# ATTITUDE ISSUES ON THE HUYGENS PROBE: BALLOON DROPPED MOCK UP ROLE IN DETERMINING RECONSTRUCTION STRATEGIES DURING DESCENT IN LOWER ATMOSPHERE.

**C. Bettanini (1), F. Angrilli (1)**
*(1)Centre of Studies and Activities for Space, CISAS "G.Colombo", University of Padova, via Venezia 15, 35131 Padova – Italy, Email :carlo.bettanini@unipd.it*

## ABSTRACT
As part of the collaboration with Italian Space Agency on HASI instrument for Huygens mission, University of Padova has been conducting since 2001 scientific activity on Stratospheric Balloon Launches from the Trapani base in Sicily. The most recent boomerang flight in July 2003 has successfully flown a mock up of the Huygens probe hosting spares of flight scientific units and extra housekeeping and scientific sensors on a parachuted descent from 33 kilometre altitude. This work presents the studies conducted on attitude reconstruction of the probe, as well as the utilisation of iterative extended Kalman filtering in investigating vanes induced spin rate and in providing a baseline for the performance evaluation of Huygens accelerometers operations. Finally some possible contributions on the reconstruction of the lower part of Titan descent for Huygens probe are suggested based on the confrontation of sensor data for 2003 flight.

## 1. HUYGENS PROBE OVERVIEW
Huygens is part of the Cassini-Huygens mission, a joint NASA-ESA-ASI mission for the exploration of the Saturn system. Built by an industrial consortium led by Aerospatiale, the Probe System comprises two principal elements: the 318 kg mass Huygens Probe and the 30 kg Probe Support Equipment, which remains attached to the Orbiter after Probe separation. Huygens probe will be parachuted through the atmosphere of Titan, Saturn's larger satellite, on January 14th 2005 after a dormant interplanetary journey of 7.25 years.
The scientific payload of the probe consists of a complement of six scientific instruments, which are each designed to perform a different function as the probe descends into Titan's mysterious atmosphere. The instruments are the following: Aerosol Collector and Pyrolyser (ACP), Descent Imager/Spectral Radiometer (DISR), Doppler Wind Experiment (DWE), Gas Chromatograph and Mass Spectrometer (GCMS), Surface Science Package (SSP) and Huygens Atmosphere Structure Instrument (HASI).
This last is a multi-sensor instrument that will measure the physical and electrical properties of Titan's atmosphere, which has been partially developed by University of Padova and is as a package managed by the centre for space studies of the same university. The sensors suite consists of a 3-axis accelerometer, a temperature sensor, a multi-range pressure sensor, a microphone and a electric field sensor array.
In parallel to utilising measurements from scientific packages, probe is equipped with dedicated sensor packages for health monitoring, house keeping, timing of operative sequences mainly related to shield separation and chutes deployment and attitude determination. Acceleration measures are based on a triply redundant Central Acceleration Sensor Unit (CASU) and a Radial Acceleration Sensor Unit (RASU) constituted by two equal accelerometers, all positioned on the main probe plate.
All on board data are handled by the Command and Data Management Subsystem relying on a very safe redundancy scheme, comprising two identical Command and Data Management Units which work simultaneously and are configured with hot redundancy and report data to the experiments in the so called Descent Data Broadcasts.

## 2. BALLOON BORNE HASI MOCK UP PROBE
HASI balloon flight campaign aim is to test the performance of scientific instruments of Huygens probe and specially the response of HASI instrument package to the thermal and fluidodynamic disturbances in an atmospheric descent.
To achieve this target University of Padova has developed a low cost mock up of Huygens probe, which hosts spare instruments of the real probe and several add on instruments, mechanically and electronically designed to be suitable for stratospheric balloon launches. A balloon mission is hence an efficient and economic way to lift a payload to a desired altitude and then drop it in a parachuted descent. The probe has been completely engineered at University of Padova and from 2001 has undergone several mechanical, electronic, thermal and fluidodynamic optimisations conducted in order to increase the available space for payloads, guarantee accessibility and maintainability of subsystems and improve performance during foreseen mission operations. The development activities have included:
- Design, development and assembly of probe mechanics

- Design, development and integration of power system
- Design, development and integration of probe electronics. Procurement of H/K sensors for probe status (attitude, temperature) monitoring.
- Design, development and coding of data acquisition system, for real-time monitoring, diagnostic and redundancy.
- Full system integration and verification.

The last evolution of the probe hosts 12 different scientific instruments with 84 different channels, acquired at different sampling rates by the on board integrated data acquisition and instrument control system during ascent, floating and descent phases.

This system is based on PC architecture and soft-real-time application allowing onboard storage and telemetry transmission satisfying all requests for real-time monitoring, diagnostic and redundancy.

**Table 1. List of payload instruments hosted in 2002 and 2003 Balloon campaigns**

| *Acronym* | *Sensor* | *provided by* |
|---|---|---|
| HASI ACC | Triaxial accelerometer | PSSRI/Open University, UK |
| HASI PPI | Pressure Profile Instrument | FMI, Finland |
| HASI TEM | Dual Pt wire thermometers | CISAS – University of Padova, I |
| HASI PWA | Permittivity, Wave and Altimetry | CETP, France<br>ESA-ESTEC/RSSD, NL<br>IAA, Spain<br>IWF, Austria |
| Huygens CASU | Single axis central accelerometer | ESA-ESTEC/RSSD, NL |
| Huygens RASU | Radial accelerometers (2) | ESA- ESTEC/RSSD, NL |
| Huygens RAU | Radar altimeter unit | ESA-ESTEC/RSSD, NL |
| Huygens SSP TILT | Science Surface Package tilt sensor | PSSRI/Open University, UK |
| Beagle2/UV sensor | UV sensor for Beagle2 on MarsExpress | PSSRI/Open University, UK |
| AD590 | Temperature housekeeping sensors (7) | CISAS – University of Padova, I |
| MAG | Triaxial fluxgate magnetometer | CISAS – University of Padova, I |
| Inertial platform | Gyro enhanced orientation sensor | CISAS – University of Padova, I |

A more challenging thermal environment is to be encountered in 2004 Antarctica flight but a new dedicated design and extensive testing have lead to a new probe configuration that can nominally operate almost in any atmospheric condition.

For data communication to ground probe relies on a dedicated ASI gondola, which provides telemetry capability for data download and sending/ receiving telecommands.

Both flights conducted in 2002 and 2003 very extremely successful, since probe was correctly launched and recovered in Sicily providing all expected scientific data.

## 3. HUYGENS ATTITUDE RECONSTRUCTION

Referring to [1] Huygens parachute system is designed to minimise the influence of external perturbations on probe attitude during descent thanks to a double pendulum configuration which will limit maximum probe oscillation to a 5 degree angle in presence of strong transversal winds. Furthermore the lower dome vanes configuration has been designed and tested to spin stabilise the probe and allow fast damping of aerodynamic oscillations thanks to optimised dynamic moment coefficients for angles of attack different from zero.

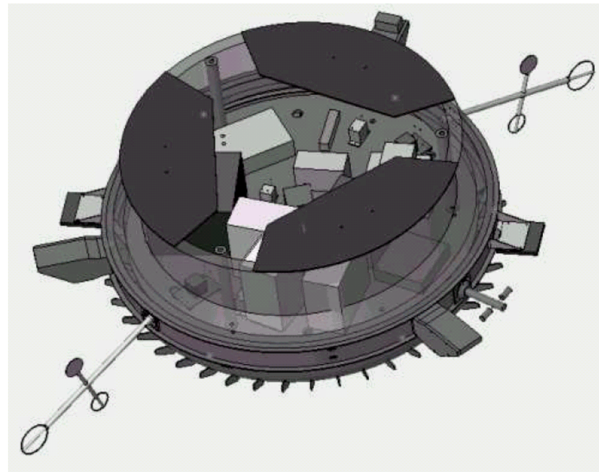

**Fig. 1. 3D model of 2003 Huygens mock up.**

Being attitude control of the probe mainly based on passive systems no extensive direct measurement of attitude is provided aboard the Huygens probe. Two accelerometric data sets (HASI and CASU) will be available during entry and descent to provide information on angle of attack, but the sole information about rotation will be given as spin rate around probe main axes from data of the radial accelerometer units RASU. Internal RASU electronics controls acquisition at 8 Hz sampling frequency and performs low pass filtering at 2 Hz before providing values to the CDMUs, which perform the spin calculation based on a simple radial acceleration algorithm. ($a=r\omega^2$)

Before using this algorithm two different averages are calculated, a first one every 2 second and therefore based on 16 measured values , called F1 and a second one based on the average of 64 consecutive F1 values, called G value. This last is the value used directly in the spin rate calculation algorithm which is therefore executed every 2 second basing on a average over 1024 measurements.

The two RASU accelerometers are located very close to each other on the same side of the probe main plate, so they provide redundant measurements but are also subject to several perturbing effects which should be taken in proper consideration. This effects are mainly related to the gravity acceleration which is sensed by the sensors in presence of probe oscillations and

varying lateral winds which provide acceleration inputs and as well induce probe oscillations.
The entity of this disturbance on correct spin rate detection has been evaluated with a 3D dynamical model of the probe taking into consideration the most severe foreseen probe oscillations (maximum oscillation amplitude: 5 deg, maximum oscillation velocity: 2.5 deg/s) during a descent at the maximum expected spin rate (30 deg/s).[1] A 60 second long oscillation has been supposed and a gravity value of 1.35 m/s^2 as the one of Titan has also been assumed.
RASU acquisition has been simulated at 8 Hz ( 0.125 s time step for simulation output) and filtered with 2 Hz low pass filter. It is also notable that on Huygens probe RASU working range is software limited to 0 - 0.12 g and therefore negative readings are not considered .
Result of the simulation is shown in the following Fig. 2 where the nominal acceleration value (0.112 g at sensor radial position for expected spin rate) is perturbed by gravity because of probe oscillation.

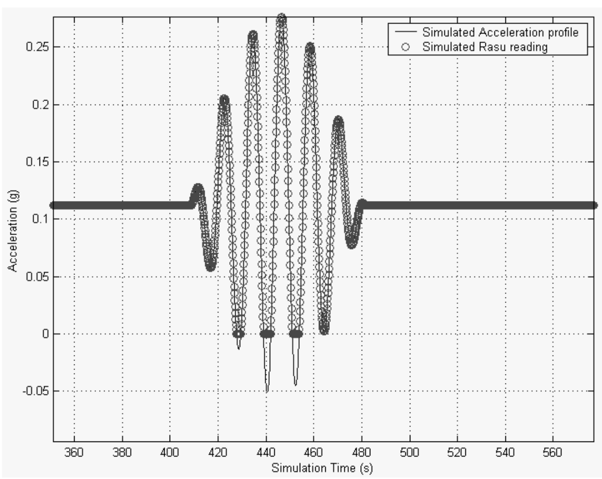


**Fig. 2. Perturbing effect on RASU sensed acceleration due to gravity coupling thorough oscillation during spin controlled descent.**

It can be noted that since RASU is sensing only positive accelerations, some "signal" is lost, but this does not affect much the calculations for small angles.
For larger oscillation angles (if present) the perturbation due to gravity increases and the effect on measurements can be such to not allow a accurate velocity profile reconstruction due to loss of too much information on probe dynamics.
Executing the spin rate algorithm on the simulated data produces the profiles shown in following Fig.3 and Fig.4 .

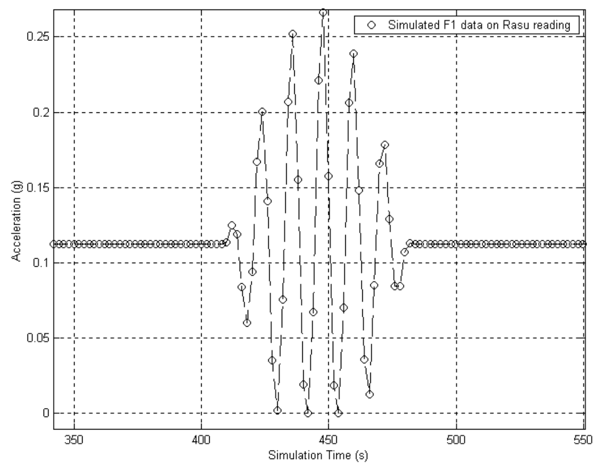


**Fig. 3. F1 value on simulated RASU reading.**

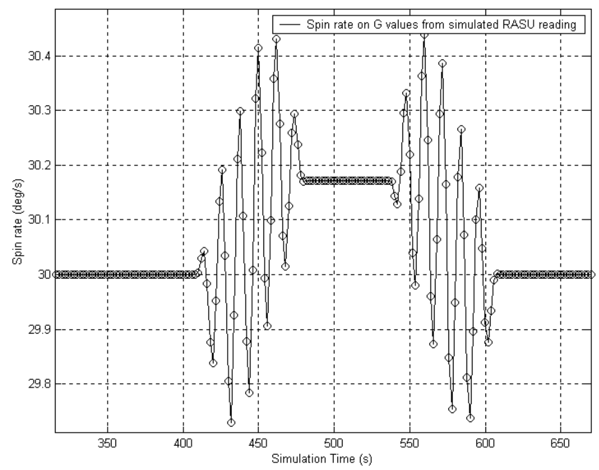


**Fig. 4. Spin rates obtained through Huygens spin rate algorithm .**

It can be seen that probe oscillation affects spin rate calculation for a period that is twice the extension of the oscillation due to the properties of the algorithm. A maximum 1,5% relative error on spin rate calculation can be expected for the foreseen oscillations at the maximum expected spin rate. In presence of lower spin rates a greater relative error affects measurements with values up to the same size of the expected reading. This problem can not be completed avoided through data averaging since as shown before part of the expected reading will be negative and therefore considered as zeros in data acquisition thus driving to an overestimation of the spin rate.
It should be considered that since no direct measurement of the angle of rotation is available probe rotation can be calculated only through integration of spin rate. Simulations show that in this case even a very small relative error on rotation velocity can cause the reconstructed angle value to depart in a short time from

the real one. Being the knowledge of angle of rotation of great importance for some instruments like PWA improved techniques based on sensor fusion and Kalman filtering are currently under testing for reducing uncertainty in probe angle determination.

## 4. HUYGENS MOCK UP ATTITUDE RECONSTRUCTION

Although the mock up we realised for the balloon tests has been designed to be similar to the real Huygens some adjustments had to be conceived to adapt the configuration to a descent in earth atmosphere. This has mainly influenced the vanes configuration in order to achieve the same spin rate profile in presence of denser atmosphere but has also required a different configuration for RASU sensors. Since, as said in the previous paragraph, these accelerometers can sense gravity in case of oscillations and gravity on earth is almost eight time bigger than on Titan, the disturbance could be of the same value of the spin borne centrifugal contribution for probe inclinations around 3 degree from vertical. We also knew from previous balloon campaigns that the balloon train configuration provided by the Italian Space Agency did not have a double pendulum configuration and therefore probe oscillations can easily reach 40 degree during descent .

We had therefore to design a different configuration installing the two RASU units at the same radial distance from the center of mass but 180 degree apart facing each other. Thanks to this sensor configuration we are able to eliminate oscillation and lateral winds contributions with post mission data elaboration of units readings. A picture of the probe main plate is shown in Fig. 5.

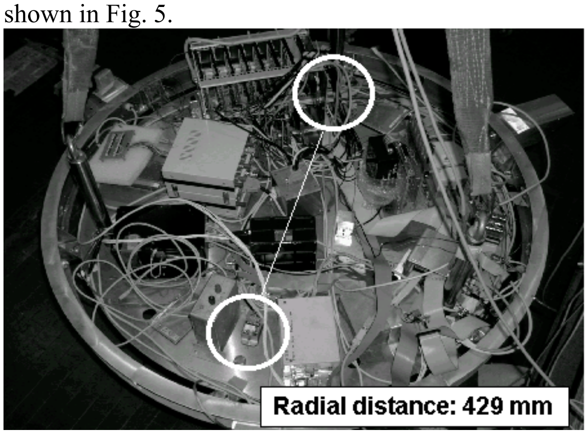


**Fig. 5. RASU sensor configuration on Huygens mock up for balloon mission.**

In order to test the quality of attitude reconstruction with Huygens sensors and investigate possible perturbations we installed a commercial inertial measurement unit with high accuracy attitude determination capability.

The 2003 flight was successfully launched and recovered on June 7th 2003, starting at 6.54 AM local time and lasting around 3 hours. (130 minute ascent to 33 kilometre altitude and a 65 minutes parachuted descent).

Elaboration of IMU through quaternions shows that probe oscillations during the descent have reached values as high as 40 degree as shown in Fig.6.

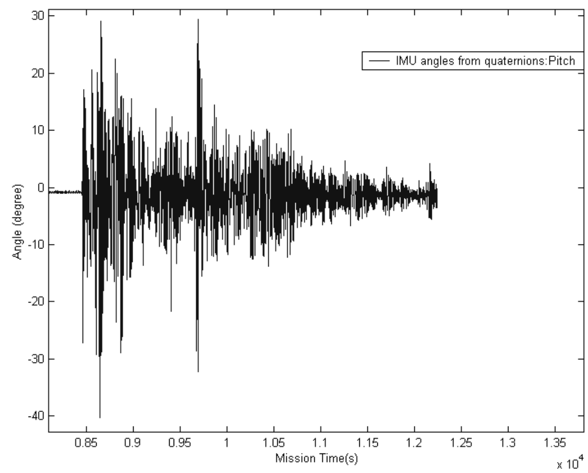


**Fig. 6. Probe pitch angle during descent**

Probe rotation around spin axes is also provided by IMU data elaboration as in the following Fig.7.

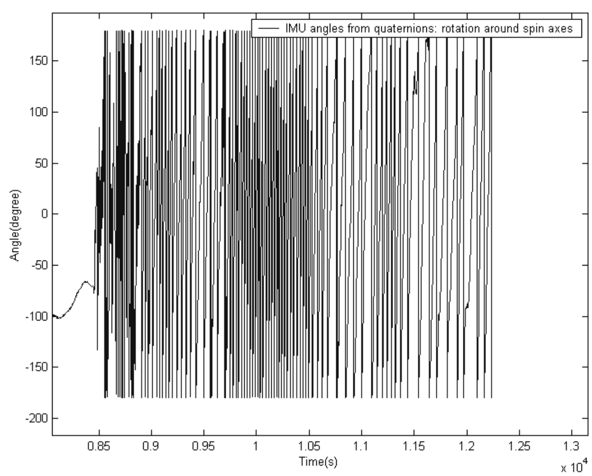


**Fig. 7. Probe rotation around spin axes during descent**

Since a slip ring de-coupling device has been introduced between the probe and the above telemetry gondola, probe rotation is with good confidence not perturbed by the dynamics of any parachute train element and can therefore be directly related to fluidodynamic interaction with atmosphere during the descent.

In order to calculate the descent spin rate profile and the perturbations due to lateral and vertical winds a reconstruction algorithm has been developed based on Extended Kalman filter. The Iterative Extended Kalman filter is a very good mean to address the general problem of trying to estimate the state of a discrete-time controlled process that is governed by the non linear stochastic difference equation and with non linear measurements relationship to the process. Reducing it to the essentials Kalman filter behaves as a predictor corrector where a time update based on a good knowledge of the system dynamics projects the current state estimate ahead in time. The state equation has been calculated with CFD models and relates the attitude parameters to the descent profile characteristics. The measurement update adjusts the projected estimate by an actual measurement at that time. The extended filter implies wide use of jacobian matrices with partial derivatives and for the complex parachuted descent dynamics this yields to complex symbolic calculations and long calculation time. The developed filter investigates the evolution of 7 state variables using 7 measurement data sets at different sampling rates through a so called sensor fusion algorithm.

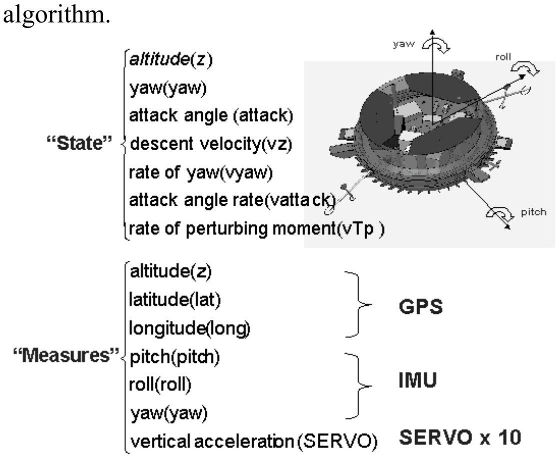


**Fig. 8. Iterative Extended Kalman filter parameters**

The Kalman filter has allowed the calculation of the mission spin rate profile from inertial platform measurements and its evolution is shown in the following Fig.9. It must be noted that after parachute opening the probe undergoes an unexpected counter clockwise rotation before starting the nominal clockwise rotation. This behaviour is still under investigation and is though to be caused by internal friction in the slip ring device triggering the rotation. Besides this first phase the spin rate profile is in good accordance with the expected profile[2] and the achieved rates are consistent with the ones that Huygens should encounter during the Titan descent [1].

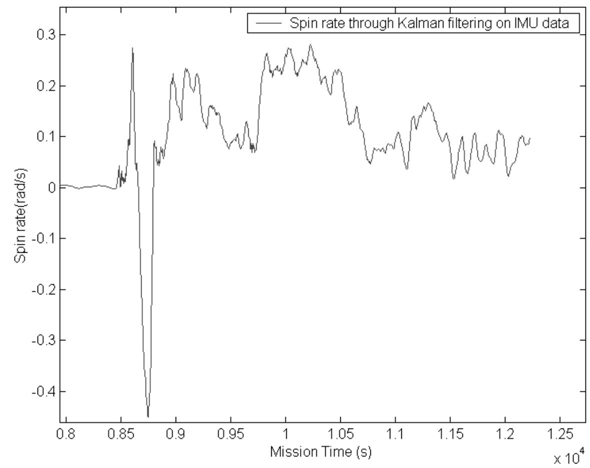


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**Fig. 9. Spin rate calculated with Iterative Extended Kalman on IMU data**

In parallel to Kalman filtering processing of RASU data has been conducted. The previously described Huygens spin rate algorithm has been used to evaluate the spin rate of the probe to simulate an Huygens-like mission. As already described a pre processing of accelerometer data has been performed in order to disregard perturbing inputs due to undesired probe dynamics. The resulting spin rate profile based on RASU data is shown in the following Fig.10.

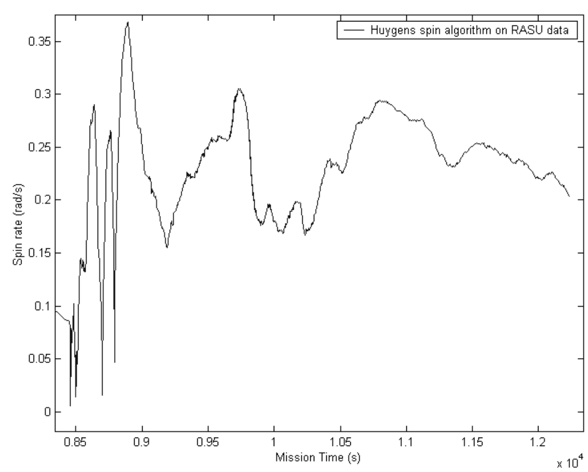


**Fig. 10. Spin rate calculated with Huygens spin algorithm on RASU data**

RASU derived profile seems to differ a lot from the one from Fig. 9 especially in the first phase of the descent . This is due to the fact that RASU based spin rate

algorithm can not reconstruct the sign of rotation. Considering only absolute rotation values the profiles are very similar and therefore RASU based rate reconstruction provides values that are consistent with the ones derived by the more accurate inertial platform unit. The main difference is that RASU based reconstruction tends to overestimate spin rate with a maximum relative error around 20%. This happens when rotation rate is low and therefore remaining dynamic disturbances affect mostly the reconstruction as also shown in the simulations.
This effect is unlikely to be encountered on the real Huygens mission thanks to the double pendulum configuration which should consistently limit undesired motion of the probe.
Concerning rotation angle reconstruction the studies conducted on balloon flight data has shown that RASU data do not allow an accurate reconstruction through spin rate integration, either because they don't give information on probe rotation sign also because signal to noise ratio is too low to prevent drifting of state estimation. Simulation showed also that same problem is likely to be encountered in the reconstruction of the real Huygens profile angular position.
The development of new algorithm based on other fusion with other instrument data (HASI ACC or DISR) is therefore under investigation both for the balloon flight and the real Huygens mission interpretation.

## 5. CONCLUSIONS

Flying a mock up of the Huygens probe in a stratospheric balloon campaign has provided information on several issues related to probe attitude determination. Data elaboration has shown that radial accelerometers RASU can provide a good spin rate profile reconstruction during the descent also in earth atmosphere although several requirements must be met to relate accelerometer data to probe rotation.
Some possible perturbations on RASU readings have been underlined in case of probe oscillation and these should be considered for data investigation during the Titan descent.
Concerning the determination of probe rotation angle around the spin axis this work has underlined that RASU derived data are not sufficient for an accurate reconstruction and therefore new strategies based on sensor fusion with other on board equipment data should be implemented for Huygens and are currently under investigation.

## 6. REFERENCES

1. *ESA Huygens Probe Entry and Descent Analysis* , E.W.P. 1679

2. M. Antonello, C. Bettanini, *Aerodynamics Design of the Huygens Spin Vanes for the HASI*, Proceedings of International Workshop on Planetary Probe Atmospheric Entry and Descent Trajectory Analysis and Science, Lisbon 2003, ESA - SPP - 544