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

Accelerometers / Gyros

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EDLS measurements

• **Entry, Descent, Landing System (EDLS)** of an atmospheric probe or lander requires measurements 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.
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

- **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, rigidly 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.

**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

16-17 June 2012, Toulouse, France
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ACC / Gyros
F. Ferri / UniPD-CISAS
High Accuracy Accelerometers

Force-balance (Servo) Accelerometers

- 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.

HASI ACC principle, performance and accommodation

<table>
<thead>
<tr>
<th>Mode</th>
<th>Range High Gain</th>
<th>Resolution High Gain</th>
<th>Range Low Gain</th>
<th>Resolution Low Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>High resolution</td>
<td>±2 mg</td>
<td>0.3 µg</td>
<td>±20 mg</td>
<td>3 µg</td>
</tr>
<tr>
<td>Low resolution</td>
<td>±1.85 g</td>
<td>3 mg</td>
<td>±18.5 g</td>
<td>1 mg</td>
</tr>
</tbody>
</table>

Example: Huygens HASI x-axis servo accelerometer

<table>
<thead>
<tr>
<th>Type</th>
<th>Honeywell QA 2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (servo sensor / total)</td>
<td>71g / 300g</td>
</tr>
<tr>
<td>Power</td>
<td>~1.7 Watts</td>
</tr>
<tr>
<td>Accuracy</td>
<td>1% full scale</td>
</tr>
</tbody>
</table>
Piezoresistive Accelerometers

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

Example: Huygens HASI X / Y / Z accelerometers

<table>
<thead>
<tr>
<th>Type</th>
<th>Endevco 7264A-2000T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency range</td>
<td>0 – 1000 Hz (5%)</td>
</tr>
<tr>
<td>Range / Resolution</td>
<td>+/- 20g / +/- 50 mg</td>
</tr>
<tr>
<td>Nonlinearity / Hysteresis</td>
<td>+/- 3%</td>
</tr>
<tr>
<td>Mass</td>
<td>1g (sensor)</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass / size</td>
<td>&lt; 1 g, 5 x 5 x 2 mm</td>
</tr>
<tr>
<td>Acceleration range</td>
<td>+/- 35 g to +/- 70 g</td>
</tr>
<tr>
<td>Temp range</td>
<td>-40 to +105 deg C</td>
</tr>
<tr>
<td>Accuracy</td>
<td>Linearity 0.2%</td>
</tr>
<tr>
<td>Power @ Supply voltage</td>
<td>6.5 mW @ +5 V</td>
</tr>
</tbody>
</table>
Gyroscopes (‘Gyros’)

Gyroscope

- Devices for measuring orientation, based on the principle 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

Fiber Optic Gyros (FOG)

- Use optical fibre as propagation path
- Measure angular motion by detecting phase difference
- Very robust

Example: high performance fiber optic gyro performance for space

<table>
<thead>
<tr>
<th>Type</th>
<th>FOG 2500, Northrop Grumman</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drift rate</td>
<td>0.001 deg / hr</td>
</tr>
<tr>
<td>Max rate</td>
<td>100 deg / sec</td>
</tr>
<tr>
<td>Power</td>
<td>5W</td>
</tr>
<tr>
<td>Size</td>
<td>170 mm dia x 54 mm</td>
</tr>
<tr>
<td>Mass</td>
<td>~2 kg</td>
</tr>
</tbody>
</table>
**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)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>I/F / rad-hardness</td>
<td>RS422 / MIL1553, 100 krad</td>
</tr>
<tr>
<td>Mass</td>
<td>4.44 kg typ.</td>
</tr>
<tr>
<td>Size</td>
<td>~233mm dia x 169mm</td>
</tr>
<tr>
<td>Power</td>
<td>22W typ.</td>
</tr>
<tr>
<td>Gyro bias (1-sigma)</td>
<td>&lt; 0.005 deg /hr</td>
</tr>
<tr>
<td>Scale factor</td>
<td>&lt; 1 ppm</td>
</tr>
</tbody>
</table>

**Example: NASA MER IMU Litton LN-200S**

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>750 g</td>
</tr>
<tr>
<td>Size</td>
<td>~90mm dia x 90mm</td>
</tr>
<tr>
<td>Power</td>
<td>12W</td>
</tr>
<tr>
<td>MTBF</td>
<td>20,000 hrs</td>
</tr>
</tbody>
</table>

**Accuracy related parameters**

- Bias, Scale factor (acc, gyro)
- Random walk (gyro)
- Measurement limits (acc & rotation)
Operational scenario

- Ballistic entry trajectory
- 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) 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)
Mars Science Laboratory EDL

Guided Entry (GNC)

Expected arrival: August 2012

Powered descent

Descent Imaging

Bigger Parachute

Sky Crane

Expected arrival: August 2012

Powered Descent, Sky Crane & Flyaway

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The Huygens Probe Mission

An example for a probe mission, data analysis and technical and science issues
Huygens Probe Exploded View

1. Heat Shield
2. Front Shield
3. Back Cover
4. Parachute Compartment
5. Descent Module with Scientific Instruments

Huygens Titan Probe Mechanical Exploded View

- SPIN/EJECT DEVICE
- AFTER CONE
- EXPERIMENT PLATFORM
- BACK COVER
- TOP PLATFORM
- FORE DOME
Huygens Integration

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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*
Entry

T0 = 0 sec
Mach 1.5
h=159 km
Fire PDD

T0 = +1.4 sec
2.59 m dia
DGB Pilot Chute Inflation

T0 = +2.5 sec
Release Aft Cover Deploy 8.30 m dia DGB Main

T0 = +32.5 sec
Mach < 0.6 Release Front Shield

T0 = +10 sec

Huygens Instruments beginning activities

T0 = +4.9 sec
Main chute Inflation

T0 = +3.4 sec
Stabilizer Inflation

T0 = +15 min 3.4 sec
Stabilizer Inflation

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

Nominal 1270 km Interface Altitude

Start of Descent Phase

Entry

About 3 minutes; Depends on atmospheric conditions

Huygens mission scenario

Huygens Probe Descent Events
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
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Descent Phase
- HASI on ~ 2787 km
- Mach 20, 300-250 km
- Mach 1.5, 150-180 km
- $T_0 + 32.5s$, 145-170 km, 95 m/s
- $T_0 + 42s$
- $T_0 + 15$ min, 105-125 km, 35 m/s
- 5-6 m/s, $T_0 + 150$ min (maximum)
- Stabiliser-parachute inflated
- Surface mission phase duration >3 min

Surface Phase
- Surface impact
- Instrument configuration for descent
- Main-parachute jettison
- Front-shield separation
- Pilot-chute deployment
- 1270 km above surface
HASI ACC subsystem

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

<table>
<thead>
<tr>
<th>Mode</th>
<th>Range</th>
<th>Resolution</th>
</tr>
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<tr>
<td></td>
<td>High Gain</td>
<td>Low Gain</td>
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<td>±20 mg</td>
</tr>
<tr>
<td>Low resolution</td>
<td>±1.85 g</td>
<td>±18.5 g</td>
</tr>
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</table>

- **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

<table>
<thead>
<tr>
<th>Missions</th>
<th>Uncertainty in High Sensitivity Range (μg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Venera 8-14</td>
<td>3x10⁶</td>
</tr>
<tr>
<td>Viking 1 &amp; 2</td>
<td>±6.1</td>
</tr>
<tr>
<td>Pioneer Venus</td>
<td>Most sensitive channels (100 μg &amp; 10 mg) failed</td>
</tr>
<tr>
<td>Galileo probe</td>
<td>4000</td>
</tr>
<tr>
<td>Mars Pathfinder</td>
<td>~ 4 (noise)</td>
</tr>
<tr>
<td>Mars Exploration Rover (MER)</td>
<td>35 (noise)</td>
</tr>
<tr>
<td>Huygens CASU</td>
<td>range 0-10 g; resolution 4 mg</td>
</tr>
<tr>
<td>Huygens RASU</td>
<td>range 0-120 mg; resolution 470 μg</td>
</tr>
<tr>
<td>Huygens HASI ACC</td>
<td>Noise: 0.3; resolution: 0.3; offset: ≤ 4</td>
</tr>
</tbody>
</table>

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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 \( ms^{-2} \))

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

where: \( sf = \text{scale factor} \), \( R_L = \text{load resistor} \).
- Cruise in-flight check-outs and calibration.
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 mission

14th January 2005

Entry phase

Descent phase

• 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

Surface phase
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.

• Atmosphere detected at ~ 1600 km
• During entry, atmospheric physical properties from accelerometer data

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

Spin derived from ACC: 7 rpm
Spin in pre-entry

\[ \omega_X = \omega_p \frac{1}{\sqrt{\text{abs}((I_{ZZ} - I_{XX})(I_{XX} - I_{YY}))}} \]

\[ \omega_X = \omega_p / (I_{xx} / I_{\text{later}} - 1) \]

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

FFT ACC xServo pre-entry (800pti-42min)

0.086 Hz

5.16 rpm \sim \omega_p

\( \omega = 6.9970 \text{ rpm} \)
**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 redundant 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

max acceleration

CASU vs HASI [m/s²]

PDD firing

Main chute deployment

Credit: ESA / ASI / UPD / OU /
HASI ACC: beginning of descent

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Pilot chute deployment
Front shield separation

Mach 1.5
150–180 km

$T_0$ + 32.5 s
145–170 km
95 m/s

$T_0$ + 2.5 s

Beginning of descent

CASU vs HASI [m/s²]

- Main chute deployment
- Front shield jettison
- Pyro activation?
- PDD firing

HASI ACC: beginning of descent

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Main parachute jettison – Drogue chute deployment

drogue chute

ACC XServo during descent

ACC XServo during descent

Main parachute jettison – Drogue chute deployment

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Spin measurement

Huygens spin vanes

- 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)

\[ L = C_L \cdot q \cdot A = C_L \cdot \frac{1}{2} \cdot \rho \cdot v^2 \cdot A \]

where \( L \) = lift force, \( C_L \) = lift coefficient, \( q \) = dynamic pressure, \( \rho \) = density, \( v \) = speed, and \( A \) = area
Trajectory and attitude reconstruction

- Algorithms for simulation and reconstruction of trajectory and attitude reconstruction have 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

\[
\begin{align*}
\dot{\omega} &= \dot{b} \left[ I_P^{-1} \omega \times I_P^{-1} \omega \right] + \epsilon_w \\
\dot{q}_i &= \frac{1}{2} \Omega \omega \cdot q_i \\
\dot{v} &= \frac{1}{m} \left( f_A + f_N + f_G \right) - \dot{b} \omega \times v + \epsilon_v \\
\dot{p} &= R v \cdot v \\
\dot{\delta}_p &= -\frac{1}{\beta} \delta_p + \epsilon_\delta \\
\dot{\rho} &= \rho f_G \cdot v
\end{align*}
\]
Huygens trajectory reconstruction

1. Angle of attack can be estimated from acceleration ratio

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

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.
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

Roll
Pitch
Yaw

[Aboudan et al. PSS 2008]
Needed info/requirements

- Entry state (e.g. through flight 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)
Entry phase

Upper atmospheric profile

From acceleration measurements

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

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

\[ V_r \text{ and } z \text{ from measured acceleration & initial conditions} \]

Indirect temperature and pressure measurements

Hydrostatic equilibrium \[ dp = -g\rho \, dz \]

Equation of state of gas \[ \rho = \mu p / RT \]

\[ \rho(z) \text{ and } T(z), T = \mu p / \rho R \]

Upper atmosphere parameters: uncertainty

\[ \rho = \frac{2 m a}{v^2 C_d A} \Rightarrow \Delta \rho/\rho \sim 10\% \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>value</th>
<th>comment</th>
<th>Uncertainty %</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>Probe mass</td>
<td>Measured &amp; estimated (ablation)</td>
<td>~ 1%</td>
</tr>
<tr>
<td>v</td>
<td>Velocity relative to atmosphere</td>
<td>To be derived from time integration of acceleration</td>
<td>~ 2%</td>
</tr>
<tr>
<td>Initial conditions</td>
<td>Entry state 1 sigma altitude FPA</td>
<td>Provided by Cassini NAV</td>
<td>~ 30 km</td>
</tr>
<tr>
<td></td>
<td></td>
<td>± 0.3°</td>
<td></td>
</tr>
<tr>
<td>C_d</td>
<td>Aerodynamic drag coefficient</td>
<td>From Huygens aerodynamical data base</td>
<td>5%</td>
</tr>
<tr>
<td>A</td>
<td>Probe cross-sectional area</td>
<td>Measured &amp; estimated (ablation)</td>
<td>0.1%</td>
</tr>
<tr>
<td>a</td>
<td>Probe acceleration</td>
<td>measured</td>
<td>@1300 km ~ 5%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>@1200 km ~ 1%</td>
</tr>
</tbody>
</table>
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].
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
- Zpiezo at 200 Hz

**Impact detection**

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

\[ Y(n) = QfA \times Y(n-2) + QfB \times Y(n-1) + QfC \times Xs(n) \]

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 \( QfT = +5\text{Volt} \)).

Formula I: Impact detection filter
Huygens impact detection

Impact velocity $\sim 4.33$ m/s
Penetration $\sim 10$ cm

Post-impact

Impact detection

3 axis ACC piezo-resistive sensors for 6 s 200Hz

T$_{\text{impact}} = 2:27:49.840$ (8869.840s)

Probe change of orientation?

Bounce (0g + structure vibrations)

Rest position from XServo

$\Rightarrow$ probe tilted of $\sim 11^\circ$
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]
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