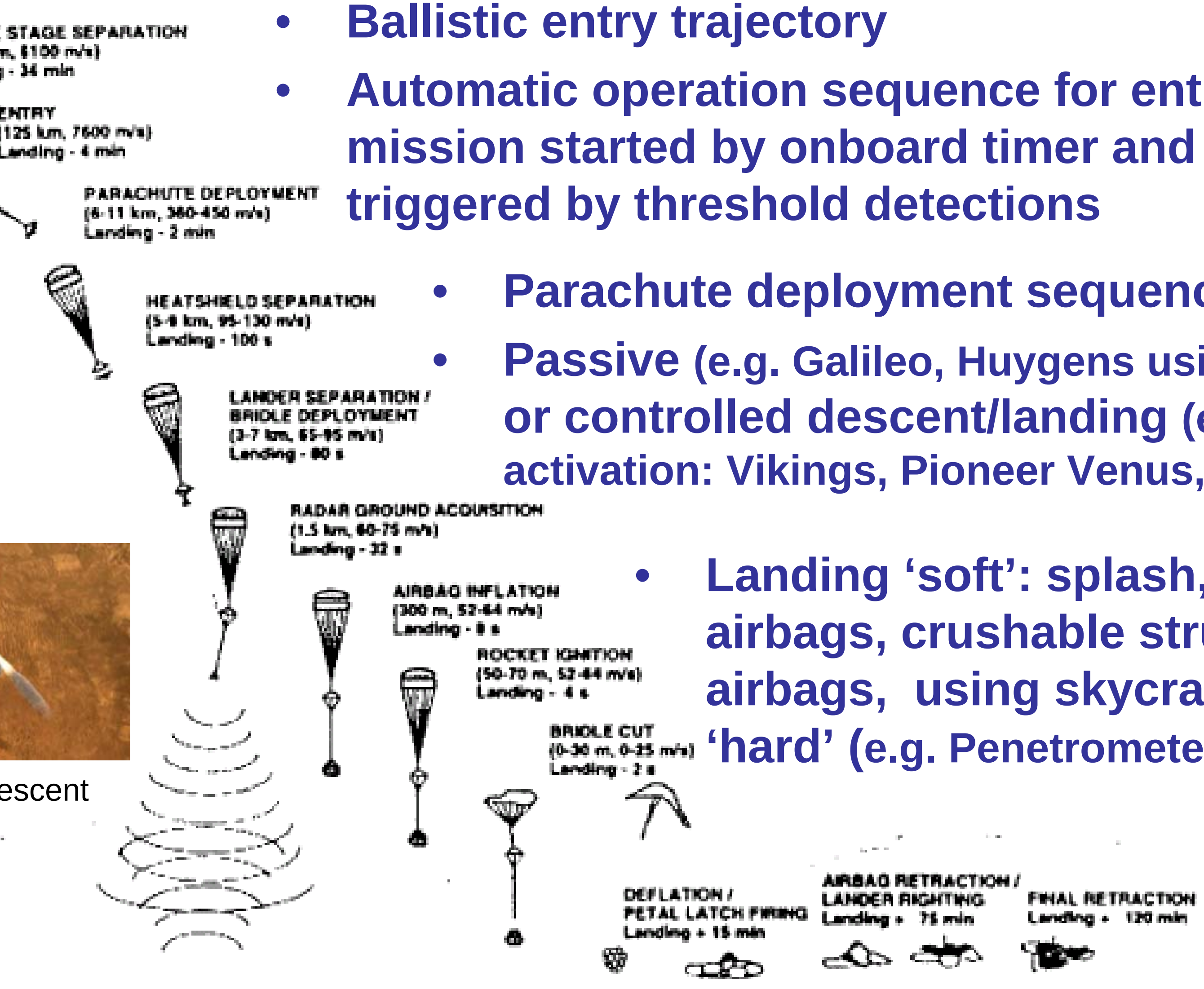


- 3 solid state fiber optic gyros
- 3 solid state silicon accelerometers

Mass	750 g
Size	~90mm dia x 90mm
Power	12W
MTBF	20.000 hrs

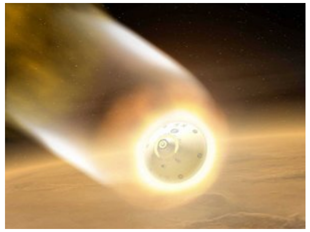
Accuracy related parameters
- Bias, Scale factor (acc, gyro)
- Random walk (gyro)
- Measurement limits (acc & rotation)

Operational scenario



Mars Pathfinder entry, descent and landing

- **Ballistic entry trajectory**
- **Automatic operation sequence for entry mission started by onboard timer and triggered by threshold detections**


MER entry

- **Parachute deployment sequence by pyros activations**
- **Passive (e.g. Galileo, Huygens using atmospheric drag) or controlled descent/landing (e.g. by retrorockets activation: Vikings, Pioneer Venus, MERs, MSL)**
- **Landing 'soft': splash, rebouncing airbags, crushable structure, vented airbags, using skycrane; 'hard' (e.g. Penetrometers, Deepe Space2)**


MER descent

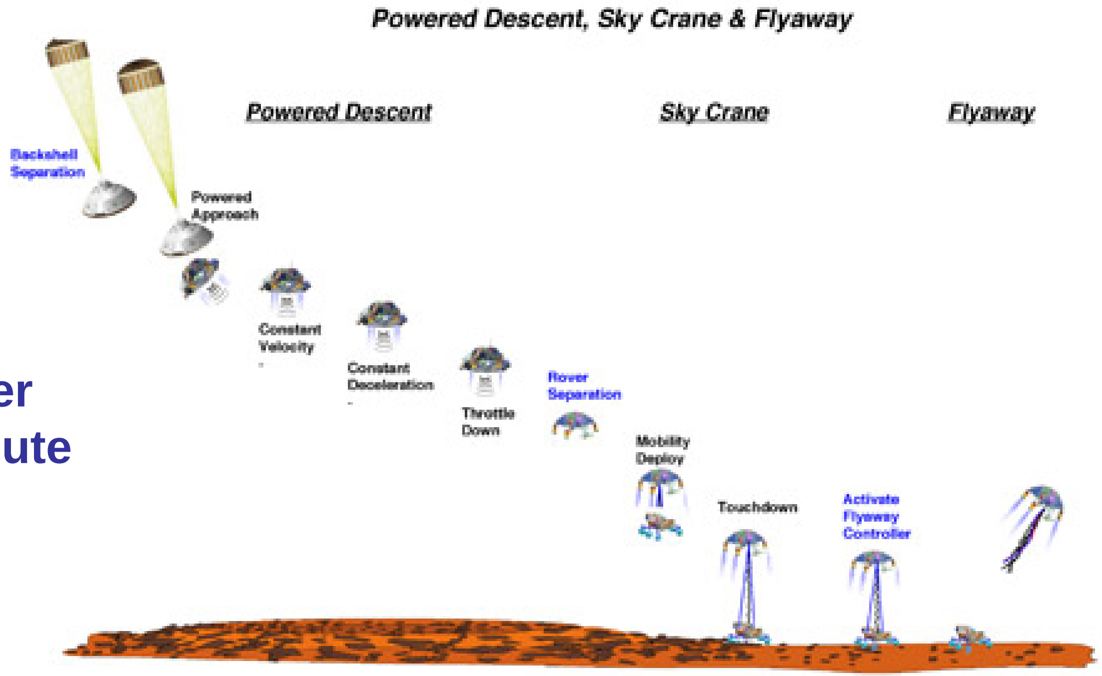

MER landing

Mars Science Laboratory EDL

Guided Entry (GNC)

Expected arrival: August 2012

Powered descent



Descent Imaging

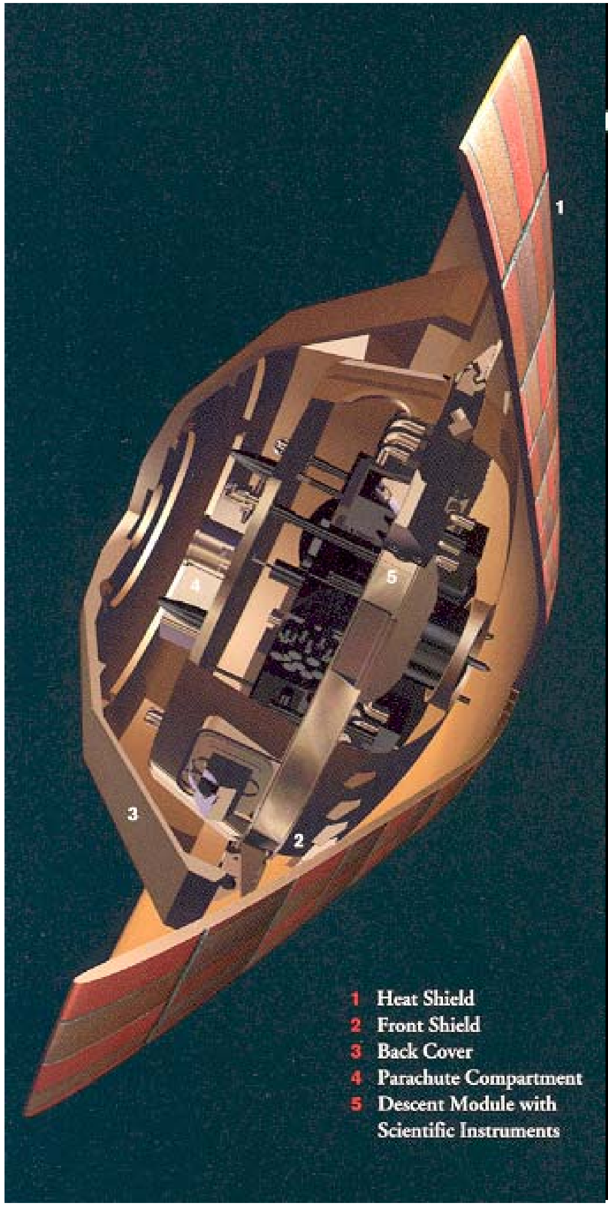
Bigger Parachute

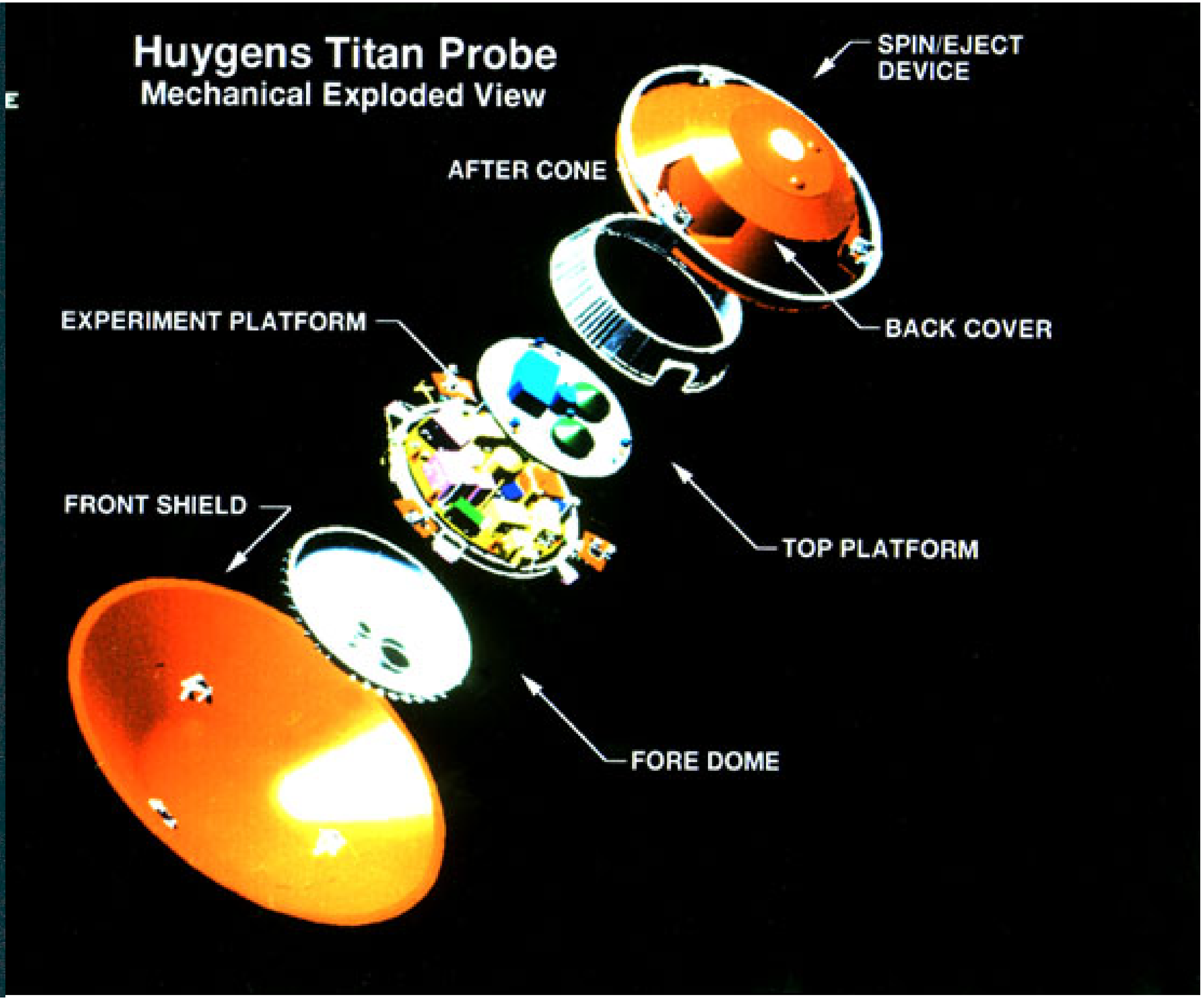
Sky Crane

The Huygens Probe Mission

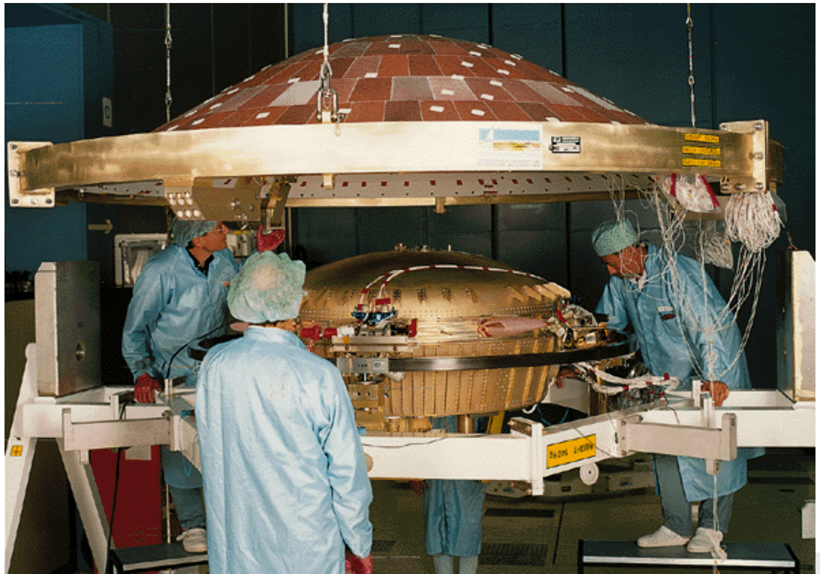
An example for a probe mission, data analysis and technical and science issues

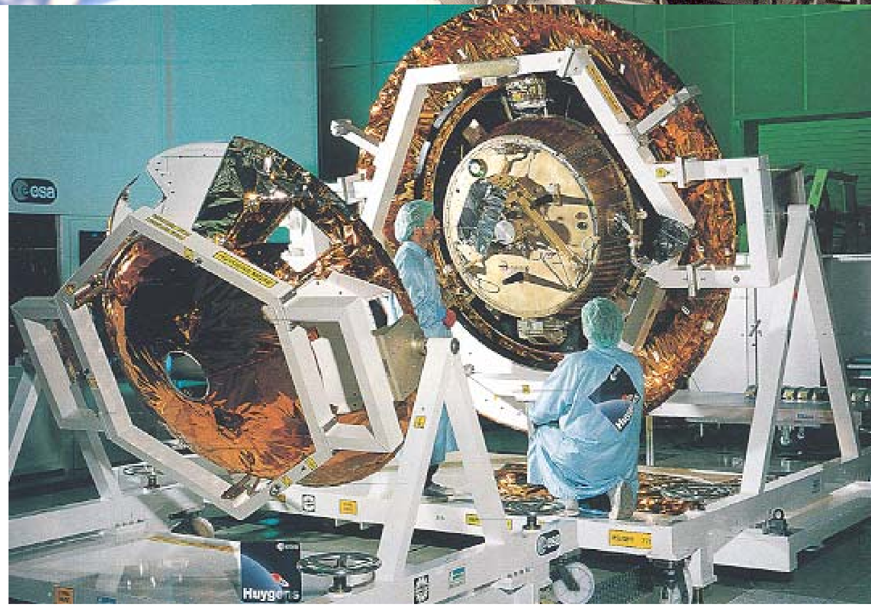
Huygens Probe Exploded View



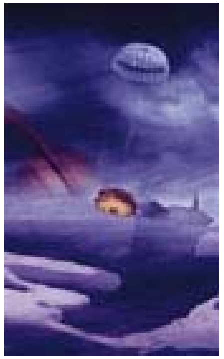


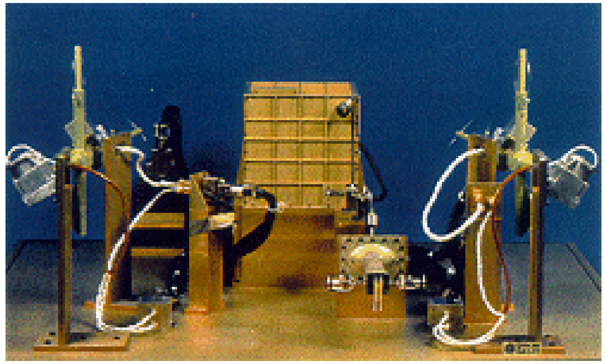
Huygens Integration

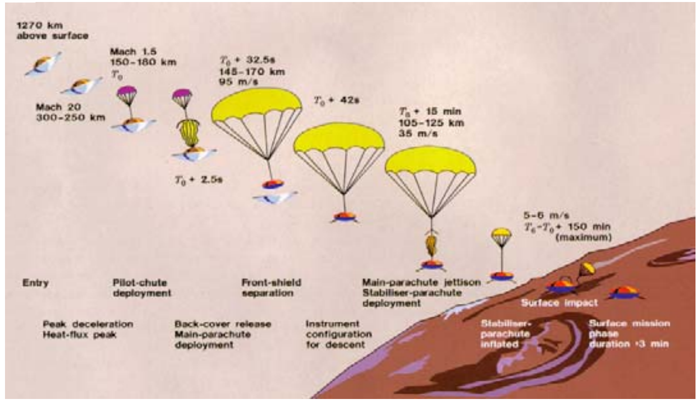




Huygens Atmospheric Structure Instrument (HASI)

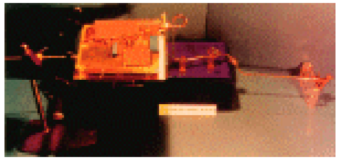






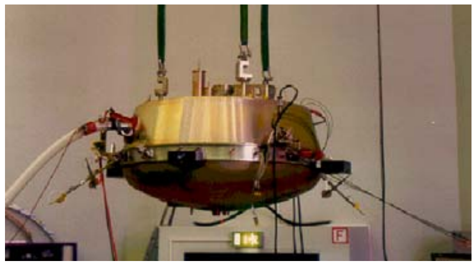
- **Study of Titan’s atmosphere and surface**

by measuring



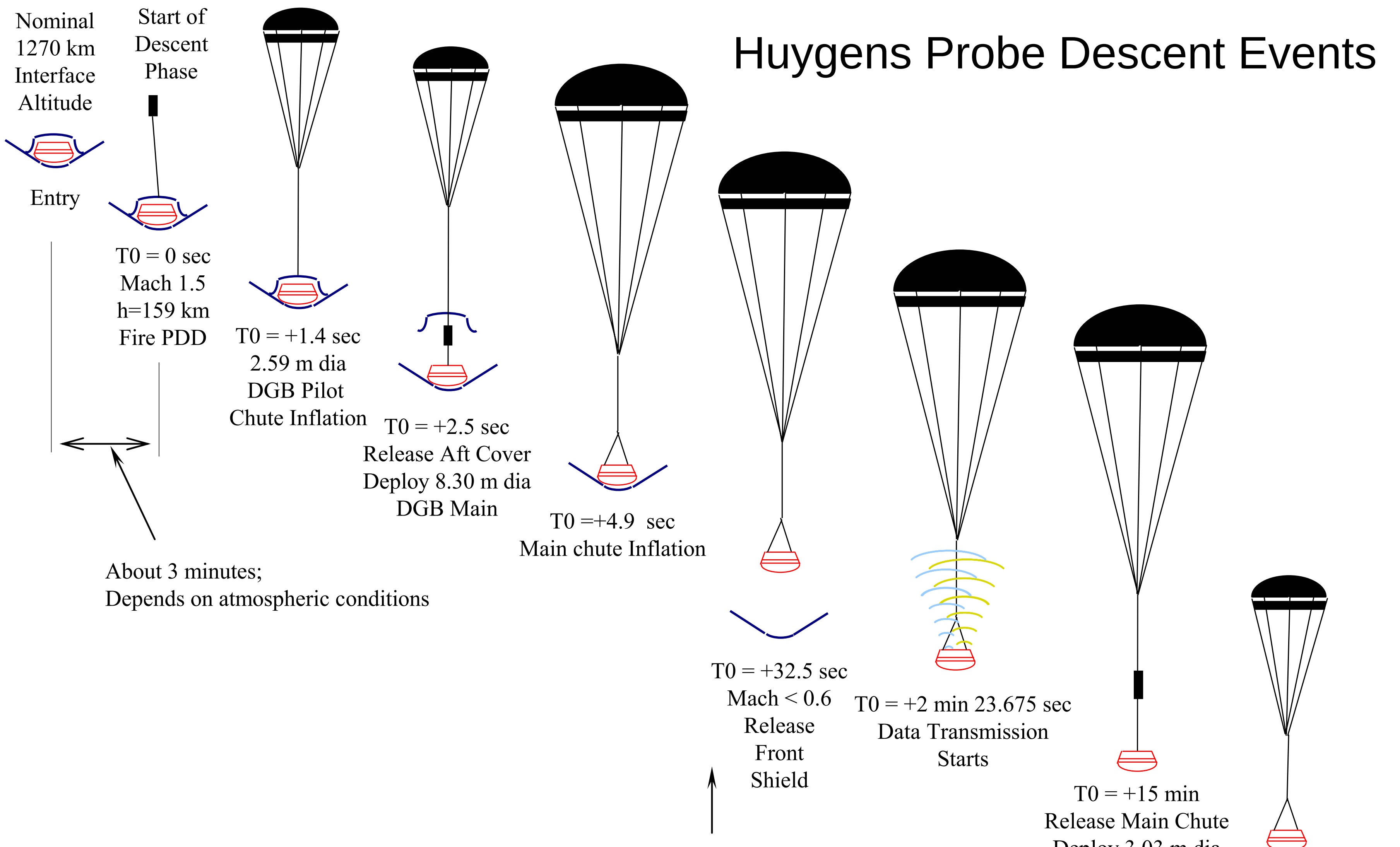
- **acceleration** (ACC)

- **pressure** (PPI)
- **temperature** (TEM)



- **electrical properties** (PWA, RAU)
- ***Heritage: Pioneer Venus, Venera, Galileo, and Viking probes***

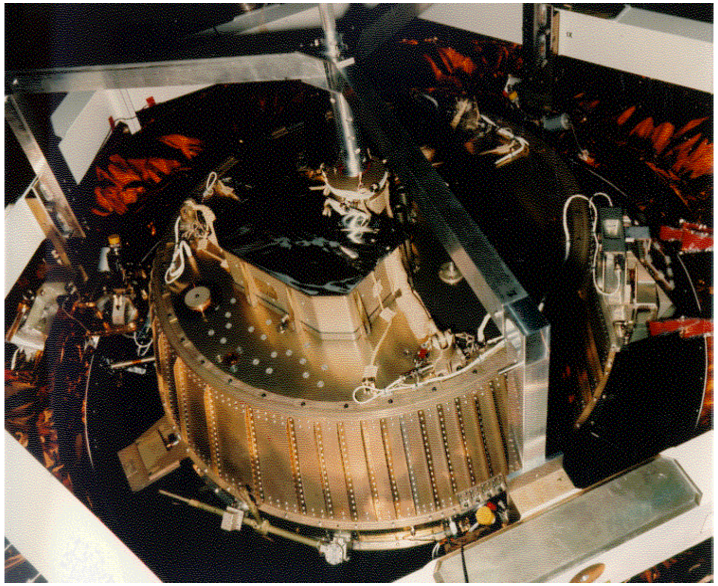
Huygens mission scenario



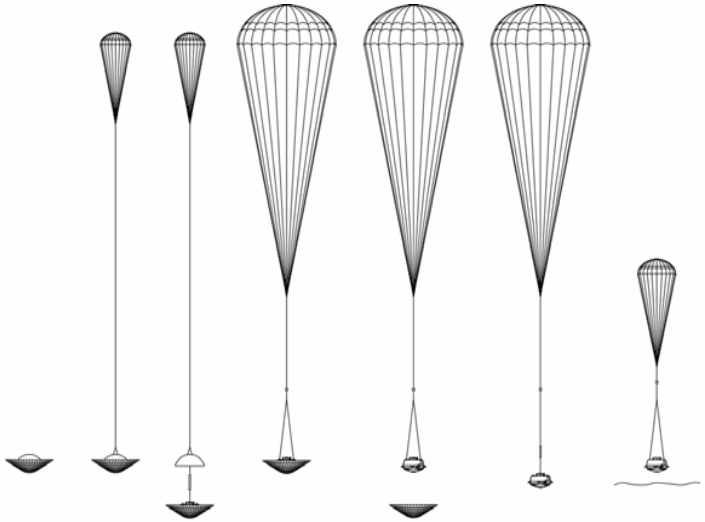
Source: Huygens User Manual Operations
HUY.AS/c.100.OP0384 rev 04 15 June 97
Table 1.9-7.

Huygens Descent Control Sub-System

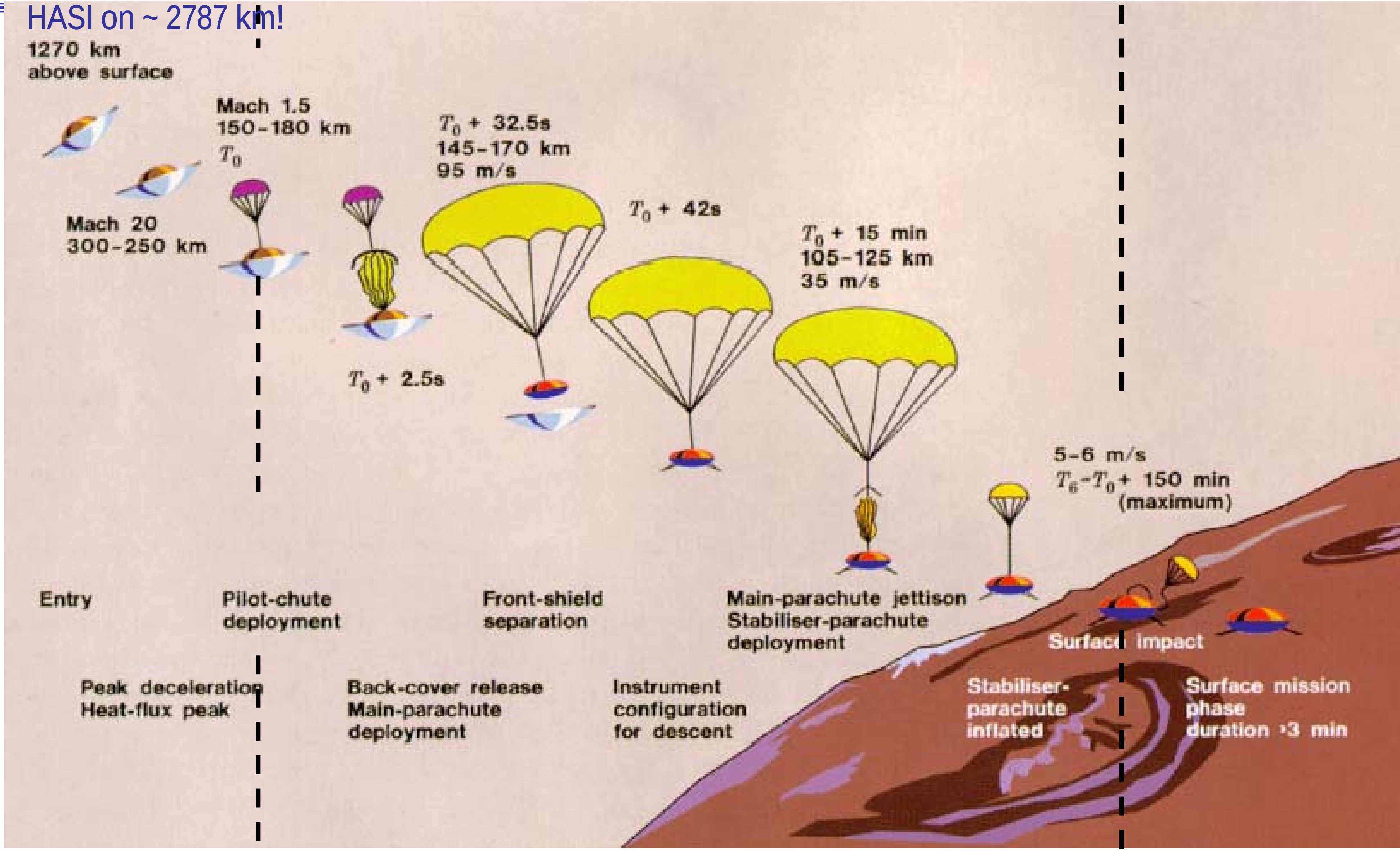
- Sequence of 3 parachutes and mechanisms that take Huygens from Mach 1.5 to the surface



- T_0 – Mach 1.5
  - Pilot Chute Deployed
- T_0 + 2.5s
  - Back cover released
  - Main parachute deployed
- T_0 + 35 sec
  - Front Shield released
  - Science starts
- T_0 + 15 min
  - Main Parachute released
  - Stabilising Drogue deployed
- Maximum descent time: 2½ hours



Huygens mission sequence at Titan

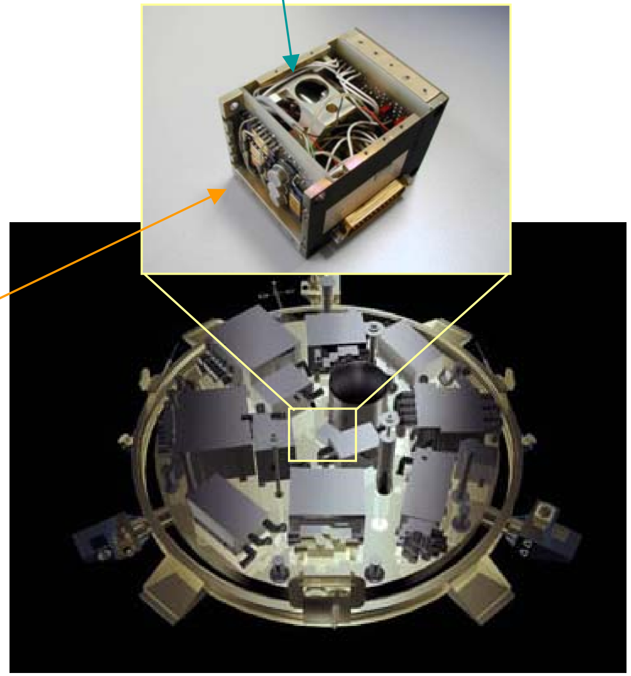


Entry Phase | Descent Phase | Surface Phase

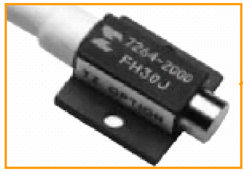
HASI ACC subsystem

- **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



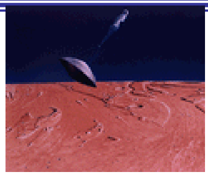
- **3 piezo-resistive accelerometers** (ENDEVCO 7264A-2000T) on the X, Y or Z axes of the Probe

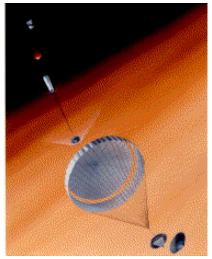
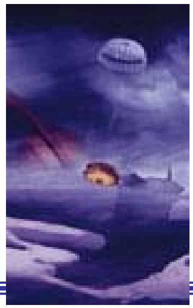


- **2 AD 590 temperature sensors**, one inside the servo accelerometer case (Temp 1) and one attached to the aluminium alloy accelerometer mounting block (Temp 2) for compensation.

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

ACC performance: comparison with previous missions

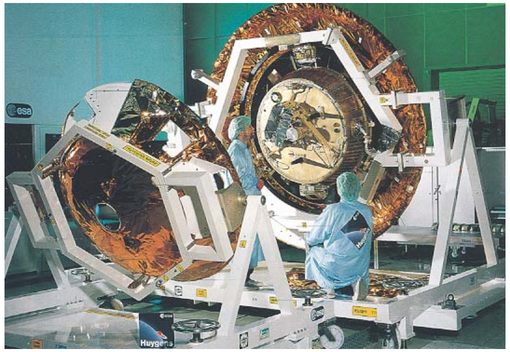


Missions	*Uncertainty in High Sensitivity Range (μg)*
Venera 8-14	$3x10^6$
Viking 1 & 2	±6.1
Pioneer Venus	Most sensitive channels (100 μg & 10 mg) failed
Galileo probe	4000
Mars Pathfinder	~ 4 (noise)
Mars Exploration Rover (MER)	35 (noise)
Huygens CASU Huygens RASU	range 0-10 g; resolution 4 mg range 0-120 mg; resolution 470 μg
Huygens HASI ACC	Noise: 0.3; resolution: 0.3 ; offset: $\leq$ 4

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.



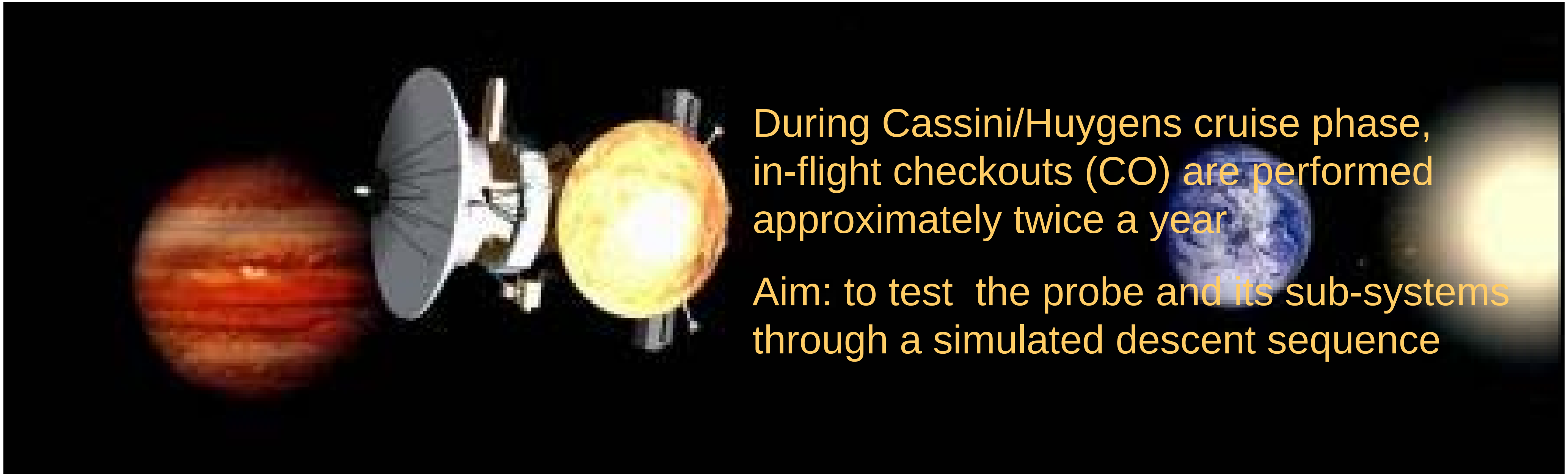
- Conversion from raw units (*Volts*) to scientific units (*acceleration* in *ms*$^{-2}$)

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

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

- Cruise in-flight check-outs and calibration.

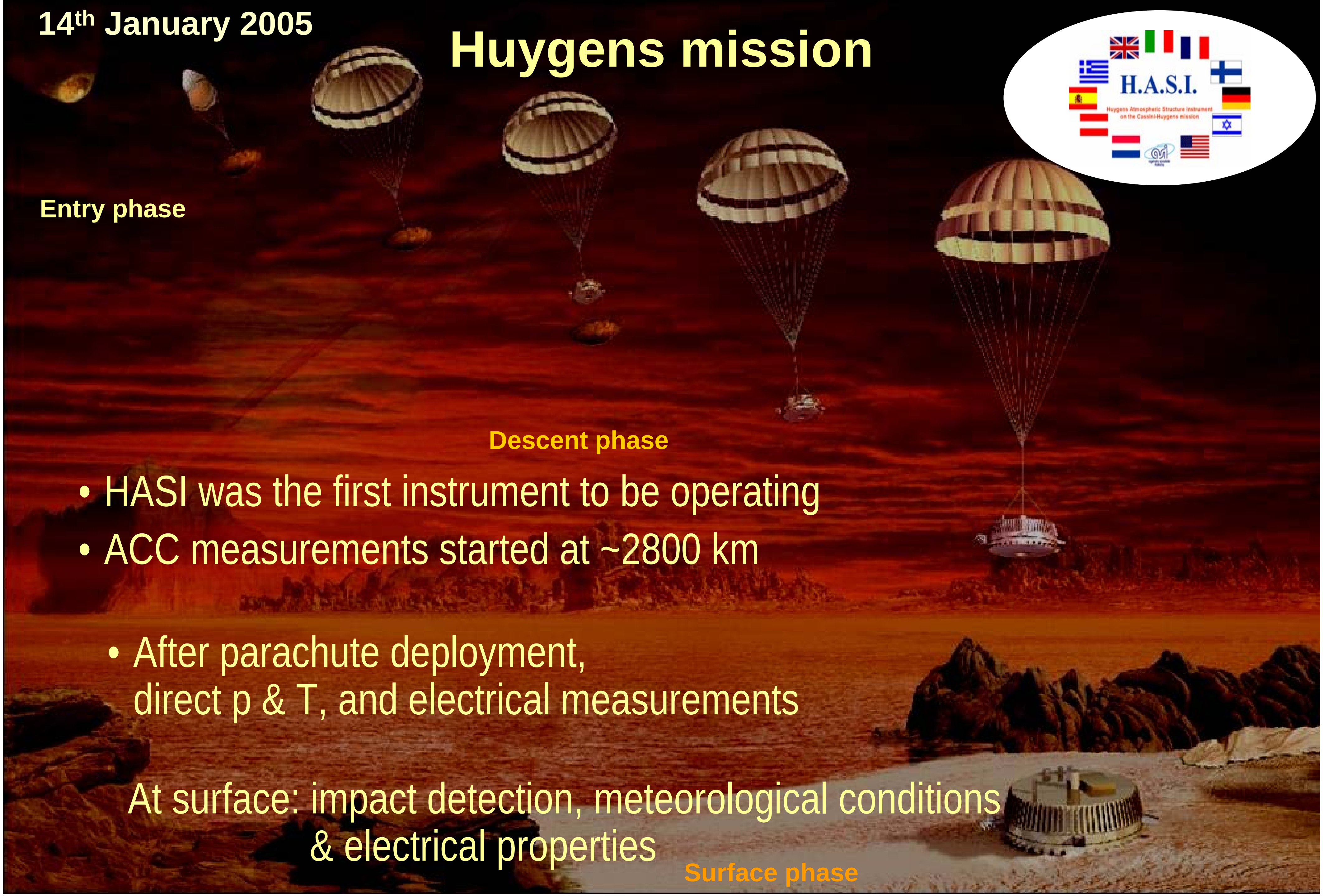
Huygens In-Flight checkouts



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.

14th January 2005

Huygens mission



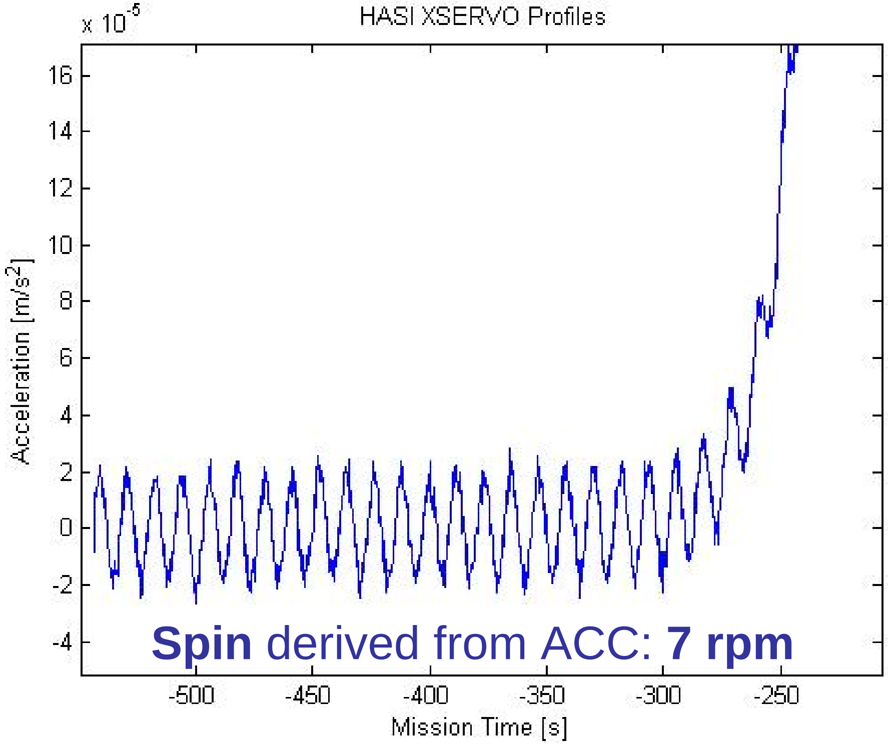
- HASI was the first instrument to be operating
- ACC measurements started at ~2800 km

- After parachute deployment, direct p & T, and electrical measurements

At surface: impact detection, meteorological conditions & electrical properties

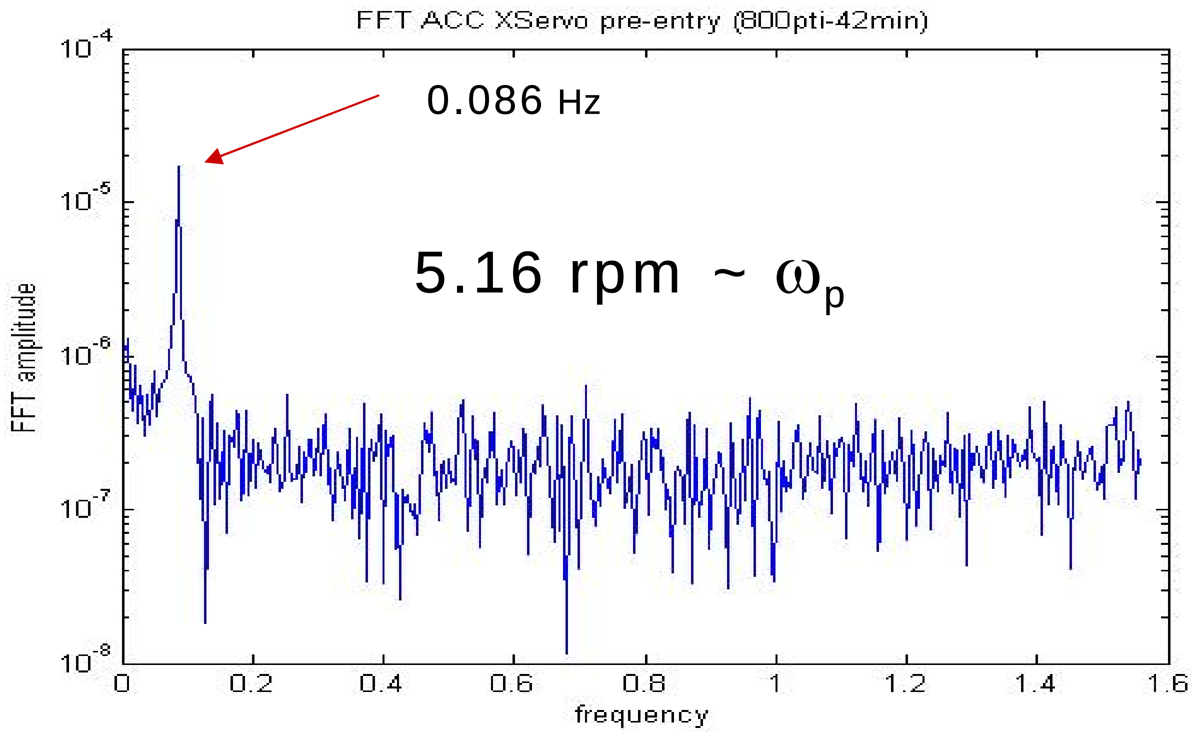
HASI operational report

- HASI switched on before atmospheric entry
- HASI ACC measurements starting from ~ 2800 km
- Most accurate accelerometer ever flown in a planetary probe
- Sensitivity threshold (0.3μg≅3E-06 m/s2) allows to measure Probe coning motion.



ACC provided by UKC-Open University
CoIs: J.C. Zarnecki, J.A.M. Mc Donnell

Spin in pre-entry

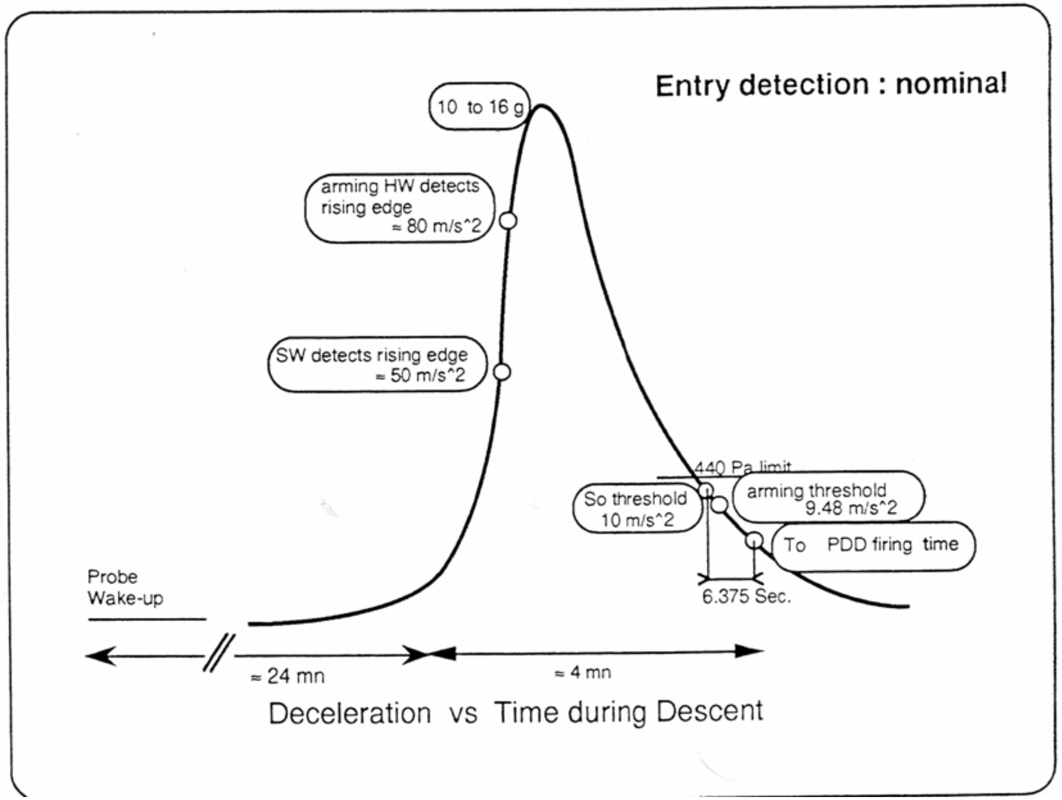


$$\omega_X = \omega_p \frac{1}{\sqrt{\frac{abs\left(\left(I_{ZZ} - I_{XX}\right)\left(I_{XX} - I_{YY}\right)\right)}{I_{ZZ} I_{YY}}}} = 6.9970 \text{ rpm}$$

$$\omega_x = \omega_p / (I_{xx} / I_{later} - 1)$$

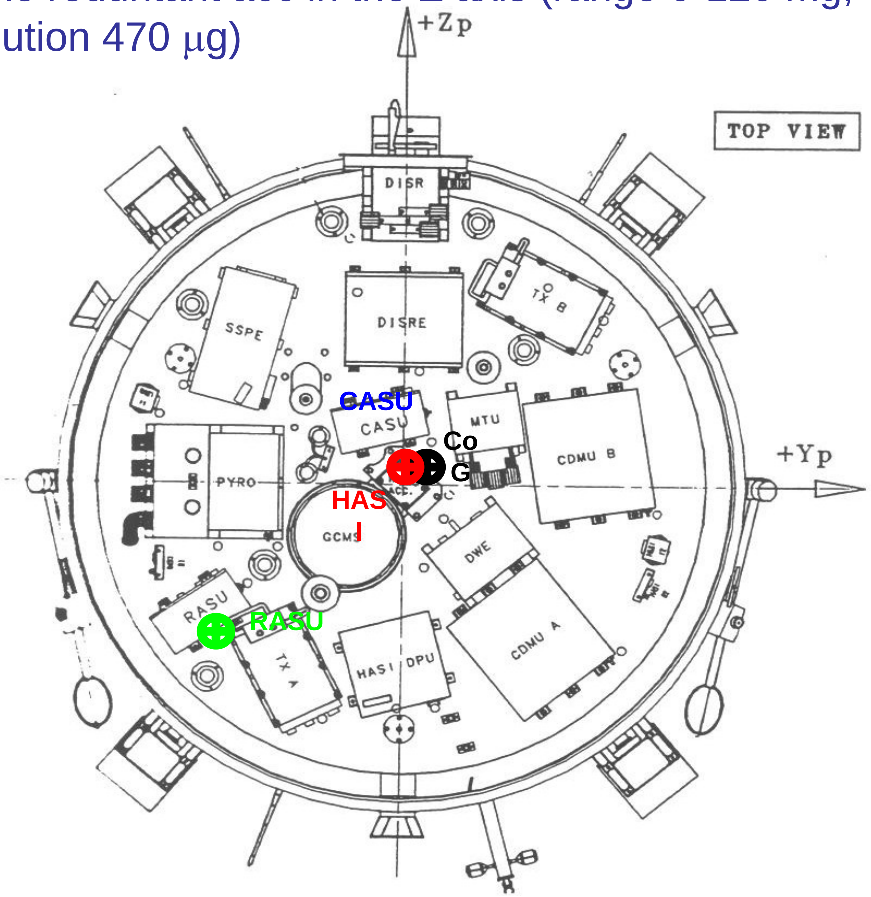
$\Rightarrow$ 7.5 ($I_{later} = I_{yy}$)
6.6 ($I_{later} = I_{zz}$)
7.05 ($I_{later} = (I_{yy} + I_{zz})/2$)

Entry detection



Huygens **CASU** (Central Accelerometer S/S Unit) a triply redundant acc on the X axis (SYSTRON DONNER 4310 F linear servo acc, range 0-10 g, resolution 4 mg)

Huygens **RASU** (Radial Accelerometer S/S Unit) a double reduntant acc in the Z axis (range 0-120 mg, resolution 470 μg)



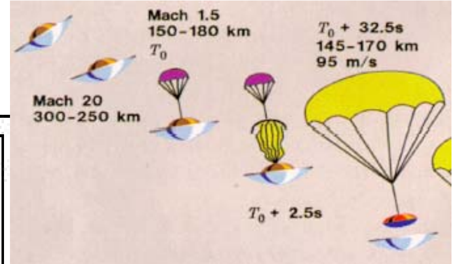
T_a arming of chute deployment pyro device (PDD); threshold 9.48 m/s²

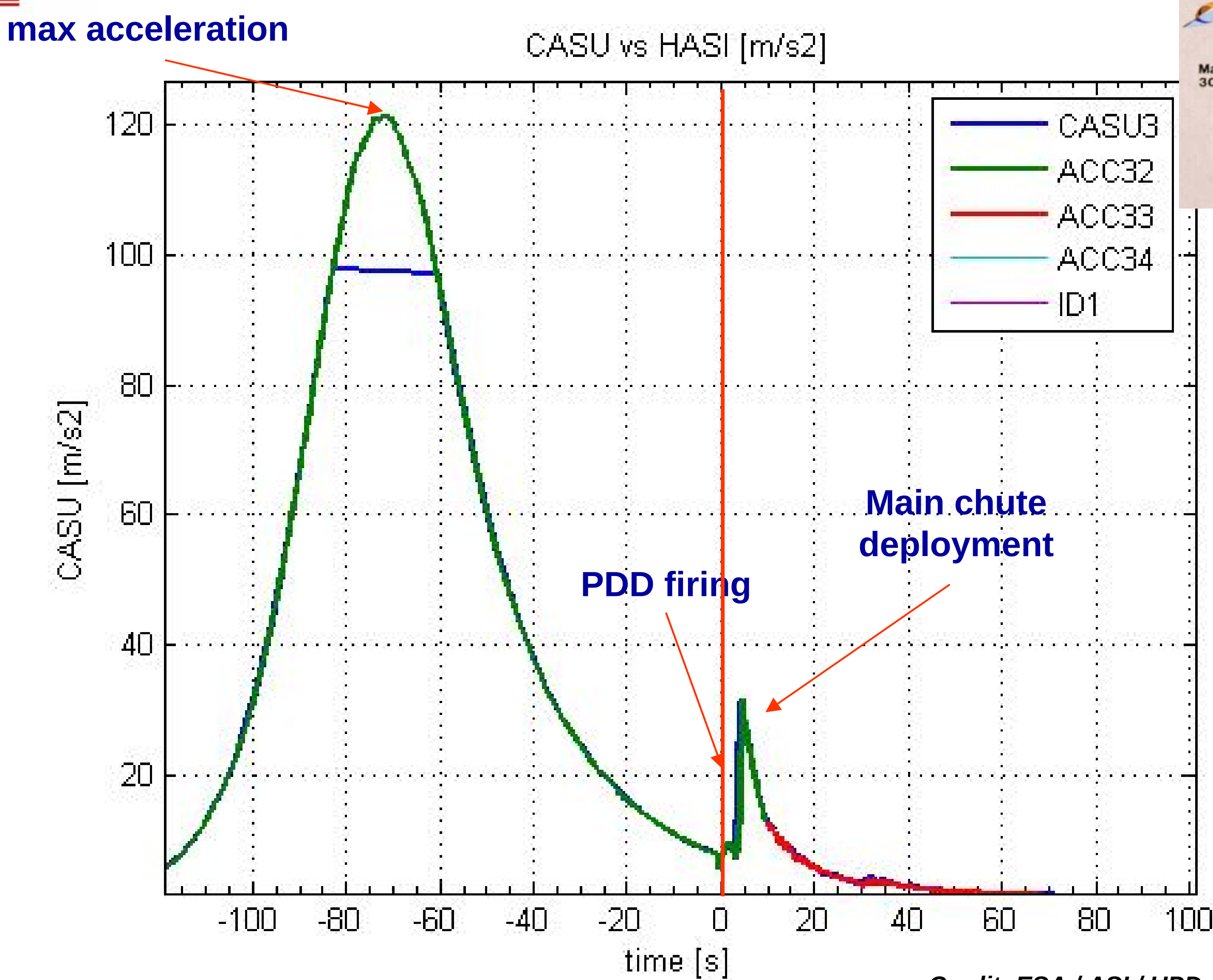
S_0 (Pilot chute deployment) threshold 10 m/s2

S_0 detection + majority voting by CDMU

T_0 (S_0 + 6.375s) PDD firing time

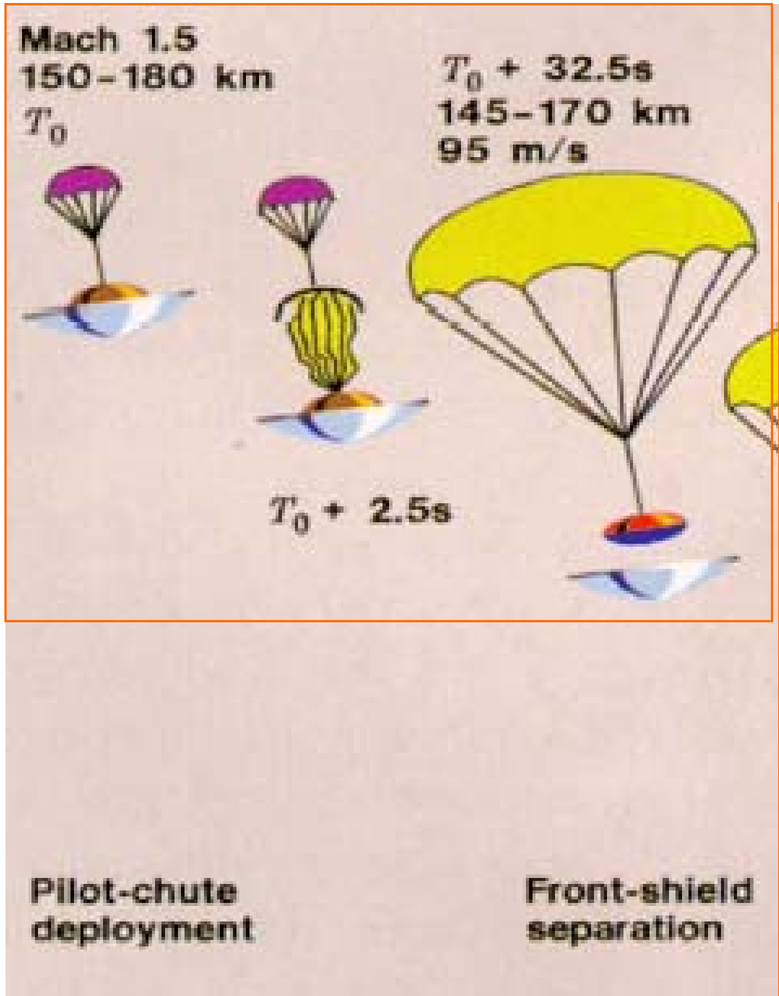
HASI ACC during entry

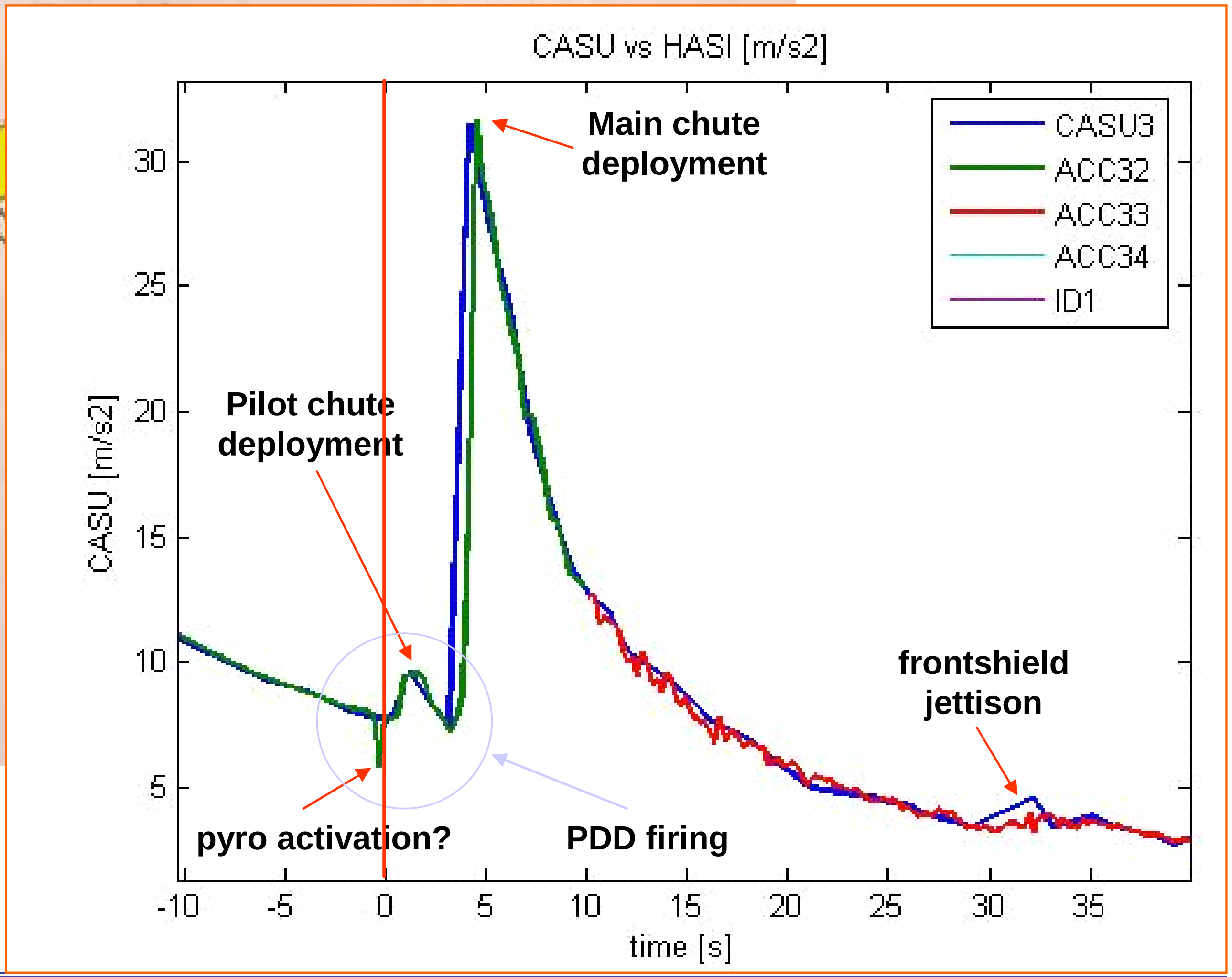




Credit: ESA / ASI / UPD / OU /

HASI ACC: beginning of descent

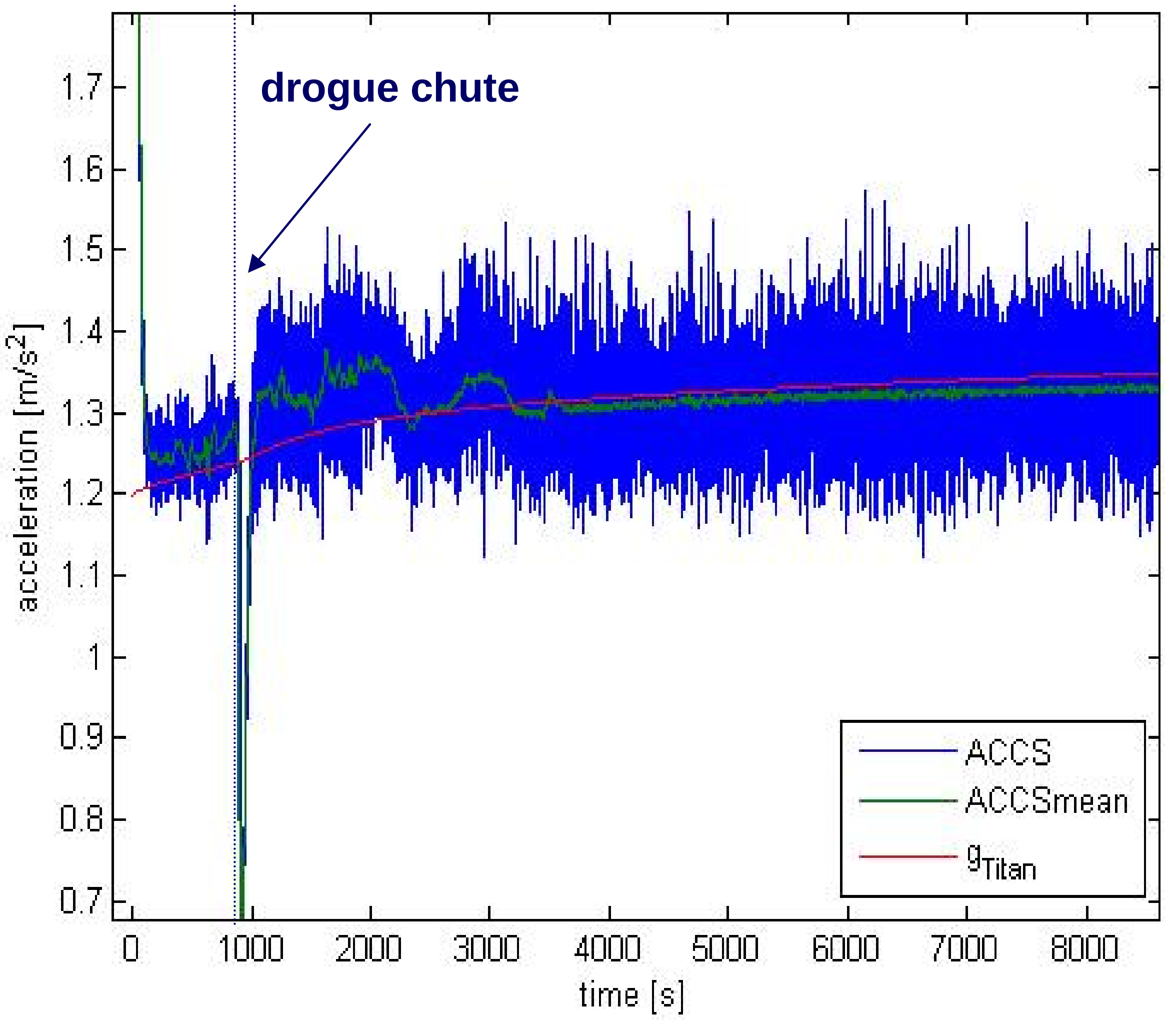




Beginning of descent

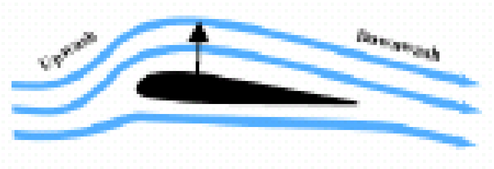
ACC XServo during descent

Main parachute jettison – Drogue chute deployment



Spin measurement

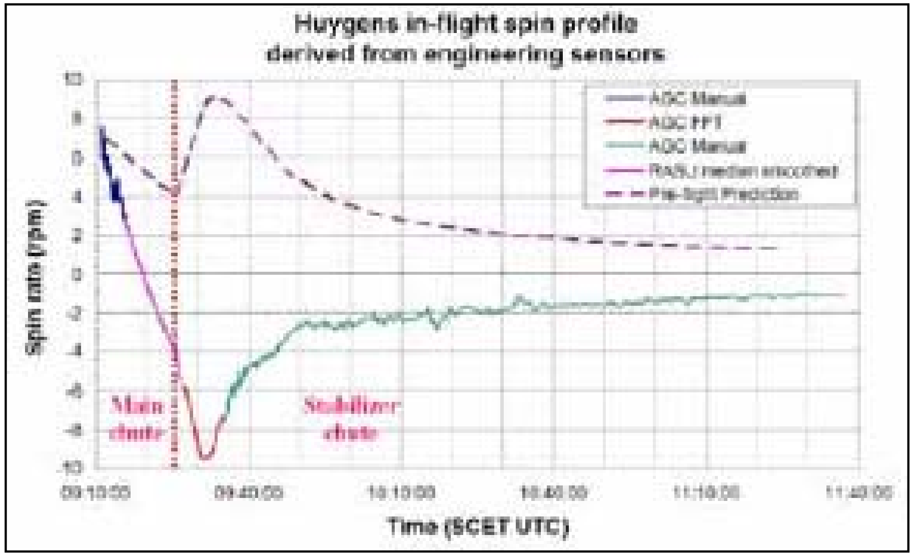
Huygens spin vanes



$$L = C_L * q * A = C_L * \frac{1}{2} * \rho * v^2 * A$$

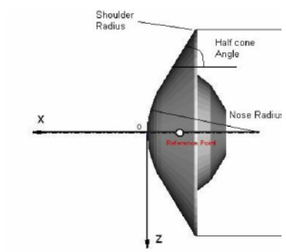
where L = lift force, C_L = lift coefficient,
q = dynamic pressure, ρ = density,
v = speed, and A=area

- Passive stabilization - Huygens spin
  - Use for dense atmosphere (e.g. Titan, Venus)
  - Aerodynamics / environment need to be well understood: Huygens spin anomaly
  - Spin measured by Huygens RASU (Radial Accelerometer Unit) a double redundant acc on the Z axis (range 0 - 0.12 mg)

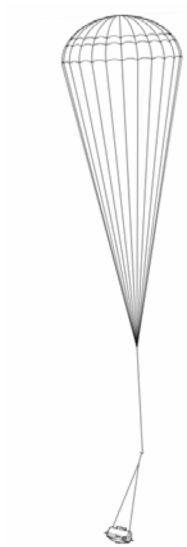


Trajectory and attitude reconstruction

- Algorithms for simulation and reconstruction of trajectory and attitude reconstruction has been developed and validated with mission data and from balloon experiments:



  – **6 DoF dynamical model + Extended Kalman Filter** for the entry phase: modelling of system dynamics and sensors (aerodynamical forces and ACC data) [Aboudan et al. PSS 2008]

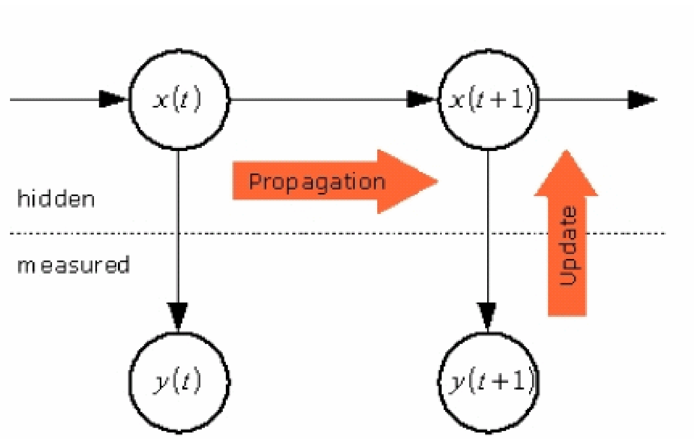


  – **1 DoF dynamical model** of the Probe under parachute with **Kalman filter** and **sensor fusion** (ACC, PPI,TEM, GCMS post Ta atmosphere reference) [Bettanini et al. 2008]

  – **3 DoF reconstruction algorithm** for atmospheric profiles reconstruction [Colombatti et al. PSS 2008; Gaborit et al. 2004; Atkinson et al. 2005]
    starting from a nominal entry state reconstruction of the trajectory and derivation of the atmospheric profile using hydrostatic equilibrium

Kalman filtering techniques

- To combine two independent estimates of a variable to form a weighted mean value
- Requires careful modelling of system dynamics and sensors
- State equations including statistical models of random phenomena: e.g. mitigate random and in-run biases on accelerometers and gyros
- Statistical description of the system uncertainty and measurements errors.
- Extended Kalman Filter (EKF) allows for dealing with no linearity in dynamical model with more accuracy than standard algorithms



State vector:

- Attitude
- Position
- Velocity

Measurement:

- Acceleration

State equations

$$^{b}\dot{\omega} = {}^{b}I\{{}^{b}\tau_{P} - {}^{b}\omega \times {}^{b}I\,{}^{b}\omega\} + \epsilon_{\omega}$$

$$^{b}\dot{q}_{i} = \frac{1}{2}\Omega({}^{b}\omega)\,{}^{b}q_{i}$$

Attitude

$$^{b}\dot{v} = \frac{1}{m}\left({}^{b}f_{A} + {}^{b}f_{N} + {}^{b}f_{G}\right) - {}^{b}\omega \times {}^{b}v + \epsilon_{v}$$

$$^{i}\dot{p} = {}^{i}R_{b}\,{}^{b}v$$

Position

$$\dot{\delta}_{\rho} = -\frac{1}{\beta}\delta_{\rho} + \epsilon_{\delta}$$

$$\dot{P} = \rho\,{}^{b}f_{G}^{T}\cdot{}^{b}v$$

Atmosphere

Huygens trajectory reconstruction

1. Angle of attack can be estimated from acceleration ratio

$$a_A = a_X \;,\; a_N=\sqrt{a_Y^2+a_Z^2} \Rightarrow \tan(\alpha)\simeq \frac{a_N}{a_A}$$

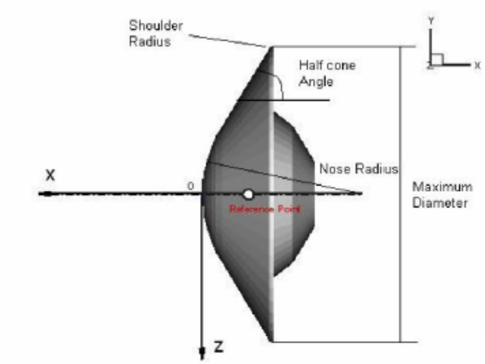
2. Acceleration can be integrated twice to compute velocity and position

$$a \Rightarrow v=\int a\,dt \Rightarrow p=\int v\,dt$$

3. Using the knowledge of aerodynamics of the probe (AEDB) the atmosphere density can be computed from measured axial acceleration

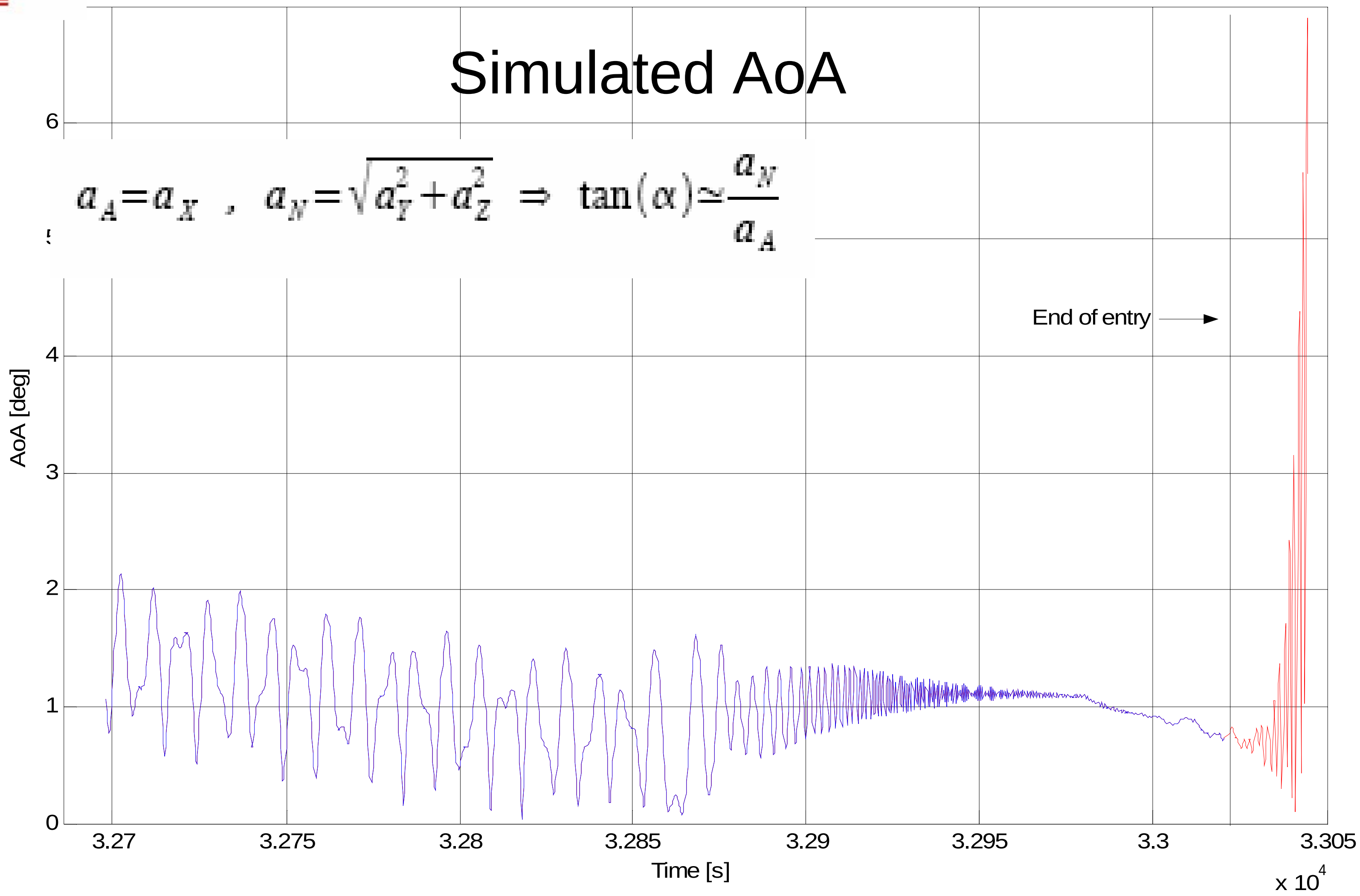
$$a_X = \frac{C_A\cdot\rho\cdot L\cdot\|v\|^2}{2\cdot m} \Rightarrow \rho = \frac{2\cdot m\cdot a_X}{C_A\cdot L\cdot\|v\|^2}$$

Steps from 1 to 3 can be iterated many times until convergence



AoA / attitude computation is the most important task for accurate trajectory reconstruction

Huygens 6 DoF dynamical model + EKF

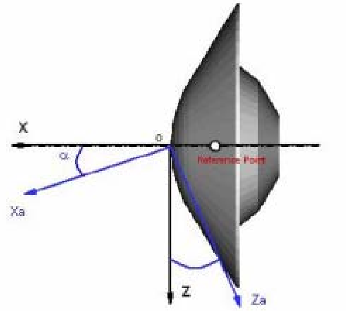


$$a_A = a_X \quad , \quad a_N = \sqrt{a_Y^2 + a_Z^2} \quad \Rightarrow \quad \tan(\alpha) \simeq \frac{a_N}{a_A}$$

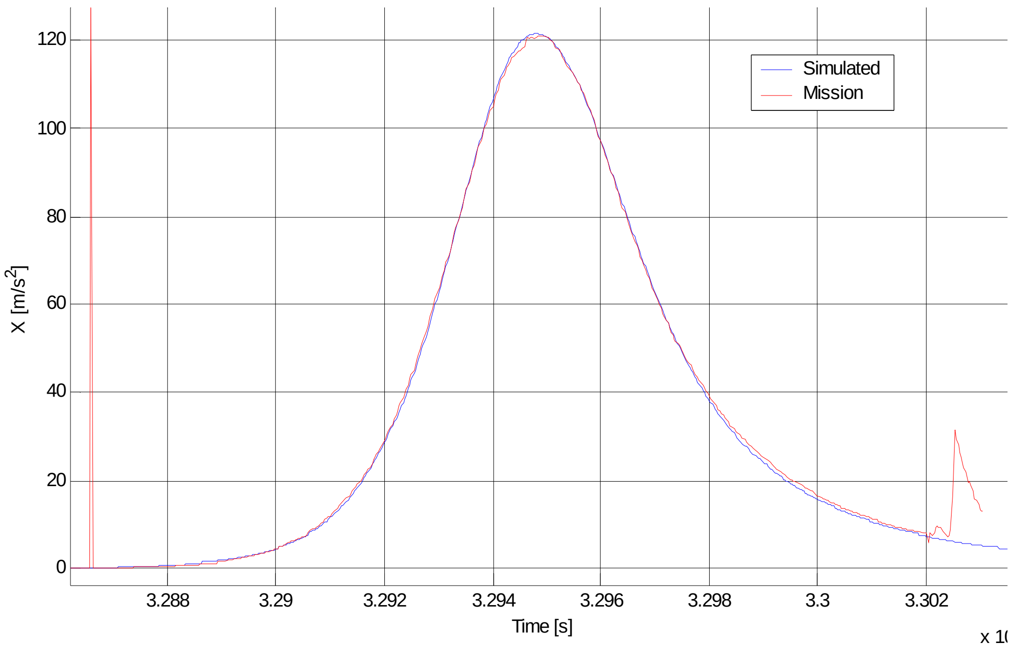
Entry phase ends before terminal dynamical instability phenomena so AoA is constrained to be less than 2 deg., about 1 deg during deceleration phase.

Huygens 6 DoF dynamical model + EKF

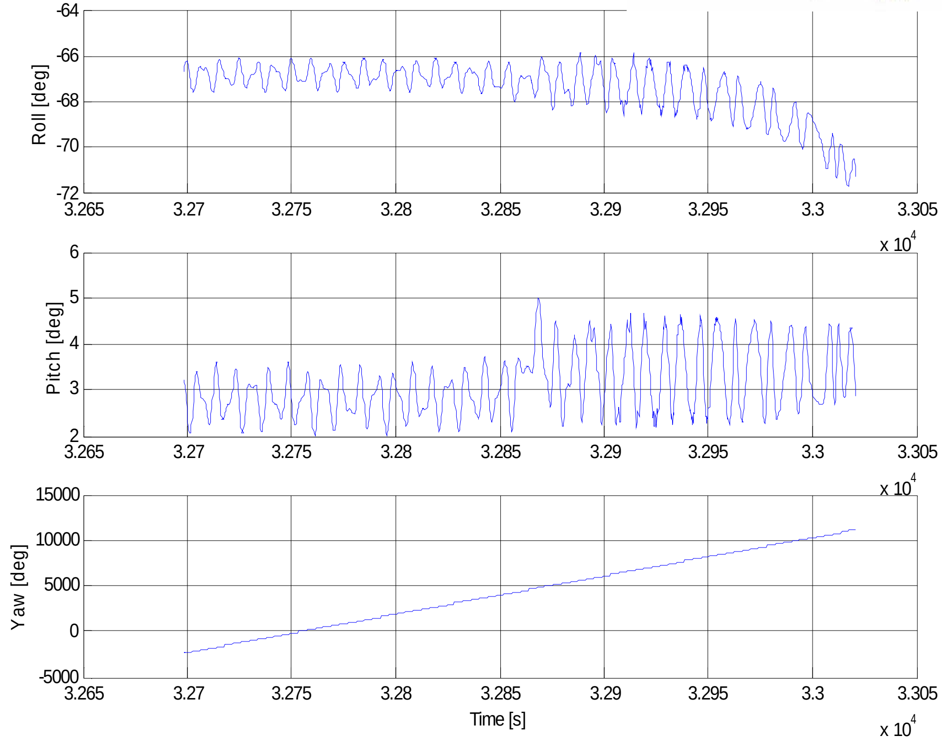
Entry phase



Deceleration peak



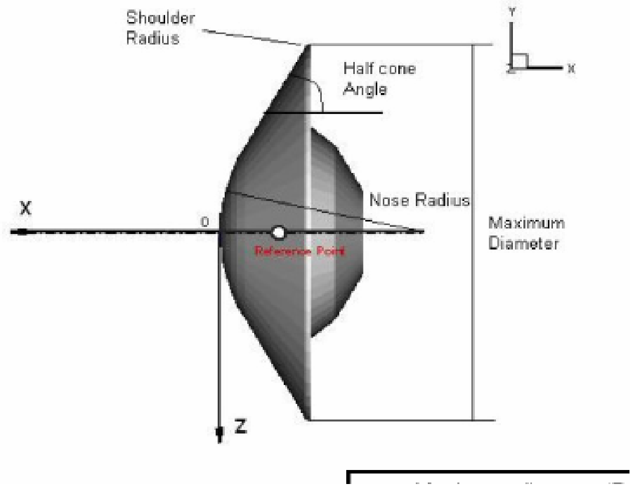
Attitude



[Aboudan et al. PSS 2008]

Needed info/requirements

- Entry state (e.g. through fligth dynamics, imaging)
- Entry/Descent module **MCI evolution**:
  - cross sectional area
  - mass & CoG (including front shield ablation)
  - inertial matrix
- **Parachute characteristics**
- Accurate **aerodynamical coefficients** (as function of Ma, Re, Kn) in free molecular flow, transitional and continuum regime



Requirements

- X-servo ACC @ CoM
- Normal acc component needed for accurate AoA/attitude (3-axial ACC or gyros)

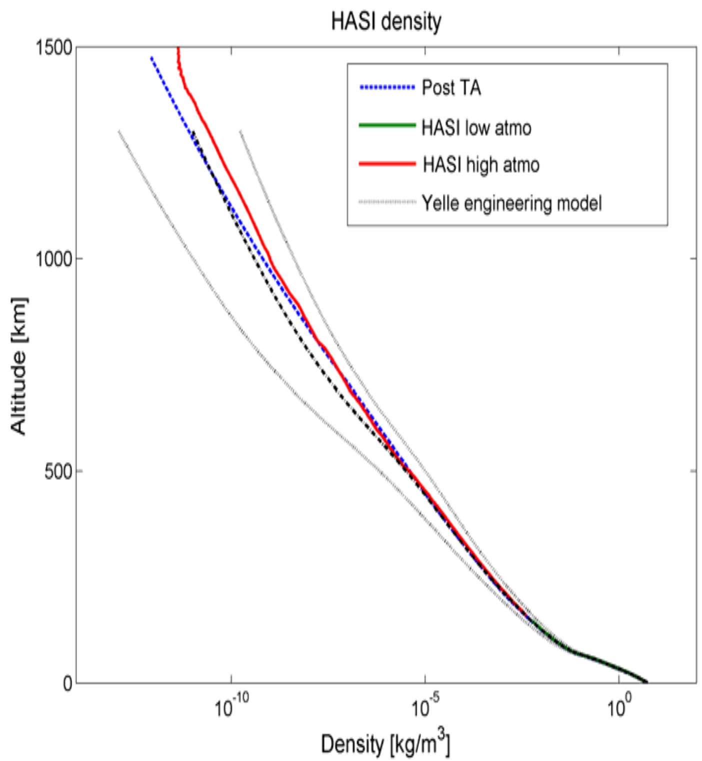
Upper atmospheric profile

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 $\rho= \mu p/RT$ ⟶ $T(z)$, $T=\mu p/\rho R$

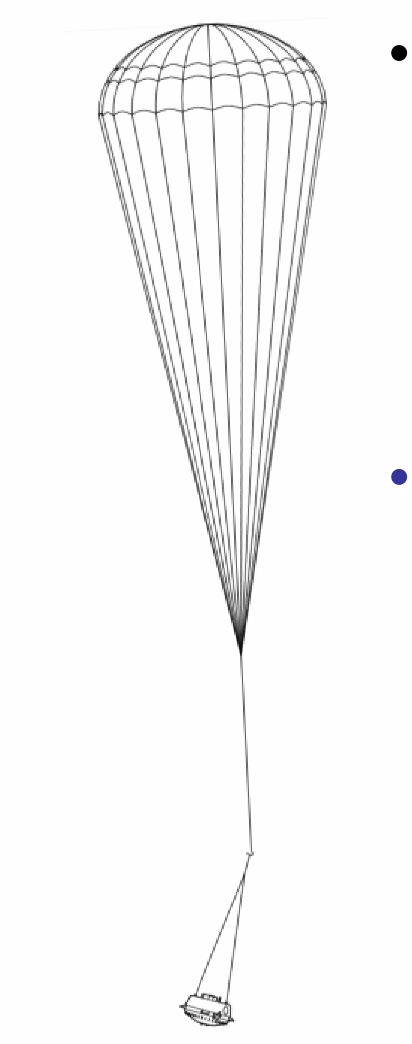
[Fulchignoni, Ferri et al. *Nature* 2005]

Upper atmosphere parameters: uncertainty

$$\rho = \frac{2\, m\, a}{v^2\, C_d\, A} \rightarrow \Delta\rho/\rho \sim 10\%$$

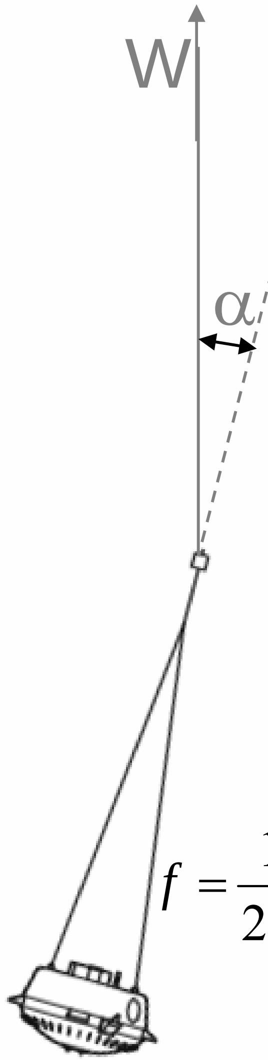
Parameter	value	comment	Uncertainty %
M	Probe mass	Measured & estimated (ablation)	~ 1%
v	Velocity relative to atmosphere	To be derived from time integration of acceleration	~ 2 %
Initial conditions	*Entry state* *1 sigma altitude* *FPA*	*Provided by Cassini NAV*	*~ 30 km* *± 0.3°*
C_d	Aerodymanical drag coefficient	From Huygens aerodynamical data base	5%
A	Probe cross-sectional area	Measured & estimated (ablation)	0.1%
a	Probe acceleration	measured	@1300 km ~ 5% @1200 km ~ 1%

Parachute-probe descent



- Measurements of the deceleration profiles and the recovery of density could be applied during descent to infer **wind** motions and rapid oscillations due to self-excited aerodynamic motions or atmospheric **turbulence**.

- Wind gusts can be observed by monitoring the periodic oscillations of the probe-parachute system with the accelerometers and thus detecting any perturbations on these oscillations caused by wind
[Seiff *et al.*1993, 1997a].



$$f = \frac{1}{2\pi}\sqrt{\frac{\lambda W}{I}}$$

HASI ACC impact detection

IMPACT state devoted to Probe impact detection.
No ACC data transmitted until SURFACE state

Impact trace 0.5 s before impact and 5.5 s after detection (66 TM packets)

Xpiezo	at 200 Hz
Ypiezo	at 200 Hz
Z piezo	at 200 Hz

Impact detection

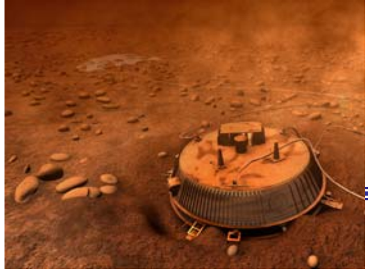
quadratic filtered 400 bHz Xservo LOW gain values (XS) against a threshold value (QfT)

$$Y(n) = QfA * Y(n-2) + QfB * Y(n-1) + QfC * Xs(n)$$

where

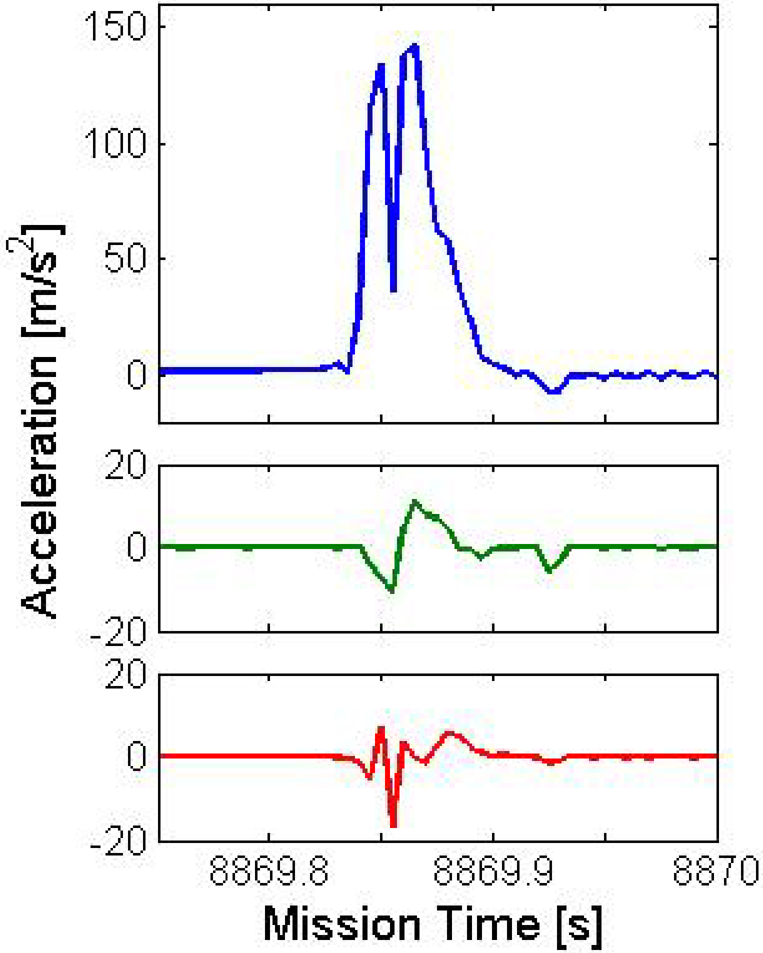
Xs(n)	is the Xservo LOW gain channel output at the n-th instant;
Ys(n)	is Filter output at the n-th instant;
Ys(n-2)	is Filter output at the (n-2)-th instant;
Ys(n-1)	is Filter output at the (n-1)-th instant;
QfA, QfB, QfC	are the filter coefficients (PROM default are **QfA** = 0.1, **QfB** = 0.2, **QfC** = 0.7);
QfT	is the threshold value (PROM default is **QfT** = +5Volt).

Formula I: Impact detection filter



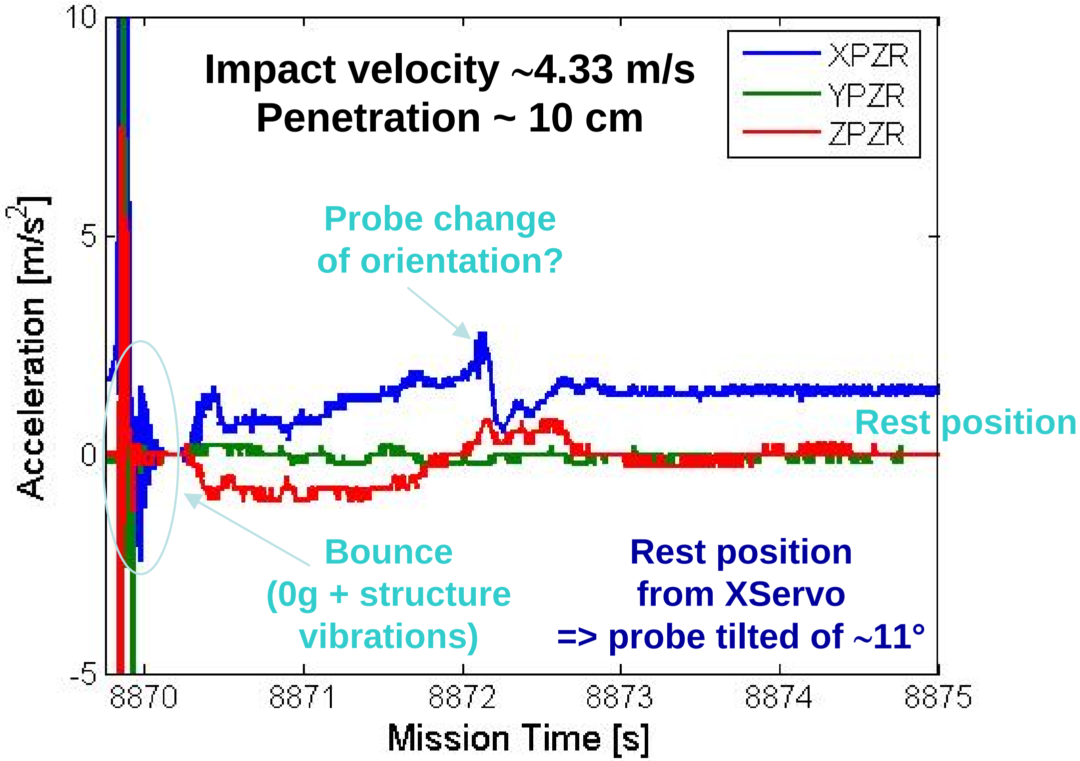
Huygens impact detection

peak

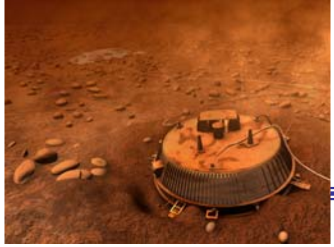


3 axis ACC piezoresistive sensors for 6 s 200Hz

Post-impact

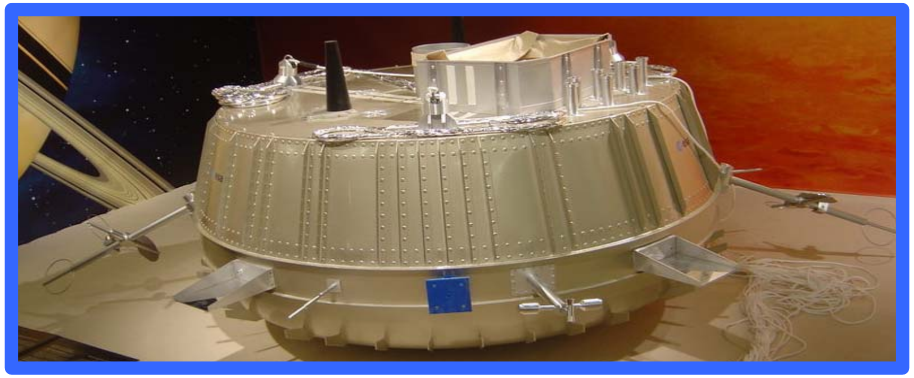


T_{impact}=2:27:49.840 (8869.840s)

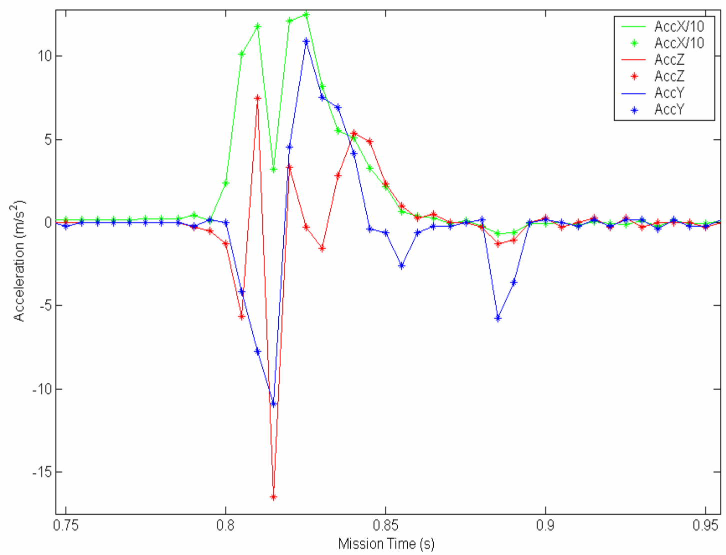


Huygens impact detection

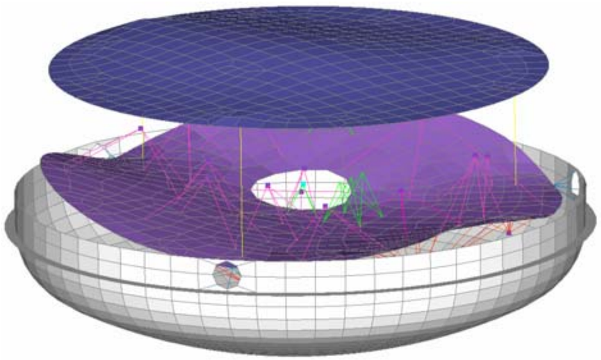
- IMPACT
  - Accelerometers can be used for to characterize the mechanical properties of the surface (e.g. Huygens SSP [Zarnecki et al. *Nature* 2005]).
  - Structural modelling of the Probe to analyse the response to the impact [Bettanini, Zaccariotto, PSS 2006]



HASI ACC data

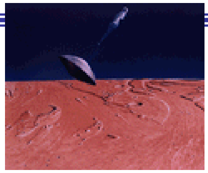


FEM model



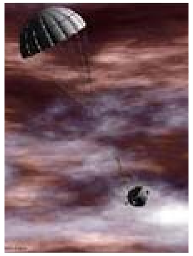
Lessons learned and requirements

Viking

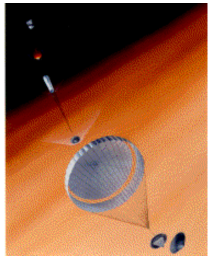


Pioneer Venus

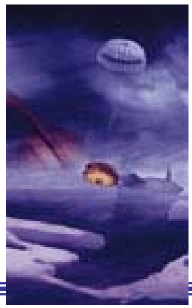
Galileo



Mars Path-finder



Huygens



Experience *and* ***lessons*** *learned with* ***Huygens*** *in perspectives for future in situ exploration:* ***ExoMars***

- **Accurate knowledge of the entry state (initial position, velocity) by flight dynamics, probe imaging, radio tracking …**
- **Instrumented heat shield for engineering assessment of entry phase and support of trajectory (and atmospheric profile) reconstruction.**
- **For EDLS dynamics reconstruction 3-axial ACC and/or gyros are necessary for a accurate attitude (AoA) determination**
- **Redundant devices to ensure safety (e.g. G-switch)**
- **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 sensor performance of with real data**

Genesis