THE HUYGENS SYNTHETIC DATASET

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ABSTRACT

The Huygens probe entered into the dense atmosphere of Titan on 14th January 2005 and landed on the surface after a nominal descent of about 2.5 hours [1]. Huygens is the ESA-provided element of the joint NASA/ESA/ASI Cassini/Huygens mission. The probe was delivered to the interface altitude of 1270 km above the surface by NASA/JPL. The propagation and reconstruction of the trajectory from that point onwards is ESA's responsibility.

An important effort was devoted to the development of an algorithm that aimed at reconstructing the descent trajectory and attitude of Huygens from the scientific instruments and probe sensors measurements ([2], this issue). In order to test this algorithm, the Huygens Synthetic Data Set (HSDS), a simulated mission dataset, was prepared.

In this paper we describe the philosophy of the approach for preparing the HSDS, the assumptions made and the limitations of the method. The different tools used for producing the simulated data set are described, mainly a 3 Degree-of-Freedom (DoF) entry and descent trajectory calculation, and 6 DoF entry trajectory and attitude simulator. We report how the scientific and engineering models were used to obtain the most realistic Huygens sensor data, and the latest updates leading to the final version on the 10th of January, just 4 days prior to the Huygens descent. The different parameters are described, with a special attention to the way the accelerations were generated.

1. THE CONTEXT

1.1. The Huygens mission

On 14th January 2005, the Huygens probe plunged in the hazy atmosphere of Titan. Huygens is the ESA contributed element to Cassini/Huygens, the joint NASA/ESA/ASI dual-craft mission for the exploration of the Saturnian system. In a nominal descent of about 2.5h [1] it unveiled some of the mysteries of this unknown world.

To fulfill its scientific objectives, the Probe payload is equipped with 6 highly sophisticated instruments [3]:

- GCMS: Gas Chromatograph / Mass Spectrometer
- ACP: Aerosol Collector and Pyrolyser
- DISR: Descent Imager / Spectral Radiometer
- HASI: Huygens Atmospheric Structure Instrument
- DWE: Doppler Wind Experiment
- SSP: Surface Science Package

Titan's environment knowledge is complemented by the use of engineering measurements from some of the Probe system sensors [4] including:

- RAU: Radar Altimeter Units
- CASU: Central Acceleration Sensor Units
- RASU: Radial Acceleration Sensor Units

1.2. Trajectory reconstruction

The reconstruction of the probe entry and descent trajectory is the responsibility of the Huygens Science Working Team (HSWT). The task has been assigned to the Descent Trajectory Working Group (DTWG), a subgroup of the HSWT. For such a purpose a complex numerical code has been developed ([2], this issue). It computes the trajectory from the data from several probe engineering systems and science instruments. A preliminary reconstruction was released on 11 January 2005, within three days before the probe descent, in order to provide a common reference to all teams to proceed with their preliminary data analysis. It is called the *official DTWG predict trajectory*. After several iterations, the final reconstructed trajectory is expected to be delivered 12 months after the descent.

1.3. The synthetic dataset: scope and philosophy

In order to help in the development, testing and validation of the DTWG tool, a Huygens Synthetic Data Set (HSDS) has been prepared. The HSDS is a collection of the Huygens engineering and scientific simulated measurements. Several mission datasets were provided and allowed DTWG to confirm the trajectory reconstruction techniques in different cases. It is important to note that the trajectory reconstruction tool and the synthetic dataset are built by two distinct groups, the DTWG and the Huygens Project Scientist Team (PST), in order to avoid the reproduction of common inconsistencies/errors that would be otherwise missed during the testing and validation phases.

The approach to the method was published in 2003 at the first IPPW conference [13]. In this paper we recall and update (chapter 2) the method to simulate the Huygens mission engineering and experiment data. The final operational datasets, as delivered to DTWG, with a selection of the main parameters are presented (chapter 3). Finally, a comparison with the real in-flight data (CASU) is performed (chapter 4).

2. THE GENERATION PROCESS OF THE SYNTHETIC DATASET

2.1. The approach

The HSDS comprises the collection of simulated in-flight probe parameters that were necessary for the DTWG reconstruction effort [2]. Several versions were released, as stated in table 1.

Release no.	Purpose	Delivery dates to DTWG
HSDS v1.x	- Test Datasets for the development and testing of the DTWG algorithm	v1.0 - v1.1 Jun-03 v1.2 Sep-03 v1.3 Dec-03 v1.4 May-04 v1.5 Oct-04
HSDS v2.x	- Test Datasets for the AoA reconstruction (only entry phase, attitude included - 6 DoF entry tool)	v2.0 Dec-04
HSDS v3.x	- Operational Datasets for the generation of the pre-mission DTWG Delivery No. 0	v3.0 8-Jan-05 v3.1 10-Jan-05 (final)

Table 1. HSDS Releases.

Successive sub-versions with increasing complexity of a particular release were generated as required to improve the dataset. Higher numbered sub-versions supersede the former ones.

2.2. The method

Seven main steps are required for creating the dataset. They are described in Table 2, and elaborated in following paragraphs.

Step	Description	Responsible
1	Scenario and atmosphere definition	PST
2	Trajectory and motion calculation	PST
3	Generation of the dataset	PST
4	Dataset validation	PI teams / industry
5	Delivery to DTWG	PST
6	DTWG reconstruction tool testing	DTWG
7	Testing and validation of the reconstructed trajectory	PST/DTWG

Table 2. The simulated dataset in 7 steps.

2.2.1. Step 1: scenario and atmosphere definition

The current baseline scenario for the Huygens mission is summarized in [5]. The initial entry conditions at the 1270 km altitude interface are defined in the handover NASA/ESA interface document, the "JPL Delivery File" as a full state vector (position and velocity) and the associated uncertainties (14x14 covariance matrix). A particular scenario may be tailored within this expected error range for the Probe targeting.

The atmospheric profile is also synthesized by the PST, within the uncertainty range of the currently accepted scientific and engineering Titan models:

- Yelle density and temperature [6];
- HRTF prograde wind profile [7];
- Gravity waves perturbations model [8];
- Wind perturbations: shear wind, gusts [8].

2.2.2. Step 2: trajectory and motion calculation

Two different tools are used to generate predicted trajectory variables and simulate the probe dynamics for the selected scenario. Here is a brief description of these tools and their main features.

a) DTAT tool (Descent Trajectory Analysis Tool). The Huygens Entry and Descent 3 DoF software tool was originally developed to compute the optimum Cassini High Gain Antenna (HGA) aiming point as a function of the estimated targeting conditions provided by NASA/JPL. To address that goal, the tool reproduces the trajectory (Probe and Orbiter) and relay link for the whole Huygens mission. Developed by GMV for ESA and maintained by DEIMOS, it turned out to be a very useful tool for mission analysis and operational purposes. Its capabilities make it the most appropriate tool to be used for the generation of the HSDS. The numerical algorithm of the trajectory propagator module is implemented with a 7th order Runge-Kutta-Fehlberg model, and adaptive stepsize, which provides good conditions for a stable descent. A covariance analysis module propagates the dispersions within the covariance matrix, saving computational time by means of a modified Monte Carlo analysis method. The mathematical background and the implementation of the DTAT tool is outlined in [5].

The main inputs required are link budget parameters, probe configuration, error sources, operational timeline, planetary ephemeredes, atmospheric and wind models, and the initial conditions vector.

b) UES tool (Universal Entry Simulator). This 6 DoF tool performs analysis of planetary re-entry vehicles. In the context of the HSDS, it is used to compute the Huygens pitch-roll-yaw axis rates and determine the effect of the attitude in the telemetered parameters. The natural range of application is the entry phase (from interface altitude to pilot chute deployment), when the probe is cocooned inside the front shield / aft cover.

2.2.3. Step 3: generation of the dataset

A core Matlab© routine controls the simulation. This complex task can be summarized as follows:

- Creation of the nominal values for a physical parameter.
- Application of diverse effects to get the ‘real’ or ‘measurable’ reference values.
- Sensor modelling to get ‘transduced’ values.
- Formatting of the data and saving into files.

The outputs of the different trajectory tools and the tabulated models of the database are processed and combined into a nominal or ideal physical property parameter.

Then, diverse effects and perturbations that could occur during the descent are applied, obtaining the ‘real’ or ‘measurable’ reference values for that parameter.

This ‘real’ data needs to be conditioned with each particular ‘sensor model’ (the sensor response). Different sensors will measure the same physical parameter in different ways. A special effort is made to ensure that each simulated sensor set is auto consistent, and consistent with each other.

Finally a formatting is applied to meet the file delivery format requirements.

Two types of parameters

Based on the way they are generated, two parameters types can be distinguished:

- *Trajectory and motion* parameters (namely probe position and accelerations) are directly computed from the trajectory and dynamics analysis tools outputs.

- *Environment* parameters (temperature, pressure, speed of sound, wind speed) depend on the instantaneous probe position and velocity, so they are interpolated from the available atmospheric models and the actual trajectory.

Sensor modelling

A ‘sensor model’ comprises the relevant features (in the context of the simulated dataset) of the transducer behaviour of that sensor. The following features are relevant:

- *Range of operation*, is the period when the sensor is putting out data. Sensor measurements might be continuous or scattered data.
- *Sampling rate* in every period of continuous data
- *Noise distribution* and *accuracy* (1σ), the statistical probability parameters that characterize the intrinsic noise of the measurement.
- *Resolution* of the values, related to the analog step size of one bit of the digital telemetry word.
- *Range limits*, related to the digital telemetry word length and instrument internal limits. No data point can go beyond these limits (drop outs are within).
- Special features: dynamic corrections, response to modes switching, physical position on the probe, non-correctable static offsets, etc.

A summary of the resolution and uncertainties of the different sensors modelling is shown in Table 3.

Sensor	Parameter	Resolution	Uncertainty
DWE	Wind	0.01 m/s	0.15 - 1.75 m/s
SSP-API-V	Velocity of sound	0.1 m/s	1%
SSP-API-S	Altitude	50 cm	1%
GCMS	Molecular mass	0.1	1%
HASI TEM	Temp.	0.02 - 0.07 K	0.5 - 2.0 K
HASI PPI	Pressure	0.005 mb	4-16 mb
HASI-servo	Acc.	1 - 10 µg 0.9 - 9 mg	1% full scale
HASI-piezo	Acc.	50 mg	1% full scale
DISR	Altitude	100 m	0.2 deg/pixel (~0.7%)
RAU	Altitude	1 m	3.6 m (average)
CASU	Central acc.	10g/256	3σ (%) = $54.72 \cdot ACC(m/s^2)^{-0.992}$

Table 3. Sensor modelling: resolution and uncertainty. API stands for Acoustic Properties Instrument.

The mode of an instrument/sensor is a particular state defined internally that may change the way the sensor operates. A typical example is the change in sampling rate when HASI declares “impact mode”. The sensor modelling must be defined for each instrument/sensor mode to guarantee its validity.

A particular parameter: deceleration

As explained in [2], the aerodynamic deceleration is the primary parameter for trajectory reconstruction, since it provides, integrating the equations of motion with the initial conditions and gravitational force model, a first reference trajectory. It is a complex and highly redundant dataset. It will be produced by smartly merging the computed figures of the 3 DoF (point-like) nominal trajectory, the correspondent disturbed attitude motion by the 6 DoF tool, and the models of some perturbing events, as shown in Table 4.

Mission PHASE	Acceleration: events	Origin
Entry	nominal entry trajectory acceleration	DTAT
	disturbed attitude motion	UES (6 DoF)
Descent	nominal descent trajectory acceleration	DTAT
	spin simulation	Tables
	other: parachutes deployment shield/covers jettison	Specific models
Impact	simulated impact profile	[9]
Surface	nominal acceleration = gravity	Sensor specs.
	other: landed probe orientation bouncing	Specific models

Table 4. Acceleration inputs.

Attitude information has been fully addressed for the HSDSv2 (entry phase). In HSDSv3, the acceleration during the descent measured along the x-axis is supposed to be equal to the deceleration due to the drag. Along the y and z axis, the acceleration is set to be equal to 0 (or an angle of attack set to zero). We also assume the acceleration after touchdown equal to Titan gravity, due to sensor measurements method. A deceleration profile of the impact has been added, with the experimental shapes of different surface materials.

Other features of the dataset

Additional events might be modelled:

- Parachute deployment transient.
- Jettisons (back cover, front shield, instrument covers), deployments (HASI booms), pyros.
- Touchdown deceleration on different surfaces (sand, clay, gravel, liquid [9]).
- Effect of atmosphere in the Probe rotation: spin rate profiles.
- Ground track altitude profile.
- Data link packet losses. Instrument packet losses.

2.2.4. Step 4: dataset validation

The generated files are previewed by the corresponding Instrument Team and industry for validation. This is a crucial step since the dataset must be representative of what the different teams will provide to DTWG in early 2005. The comments are fed-back and iterated in the steps 1, 2 and/or 3, in order to refine or correct the dataset.

2.2.5. Step 5: delivery to DTWG

The simulated dataset is delivered via a dedicated repository server, in electronic format. File formatting is an important issue to ensure a fast and unambiguous interpretation of the sets. The simulated dataset made use of a similar formatting as the flight data to train the process and spot possible inconsistencies and problems. A special effort has been made regarding this issue.

2.2.6. Step 6: DTWG reconstruction tool testing

The DTWG reconstruction tool is run and tested using the HSDS as an input.

2.2.7. Step 7: testing and validation of the reconstructed trajectory

The DTWG reconstructed trajectory is cross-checked with the initial trajectory computed in step 2, in order to assess the ability of the tool to reconstruct the trajectory of the probe.

2.3. The limitations

The data set aims at resembling as much as possible the science and engineering parameters expected to be obtained during the descent on Titan, but its accuracy depends on the reliability of the models and tools used.

- *Models*: the suitability to reality is given by the models. Nevertheless, the main goal of this dataset is not the accurate prediction of the parameters on Titan, but the generation of a consistent dataset to test the ability of the reconstruction tool to regenerate the trajectory from realistic disturbed sets.

- *Tools*: we are limited by the nature of a 3 DoF Tool (DTAT) computation of the trajectory. The attitude information is included for entry phase in the HSDS v2 only, aided by the UES tool.

3. THE HSDS DELIVERED DATA

3.1. The 3DoF Simulation: HSDSv3.1

The best product delivered to DTWG is the so-called **HSDS v3.1**. It is the evolution of the initial version v1.x, with last minute updated models:

- *Aerodynamic updated database*, released by EADS to the project on 10 Jan 2005.
- *Cassini reconstructed trajectory and error matrices,* 050107, released by JPL/NAV to the project on 7 Jan 2005, with optical navigation. ([10] and [11]).
- *Atmosphere model,* called Post-Ta, released by the TAMWG (Titan Atmosphere Model Working Group) after the Ta fly-by analysis.
- *Wind profile,* called Post-Ta, released by the TAMWG.
- *ICD v9.1* (*Interface Control Document,* [12]) for file format.

HSDS v1.x deliveries were an interactive process to aid in the development phase of the DTWG algorithm. As algorithm testers, they did not require a high fidelity to real mission parameters, but for completeness the most updated models were used.

HSDS v3.x refers to the 'operational' datasets. These sets were created shortly before the 14 Jan 2005, in an effort to provide DTWG with a representative dataset input to generate the ***official DTWG predict trajectory***. It was made available as Delivery 0 ([2] this issue]) as a reference to all the science instrument teams prior the Huygens mission.

Twenty-four different parameters have been generated for the HSDS. Some of these parameters express the same physical property but measured by different sensors. They are summarized in Table 5.

SOURCE	PARAMETER	SENSOR
Payload: DISR	Position (X, Y, Z)	Imagers
	Sun Zenith Angle	Sun sensor
Payload: DWE	Zonal wind speed	Link: doppler shift
Payload: GCMS	Molecular mass (x4: N_2, CH_4, Ar, other)	Mass spectrometer
Payload: HASI	Pressure (x2)	PRE (corrected/ uncorrected)
	Temperature (x2)	TEM (corr/ uncorr)
	Acceleration (x4)	Piezo acc (X, Y & Z); Servo acc (X)
	Impact time	Piezo acc
Payload: SSP	Velocity of sound	API-V (Acoustic trasducer)
	Impact time	ACC-I (Accelerometer)
	Altitude	API-S (Sounder)
Platform: RAU	Altitude (x2)	RAU 1 & 2
Platform: CASU	Central acc. (x1)	Best of CASU1, 2 & 3
PST	EVENT FILE: events timeline and initial conditions	Several platform and payload sensors + JPL/NAV prediction
-	Trajectory (X-Y-Z in EME2000, Q and ROT frames)	Predicted (only delivered to DTWG for crosscheck).

Table 5. HSDSv3.1 parameters.

Due to the large number of parameters, only a selection is plotted hereafter for illustration purposes.

Primary data set

The primary parameters are the critical ones for the DTWG reconstruction, namely: the entry phase deceleration (HASI SERVO), the HASI temperature (measured by 2 sets of coarse and fine accuracy sensors, TEM1F, TEM1C, TEM2F, TEM2C), HASI pressure (measured by a capacitive barocap sensor in the Pressure Profile Instrument, PPI), the impact time (SSP ACCI) and DWE landing point coordinates. Fig. 1 to 4 present some samples of the primary dataset.

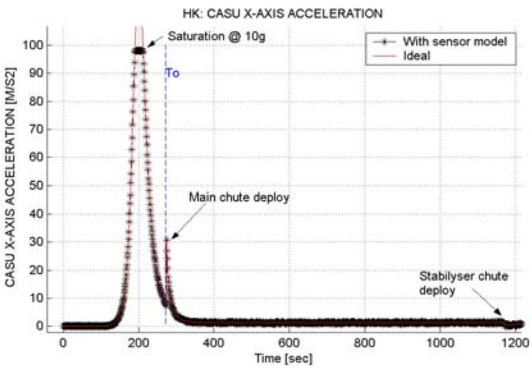

Fig. 1. CASU profile during entry phase. Data is buffered onboard for delayed transmission once the radio link is established. Peak deceleration is not measured by CASU due to the device limits (10*g*) - not the case for HASI accelerometers.

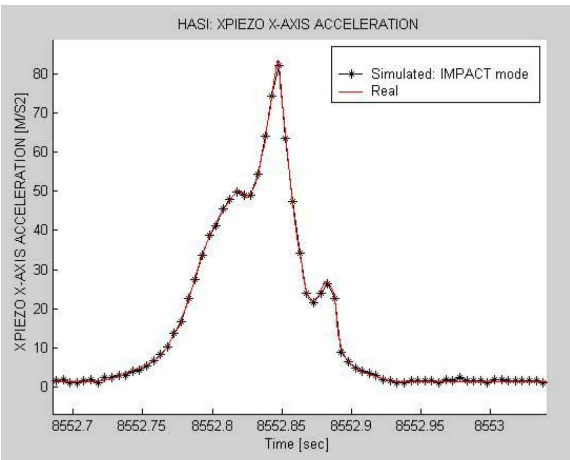

Fig 2. HASI X-piezo ACC impact profile. A special mode (*impact mode*) enables a 200Hz buffering around the event (-0.5s to +5.5s). A sand profile was selected.

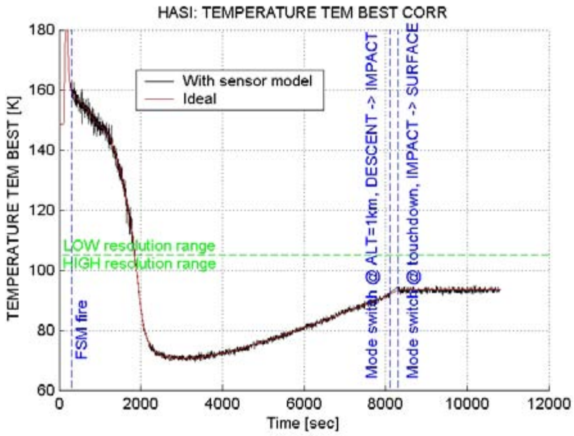

Fig. 3. HASI TEM1F sensor. Scale switching (LOW ↔ HIGH) is defined by the 105K threshold. The ‘1 km altitude’ and the ‘touchdown detection’ define the mode switching (DESCENT → IMPACT → SURFACE). Sampling rate is 0.2 Hz, except in impact mode where coarse sensors flow stops, and fine sensors double this rate.

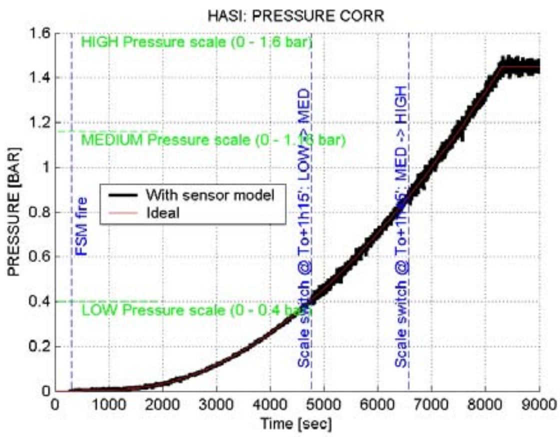

Fig. 4. HASI pressure. Pressure is measured in 3 scale ranges (LOW → MED → HIGH), with two scale switching at 1h 15min and 1h 45min after To. Noise is 1% of the correspondent full scale, and sampling rate is continuous 10 Hz.

Redundant data set

Additionally, redundant measurements will be included in the reconstruction algorithm, to further constrain and validate the trajectory. For instance, the speed of sound (SSP), zonal wind speed (DWE), altitude (RAU, DISR and SSP) and mol fractions of the main atmospheric constituents. They are shown respectively in Fig. 5 to 10.

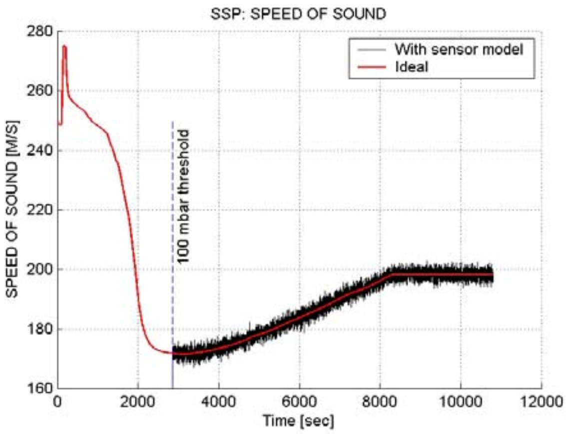

Fig. 5. SSP Speed of Sound. The maximum range where data is reliable is imposed by the 0.1 bar threshold in which the measurement method no longer works.

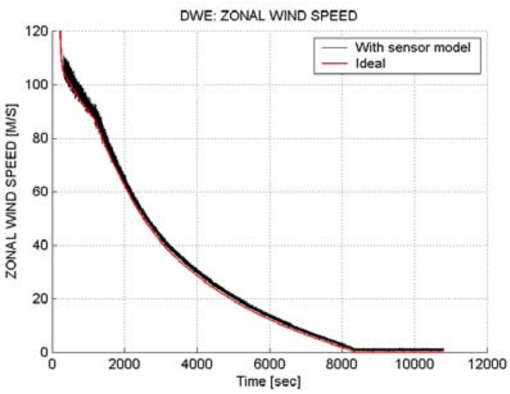

Fig. 6. DWE zonal wind speed. Noise is driven by the speed and transmitted frequency accuracy. It also depends on the frequency measurement, turbulence and aerodynamic buffeting, spin, and variations in the descent speed. A systematic error is applied due to the Huygens-Cassini geometry uncertainties.

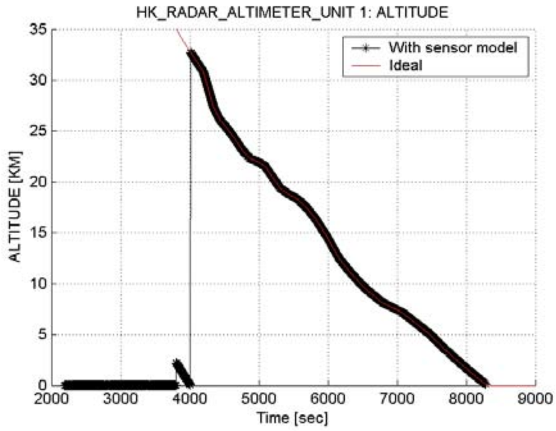

Fig. 7. Radar Altimeter Unit Altitude. An exagerated surface profile is added. The range of operation is expected to be 35km to surface, with a data rollover at 2^{15}m (32768m).

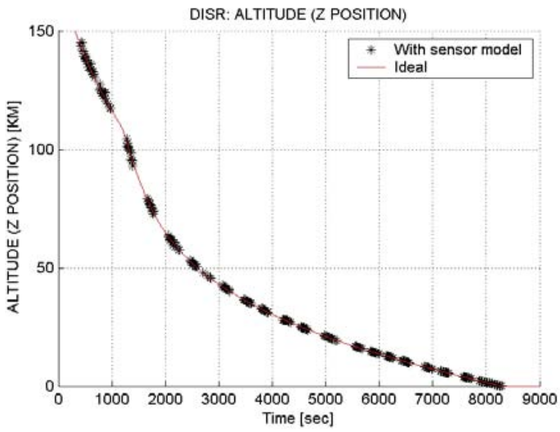

Fig. 8. DISR Altitude based on the images and. Please note the scattered nature of the measurements.

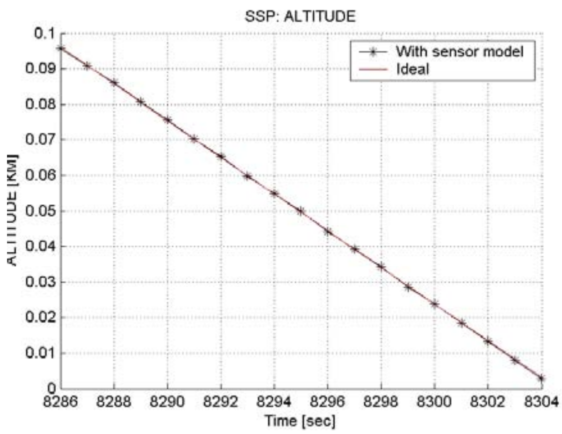

Fig. 9. SSP altitude derived from the sounder sensor (range of operation from around a hundred meters to the surface).

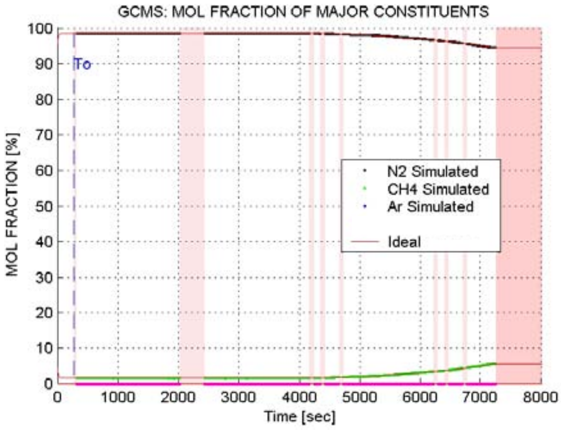

Fig. 10. GCMS mole fractions of the main atmospheric constituents (N_2, CH_4 and Ar), used to infer the mol mass of the gas mixture.

3.2. The 6DoF Simulation: HSDSv2.0

DTWG aims at reconstructing the Huygens Angle of Attack (AoA) during the entry phase, using HASI axial or lateral (Y, Z) and radial (X) acceleration, CASU radial acceleration and the Huygens aerodynamic database. The use of a 6 DoF tool was needed to take into account the attitude. A specific dataset containing 5 parameters, the **HSDSv2.0,** was created (Table 6).

SOURCE	PARAMETER	SENSOR
Payload: HASI	Acceleration (x4)	Piezo acc (X, Y & Z); Servo acc (X)
Platform: CASU	Central acc. (x1)	Best of CASU1, 2 & 3
PST	EVENT FILE: events timeline and initial conditions	Platform/payload sensors + JPL /NAV prediction
-	AoA, Trajectory (X-Y-Z in EME2000, Q, ROT frames)	Predicted

Table 6. HSDSv2.0 parameters.

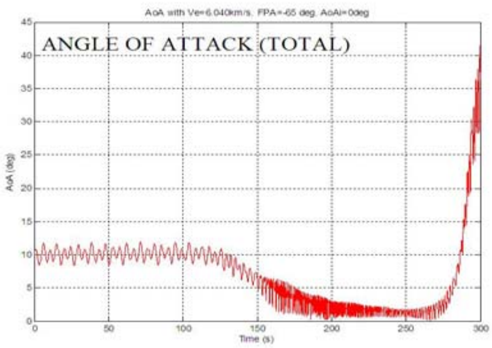

Fig. 11. Angle of Attack simulation using a 6DoF tool. The initial AoA is set to 10 deg.

Deployment of the first chute occurs around 270 sec, before the AoA diverges.

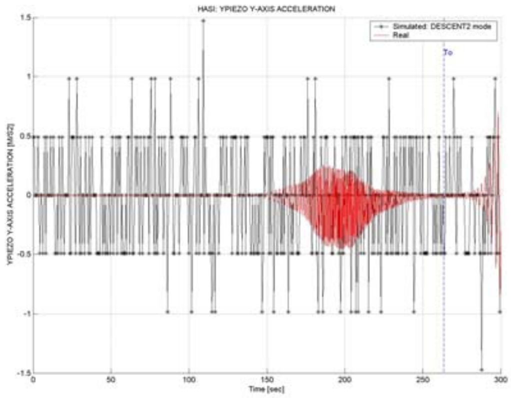

Fig. 12. Lateral (Y-axis) HASI piezo ACC simulation, from the profile in Fig. 7. The resolution of the sensor (~0.5 m/s^2) implies that the measurements are in the noise-level.

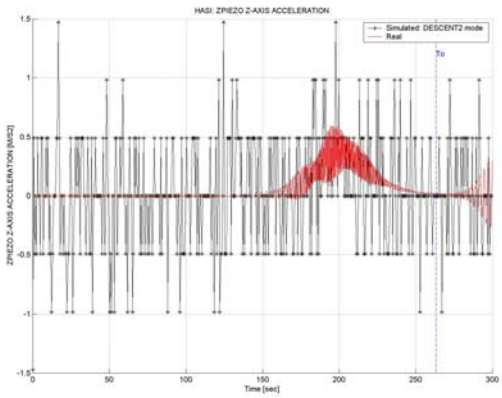

Fig. 13. Lateral (Z-axis) HASI piezo ACC simulation, from the profile in Fig. 7. The resolution of the sensor (~0.5 m/s^2) implies that the measurements are in the noise-level.

The synthesized data showed that the DTWG would not be able to retrieve the AoA from the measurements, because the resolution of the lateral piezo-sensors was not accurate enough (in the noise level). Nevertheless, in-flight data confirmed that the sensor specification provided by HASI for the generation of the HSDS was pessimistic: its real resolution is an order of magnitude better, and therefore sufficient for attempting the AoA reconstruction [Bettanini, personal communication].

3.3. Use of the HSDS

The HSDS was developed for the Huygens Science Working Team and the Descent Trajectory Working

Group use. The generation coding and all the deliveries are now available for public use, for more information please contact the authors.

4. COMPARISON WITH IN-FLIGHT DATA

A comparison between the HSDS and the Huygens data set can be made. However, the scientific data are not of public use at the time of writing (proprietary period). Therefore, we show a comparison with the platform data CASU (Fig. 14). The quality of the HSDS predictions is excellent.

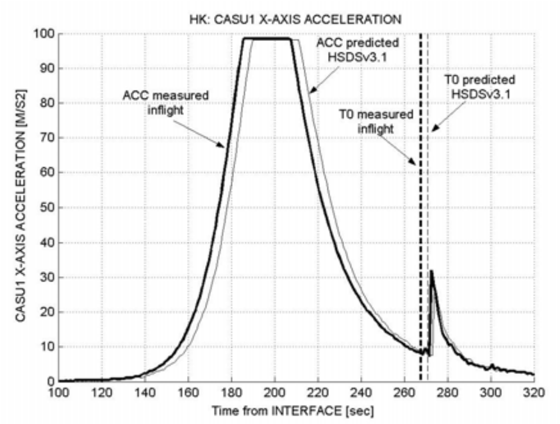

Fig. 14. CASU inflight data compared to prediction in HSDSv3.1. The only appreciable difference is a time shift of 3-6 seconds due to delivery and atmosphere uncertainties.

5. CONCLUSIONS

The HSDS was extensively used as a testbed during both the development and the validation phase of the Huygens Descent Trajectory Working Group (DTWG) tool [14]. The reconstructed trajectory based on the HSDS was furthermore used as the *official DTWG predict trajectory* and made available as a reference to all the science instrument teams prior to the Huygens mission on January 14, 2005. The HSDS tool proved to be very useful for the development, testing and validation of the trajectory reconstruction algorithm and for the preparation of the Huygens in-flight data analysis. The contents and development of the Huygens Synthetic Data Set (HSDS) were outlined in this paper. The main simulated parameters were presented.

6. REFERENCES

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