A SIMULATED DATASET OF THE HUYGENS MISSION

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ABSTRACT

Huygens is the ESA-provided element of the joint NASA/ESA/ASI Cassini/Huygens mission to Saturn and its largest moon Titan. The spacecraft, launched on 15th October 1997, will enter in orbit around Saturn on 1st July 2004. Probe separation from the orbiter is planned on the 25th December 2004. After a 3-week coast phase, the Huygens probe will dive into the dense atmosphere of Titan on 14th January 2005 and will land on the surface after a nominal descent of about 2 hours 15 minutes ([1], this issue). The probe is delivered to the interface altitude of 1270 km above the surface by NASA/JPL. The propagation of the trajectory from that point onwards is ESA's responsibility.

An important effort is devoted to the development of an algorithm that aims 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, a simulated synthetic mission dataset is being prepared.

In this paper we describe the philosophy of our approach for preparing a Huygens simulated data set, the assumptions made and the limitations of the method.

We report how these models are used to obtain the most realistic Huygens simulated synthetic dataset. The different parameters are described, with a special attention to the way the acceleration is generated.

The different tools used for producing the simulated data set are described. They are based on those used for trajectory and probe attitude prediction: a 3 Degree-of-Freedom (DoF) entry and descent trajectory calculation, a 6 DoF entry simulator, and a 12 DoF probe-parachute-tethered tool.

1. THE CONTEXT

1.1. The Huygens mission

On 14th January 2005, the Huygens probe will plunge 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 2h 15min ([1], this issue) it will reveal 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 Atmosphere Structure Instrument
- DWE: Doppler Wind Experiment
- SSP: Surface Science Package

Titan's environment knowledge will be complemented by the use of engineering measurements from some of the Probe system sensors ([4]) as:

- 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 is being developed ([2], this issue). It will compute the trajectory from several probe engineering and experiment data. A preliminary reconstruction is expected within days after the probe descent in order to provide a common reference to all

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teams to proceed with their preliminary data analysis. After several iterations, the final product is expected to be delivered 6 months after the descent.

1.3. The simulated dataset: scope and philosophy

In order to test the tool developed by the DTWG, a simulated synthetic mission dataset is being prepared. Several datasets are foreseen that will allow the DTWG to test 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 (DTWG and the Huygens Project Scientist Team, PST), in order to avoid the reproduction of common inconsistencies or errors that would be otherwise missed during the testing and validation phase.

This paper focuses on the method to simulate the Huygens mission engineering and experiment data, and the presentation of the first dataset. A selection of the results is shown.

2. THE GENERATION PROCESS OF THE SIMULATED DATASET

2.1. The approach

The synthetic simulated dataset comprises a collection of the simulated in-flight probe parameters, identified as necessary for the DTWG effort [2]. Several releases with increasing complexity are foreseen, as stated in table 1.

Release no.	Characteristics
Simulated Dataset #1	Simple atmosphere (no wind shear-gust, no gravity wave disturbance) No attitude: entry dynamics, parachute-probe motion Simple sensor models Simple (gaussian) noise
Simulated Dataset #2	More sophisticated sensor models (realistic data rates, instrument modes, sensor responses, etc)
Simulated Dataset #3	Single events Instrument failure Attitude Atmospheric disturbances

Table 1. Foreseen Dataset Releases.

Successive versions of a particular release might be generated as required to improve the simulated dataset. Table 1 shows a basic scheme, intended to be flexible to cope with new requirements that may come as the DTWG tool develops into its complete implementation.

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

Three different tools will simulate trajectory variables and dynamics for the selected scenario. Here is a brief description of the 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. For that scope, the tool reproduces the trajectory (probe and orbiter) and relay link for the whole Huygens mission. Developed by GMV for ESA and now 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 Dataset #1.

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 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 frame of the Simulated Dataset, it will compute the Huygens 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.

c) PASDA tool (Parachute System Design and Analysis Tool). It is a 12 DoF tool developed by Analyticon Limited under ESA contract to enable analysis and design of descent parachute-based systems. In the frame of the Huygens Simulated Dataset, the body motions computed by PASDA will determine the effect of the attitude of the system in the telemetered parameters. The overall set of accelerometer measurements will be affected, but there might be also subtle changes to others (RAU altitude, DWE zonal wind).

The natural range of application is the descent phase under parachute, i.e. from T0 (pilot chute deployment, nominally 4min 35 sec after interface point) to touchdown on Titan surface (139.3 min nominally). Specific changes made to the PASDA software enable a high-fidelity analysis of the Huygens mission. In fact, a bridle model has been included, as well as new attitude disturbance types: gust and shear wind disturbances, and instantaneous angle disturbances. The inputs required for running the simulation are: the scenario (physical data on the parachute and payload: size, mass, strengths...), the disturbances (type, occurrence...), the aerodynamics model (parachute, payload, wake effect) and the atmosphere (density, temperature, wind profile, coefficients...).

Work is still ongoing to fully represent the Huygens mission, in particular in the following areas:

- Damping coefficients revision/new contributors.
- Model of the 3-legged bridle.
- Addition of material hysteresis to the lines/strop.
- Behaviour of the aerodynamic effect of lines, strop and bridle.
- Response to localized height/time dependant gust.
- Long-term behaviour through the atmosphere.

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 delivery format requirements.

Two types of parameters

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

- *Trajectory and motion* parameters (probe position, 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, so they are interpolated from the available atmospheric models and the actual trajectory.

Sensor modelling

A 'sensor model' comprises the relevant features (in the frame 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)
- *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)
RASU	Radial acc.	0.12g/256	$3\ \sigma\ (\%) = 0.48 \cdot ACC(m/s^2)^{-0,965}$
CASU	Central acc.	10g/256	$3\sigma\ (\%) = 54.72 \cdot ACC(m/s^2)^{-0.992}$

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: acceleration

As explained in [2], the primary parameter is the aerodynamic acceleration, 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 merging smartly the computed figures of the 3 DoF point-like system nominal descent trajectory, the correspondent disturbed attitude motion by the 6 and 12 DoF tools, 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
Descent	nominal descent trajectory acceleration	DTAT
	disturbed attitude motion	PASDA
	spin simulation	Tables
	other: parachutes deployment shield/covers jettison boom deployment	Specific models
Impact	simulated impact profile	[9]
Surface	nominal acceleration = gravity	Sensor specs.
	other: landed probe orientation bouncing liquid movement	Specific models

Table 4. Acceleration inputs.

Attitude information has not been fully addressed for the Dataset #1. Subtle work is on-going to merge the attitude / non-attitude related tools for forth-coming releases, keeping the consistency between the datasets. For the first dataset, 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. RASU measurements are also simulated in the first dataset.

Other features of the dataset

Additional events may be modelled and included:

- 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, and instrument packet losses.

2.2.4. Step 4: dataset validation

The generated files are pre-viewed 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 will make use of a similar formatting as the real 2005 data to train the process and spot possible inconsistencies and problems. A special effort is being made regarding this issue.

2.2.6. Step 6: DTWG reconstruction tool testing

The DTWG reconstruction tool is run and tested using as input the Simulated Dataset, in the most similar way to 2005.

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*: in the first data set we are limited by the use of a 3 DoF Tool (DTAT) to compute the trajectory. The attitude information is being worked aided by the other tools, and future releases will include it.

3. THE RESULTS

Twenty-six different parameters have been generated for Dataset #1. Some of them express the same physical property sensed by different sensors. They are summarized in Table 5.

SOURCE	PARAMETER	SENSOR
DISR	Altitude	Imagers
DWE	Zonal wind speed	Link: doppler shift
GCMS	Molecular mass	Mass spectrometer
HASI	Pressure (x2)	PRE (corr/ uncorrected)
	Temperature (x8)	TEM1F,1C, TEM2F,2C (corr/ uncorr)
	Acceleration (x4)	Piezo acc (X, Y & Z); Servo acc (X)
SSP	Velocity of sound	API-V (Velocity)
	Acceleration	ACC-I (Internal)
	Altitude	API-S (Sounder)
RAU	Altitude (x2)	RAU 1 & 2
CASU	Central acc. (x3)	CASU1, 2 & 3
RASU	Radial acc. (x2) Spin rate (x2)	RASU 1 & 2
-	Trajectory [1] (X-Y-Z in EME2000, Q and ROT frames)	Simulated dataset (internal)

Table 5. Simulated Dataset #1 parameters.

[1] *This file will only be delivered to DTWG for crosscheck, in step 7.*

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

Primary data set

The measured entry deceleration and impact profiles (Fig. 1 and 2) are presented as a sample of the primary dataset (acceleration).

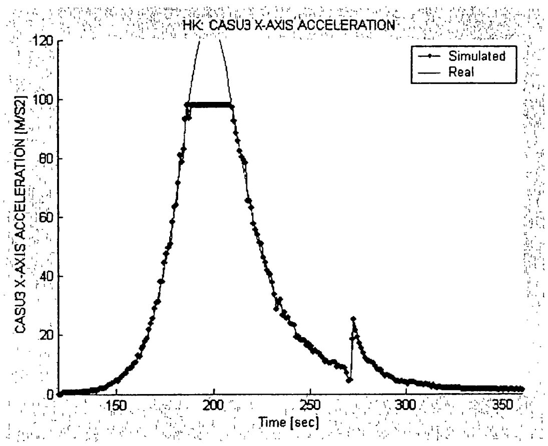

Fig. 1. CASU profile during entry phase. Data is buffered onboard for delayed transmission once the radio link is established. Peak deceleration is not measured by CASU due to the device limits (10*g*) - not the case for HASI accelerometers.

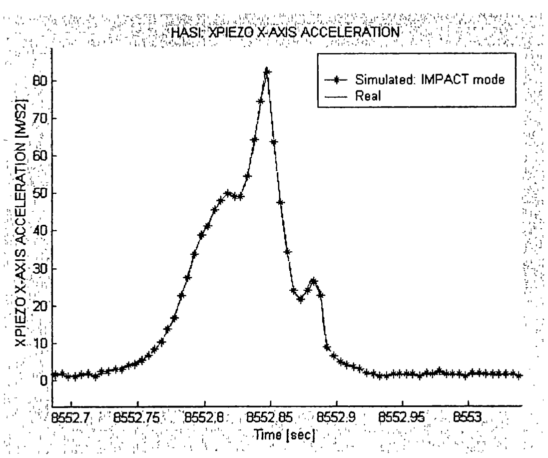

Fig 2. HASI X-piezo ACC impact profile. A special mode (*impact mode*) enables a 200Hz buffering around the event (-0.5s to +5.5s). A sand profile was selected.

Redundant data set

Additionally, redundant measurements will be included in the reconstruction algorithm, weighted with Kalman filtering techniques. Among them, HASI temperature (measured by 2 sets of coarse and fine accuracy sensors, TEM1F, TEM1C, TEM2F, TEM2C) and HASI pressure (measured by a capacitive barocap sensor in the Pressure Profile Instrument, PPI) have an important role since they can improve the accuracy of the reconstruction for the whole descent (Fig. 3 and 4).

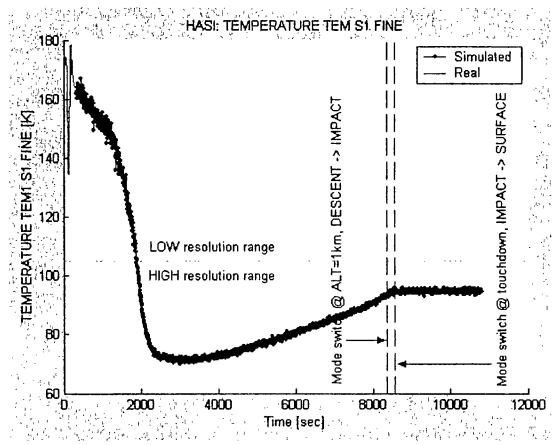

Fig. 3. HASI TEM1F sensor. Scale switching (LOW ↔ HIGH) is defined by the 105K threshold. The '1 km altitude' and the 'touchdown detection' define the mode switching (DESCENT → IMPACT → SURFACE). Sampling rate is 0.2 Hz, except in impact mode where coarse sensors flow stops, and fine sensors double this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

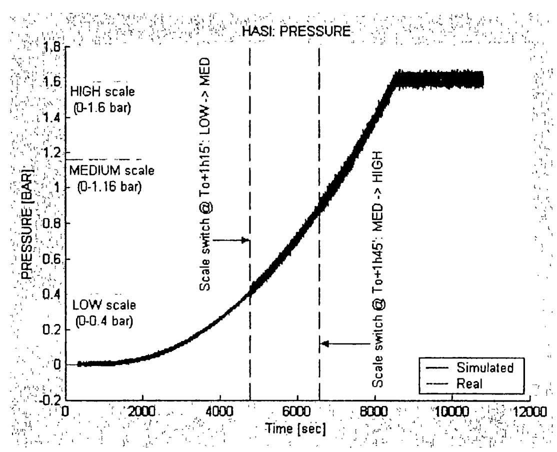

Fig. 4. HASI pressure. Pressure is measured in 3 scale ranges (LOW → MED → HIGH), with two scale switching at 1h15min and 1h45min after To. Noise is 1% of the correspondent full scale, and sampling rate is continuous 10 Hz.

Other redundant parameters may further constrain and validate the trajectory. For instance, the velocity of sound and the zonal wind speed provided by SSP and DWE instruments respectively. They are shown in Fig. 5 and 6.

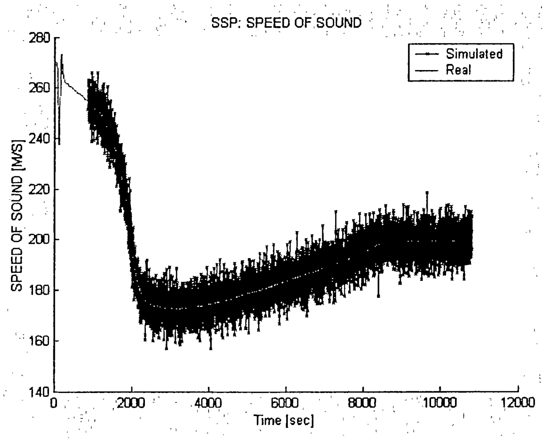

Fig. 5. SSP Speed of sound. The maximum range where data is reliable is imposed by the 0.1 bar threshold in which the measurement method no longer works.

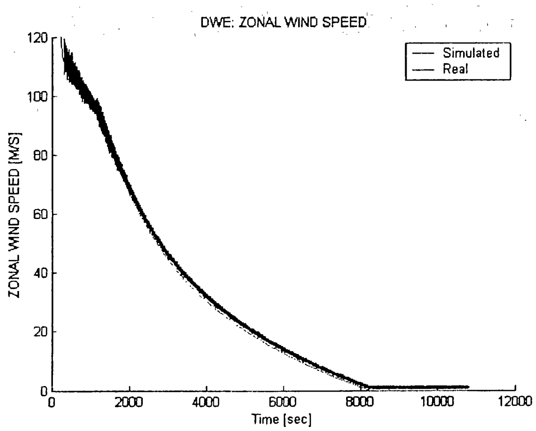

Fig. 6. DWE zonal wind speed. Noise is driven by the speed and transmitted frequency accuracy. A systematic error is applied due to the Huygens-Cassini geometry uncertainties.

The DTWG tool run (step 6) and reconstructed trajectory validation (step 7) are on-going at the time of writing.

4. CONCLUSIONS

The paper provides an overview of the generation of the Huygens Synthetic Simulated Dataset, a collection of engineering and scientific parameters measured by the Probe, which will be used by the DTWG numerical tool for the reconstruction of the Probe trajectory. We particularly focus on the various accelerations.

Because of the amount of parameters, only a selection of results is presented.

Future enhanced datasets might be simulated. The major improvements should concern:

- A better understanding of instruments behaviour.

- The use of the 6 DoF entry tool and the 12 DoF descent tool, in order to simulate the attitude effects on the parameters during those phases of the mission.

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