TOOL FOR REAL-TIME PREDICTION OF IXV TRAJECTORY IN THE MISSION CONTROL CENTER

Martins Sudars, Francesco Santilli

Thales Alenia Space Italia Spa.

Ivano Amador Caddeo

GMspazio Srl.

Gerhard Billig, Salvatore Mancuso

European Space Agency

ABSTRACT

IXV (Intermediate eXperimental Vehicle) re-entry vehicle has successfully flown a fully autonomous mission from the launch until it's splashdown in the eastern Pacific Ocean on 11th February 2015, and has been regarded as a major milestone in European re-entry technology roadmap. The vehicle has been designed to fly autonomously without the commanding from ground and without a need for a continuous downlink. It's trajectory and attitude however had to be closely monitored in MCC for operational and safety purposes including when out of the visibility window. For this purpose a dedicated too has been developed - TPVT (Trajectory Propagation and Visualization Tool).

The tool updated the current state and trajectory predictions based on the IXV vital-layer telemetry data whenever it was in the direct visibility of any of the ground stations, and also taking into account latest atmospheric measurements by the sounding balloons. In order to represent the vehicle's behavior as close as possible, the same GNC algorithms have been implemented in the propagation algorithm. For sake of propagation velocity the utilized models had to be kept simple in order to allow regular update of the trajectory every couple of seconds whenever fresh telemetry data was available. The propagated trajectory was displayed for the MCC operators for monitoring purposes, and the current state vector transmitted to the naval ground station in specific antenna pointing data format in order to facilitate the acquisition of the signal on the naval station. At the end of the mission the TPVT had an essential role in the vehicle's localization by providing an updated expected splashdown position, where it was found by the recovery ship's crew just 20 minutes later.

This paper gives and overview of various features of the tool, its interfaces with the MCC, visualization features, and also an assessment of its propagation performance during the real mission.

Index Terms— IXV, Trajectory, propagation, Mission control Center

1. INTRODUCTION

IXV experimental re-entry vehicle has autonomously performed a LEO re-entry demonstration, on 11th February 2015 when it was successfully launched from French Guyana by VEGA launch vehicle, and later recovered in the pacific ocean. It is 5,5m long and weights approximately 1840kg at launch.

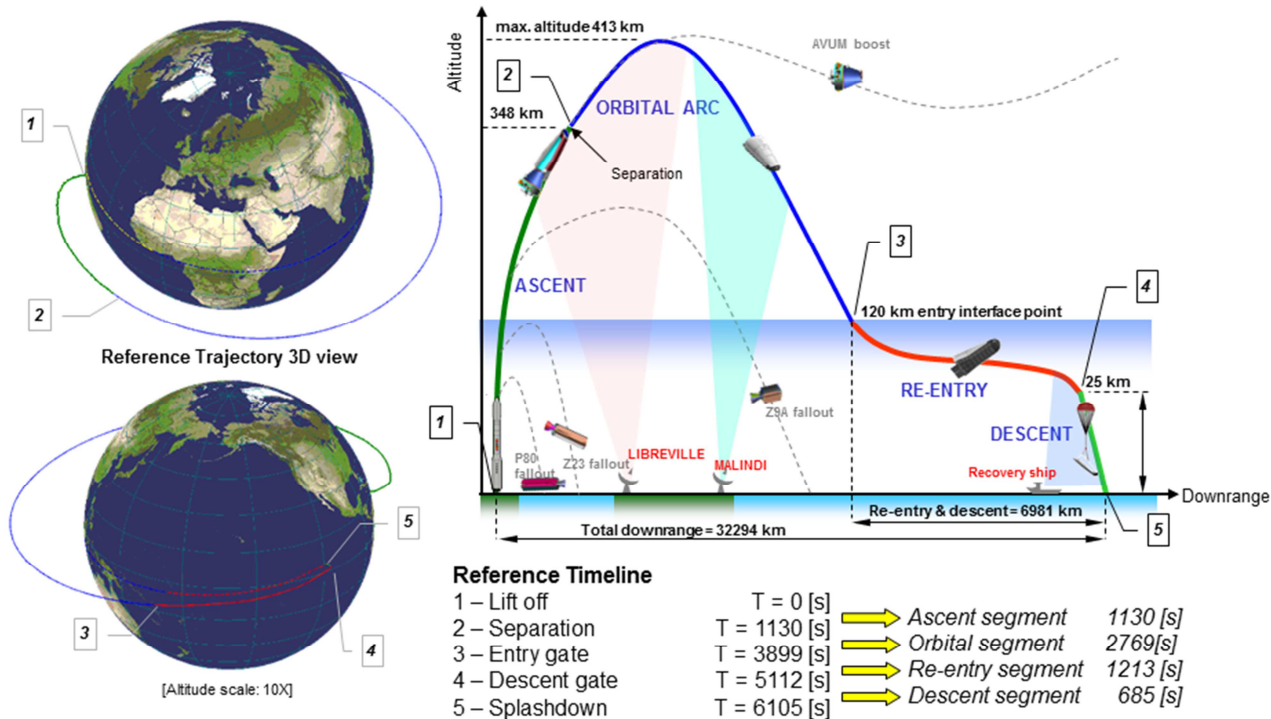**Figure 1 IXV vehicle before mating with the launch vehicle**

Figure 2 IXV mission profile overview
1 – launch, 2 – separation, 3-entry interface point, 4-DRS triggering, 5-splashdown

Although there was no commanding capability, the mission was carefully monitored from the Mission Control Center located in Altec, Turin, where the flight control team was following the vehicle's prelaunch sequence, its flight trajectory and events as well as assisted to vehicle's localization after the splashdown. 25km north from the predicted splashdown site the recovery ship was standing by for the parachute deployment and splashdown. After the splashdown, the vehicle was located by high speed boats thanks to information provided by navigation system and the localization beacons.

Figure 3 IXV after the splashdown

2. MISSION MONITORING NEEDS

Although the IXV vehicle carries out its mission completely autonomously, its trajectory has to be continuously monitored in the Mission Control Center. The telemetry parameter monitors in MCC provided detailed information on the subsystem states in numerical or plot format when the vehicle is within the coverage of ground station, however a more general overview of the vehicle's position was needed including estimation when the IXV is out of ground station coverage. This was the main reason the Trajectory Propagation and Visualization tool was developed. Moreover, the naval ground station needs to receive a pointing data, which can be used for acquisition of signal at the beginning of the visibility window, or if the auto tracking capability is temporarily lost. The availability of the data however was subject to the telemetry gaps due to absence of ground stations in very remote parts of the world, and therefore a solution was needed to cover them.

The following predicted radio coverage gaps existed:

1) Radio silence after the separation. By requirement the transmission of IXV had to be kept off until 20s after the separation.
2) Possible gap between Libreville and Malindi ground stations as foreseen conservative scenario analysis. This gap, as predicted, did not occur and the coverage of Libreville and Malindi overlapped.

3) Orbital and re-entry phase. From end of Malindi visibility until Acquisition of signal by recovery ship. This gap was the longest and covered the most critical mission phases.

4) End of descent phase. The vehicle would be below horizon and out of line of sight for the last tens or hundreds of meters (depending on distance). Due to very strong C/N of the signal only the last second of the mission was not covered by the receiving station on the ship.
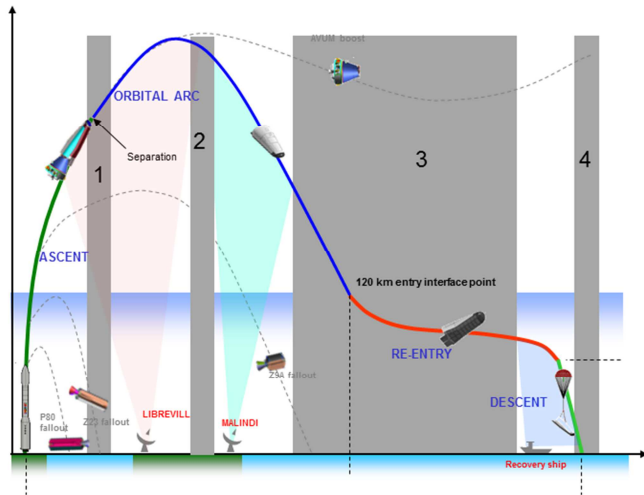

Figure 4 IXV mission profile with radio coverage gaps shaded in grey

TPVT (Trajectory Propagation and Visualization Tool) is a custom-made software tool developed and installed on a dedicated MCC console in order to allow real-time estimation of the vehicle's position and trajectory, it's visualization in the MCC on video wall, and proving the ground station antennas with the pointing data.

The tool has been built as 2 individual parts, which are running on two different workstations, but managed via a single MCC console –the TPVT console manager. One part – the TPVT is responsible for data acquisition, filtering, trajectory propagation and live trajectory data (known as "DO data") streaming, and is running on Linux server. The second – TPVTV – visualized the vehicle's trajectory, position and attitude on the screen in order to allow simple monitoring of the trajectory in the MCC, and is running on MS Windows environment. Both of the TPVT parts communicate between themselves via a standard TCP/IP interface.

The TPVT tool uses nominal trajectory (uploaded prior to the mission), VEGA DO data (until separation) or IXV TM for propagating the trajectory from the current position until the splashdown. In order to do that, a 3DOF simulator has been implemented which features IXV aerodynamic database, environment models, GNC algorithms (the same as onboard the vehicle) and also used the atmospheric data from radio soundings launched from the recovery ship to refine the trajectory prediction for the descent phase. An interpolator obtains the current position and attitude by interpolation in the propagated trajectory based on current UTC time, and passes the interpolated data for encapsulation and distribution in DO data format via UDP.

The TPVTV is a visualization engine based on AGI STK commercial software, which visualized the propagated trajectory, nominal trajectory, various boundaries, visibility range, vehicle's attitude and the main trajectory data on the dedicated screen and video wall in the front of MCC.

The tool is designed to perform the operations automatically, based on pre-established timeline, criteria and incoming telemetry. In case of a contingency the operator is able to intervene via the graphic user interface.

The main purpose of the TPVT tool is to:

- To provide to the MCC operators a visual information of the vehicle's position and mission progress

- To provide an estimation of the splashdown position, taking into account vehicle's current state, and measured winds by sounding balloons

- To provide the naval station antenna with a real-time pointing information

Further TPVT became an essential source of information to support the Safety officer, and decisions associated with contingency management. In order to support the contingency management, it was demanded to be able to distinguish between reliable or unreliable propagation information sources, or use backup sources if the baseline TM reception fails. At the same time, TPVT had to be automatized as much as possible in order to reduce a possibility of a human error to mislead the MCC or recovery teams.

Hence, the additional requirements for the TPVT was:

- TPVT shall be able to handle automated switchover between various sources of trajectory information (telemetry from GNC or GPS, VEGA DO data etc)

- TPVT shall allow the operator to manually handle the propagation process, state vector sources and the graphical representation of the information

In addition, the TPVT had to be able to run on a state of the art workstation without requiring an elevated computational power. In order to make the visualization more fluid, the TPVT was developed to run on 2 machines – the propagation engine on Linux workstation, and visualizator on MS Windows workstation.
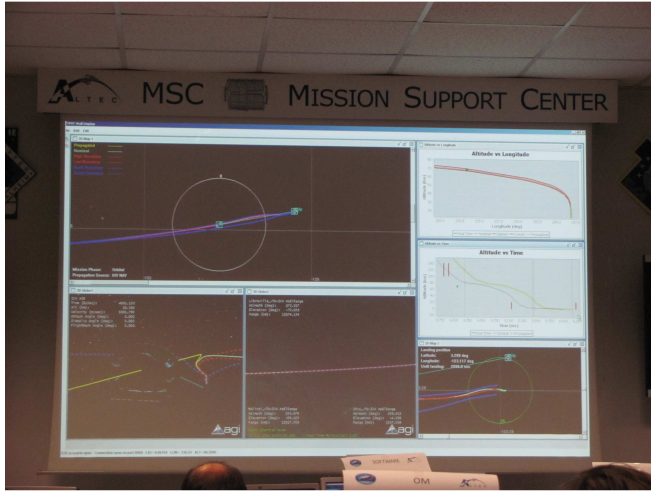
Figure 5 TPVT visualization on the MCC's video wall (from training sessions)

3. FUNCTIONS AND FEATURES

There are number of setup features, allowing to prepare the tool, and functional features, which allow management of the TM data, priorities, sources etc.

Once launched in mission mode, TPVT will carry out the following baseline tasks:

- Standby before launch and transmit just the pointing data to the ground stations

- At launch visualize the ascent phase and send pointing data based on the nominal ascent trajectory.

- After AVUM cut-off or when an updated TM is available, a new trajectory profile will be generated every 3 seconds, and passed to the interpolation process and visualization engine. The trajectory profile is a table with MET values of interval 1s as a first column.

- The interpolation process used the current MET to interpolate in the propagated trajectory profile and relay the output to the MCC DO data distribution PC; which further delivers it to the naval ground station. The same data is also provided to the visualizator on TPVTV workstation.

The TPVT features a graphic user interface (GUI) based on JAVA which manages the processes on the propagator. By the graphic user interface the console operator can:

- Setup the mission and network configuration, load nominal trajectory files, meteo files etc.

- Launch the the TPVTV in mission mode, or stop it

- Select manually the propagation source in case of contingency

- Select manually the flight phase in case of contingency

- Switch over from usage of radiosounding meteo data to model

- Monitor the status of the tool and the Telemetry coming from vehicle or VEGA,

- Filtering out invalid data packages

When an updated telemetry packet is available the TPVT calls the propagator function, which has been developed and compiled separately from the rest of TPVT tool and linked as a dynamic link library. The TPVT main features are the following:

- Developed in Mathworks Simulink environment and auto coded in C

- Propagates the trajectory from launch until MET=8000s (including on ground)

- 3DOF dynamics, position and velocity integration in ECEF Cartesian reference frame

- Features navigation and guidance algorithms and parameters exactly as they are on-board the IXV.

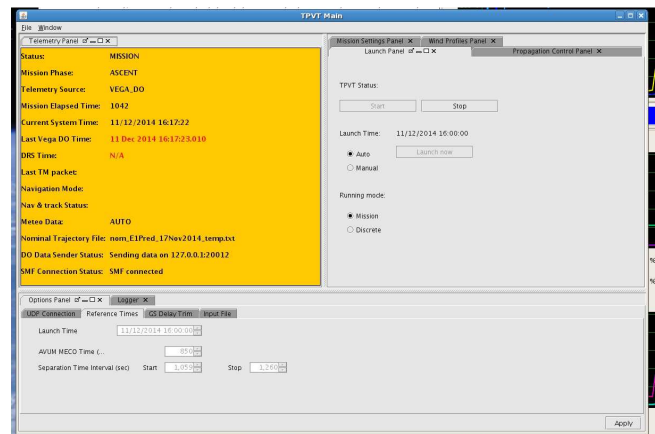- Features simplified model of the parachute system chain

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Figure 6 Main window of the graphic user interface

The TPVTV, running on a different physical machine, has got the following functionality and features:

- Uses AGI STK visualization engine

- Displays 2D map of the world and trajectories.

- Displays altitude-vs-longitude and altitude-vs-time profiles for nominal, propagated and boundary trajectories (derived from Monte Carlo analysis) which visually define the predicted envelope of dispersions.

- 3D visualization of the vehicle's attitude

- 3D visualization of the earth

- 3D visualization of the ground station antennas. This feature could be very useful for degraded mission cases in order to understand whether the vehicle could be visible. This feature was also very useful for the LEO satellite tracking during the naval antenna acceptance tests.

- Zoom-in map of the landing area with precision circles

- 3D models of IXV, VEGA and parachute for better representation of the mission phases

- Features MENU for setup if the ground station position and 2D window parameters (event markers, constraint lines)
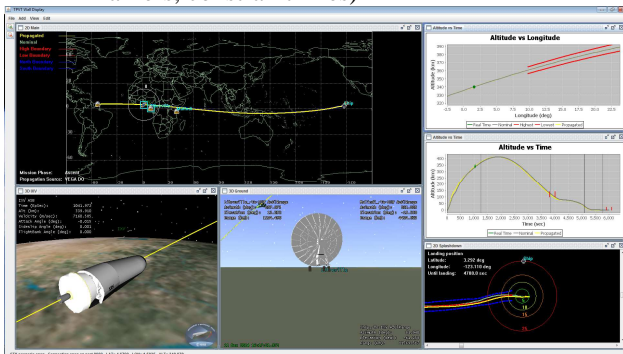
Figure 7 Visulization of the ascent phase before AVUM MECO, including 3D model (screenshot from trainings)
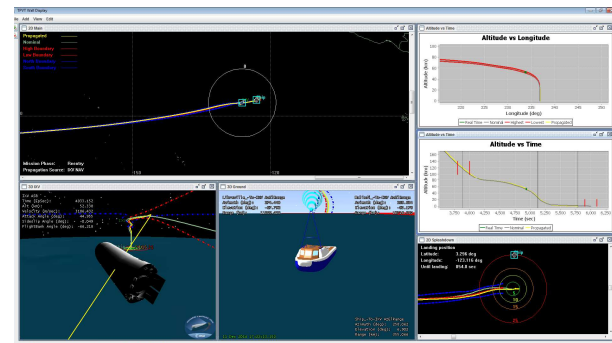
Figure 8 Visulization of final part of re-entry phase, with zoomed in 2D map, display oft the naval antenna (screenshot from trainings)
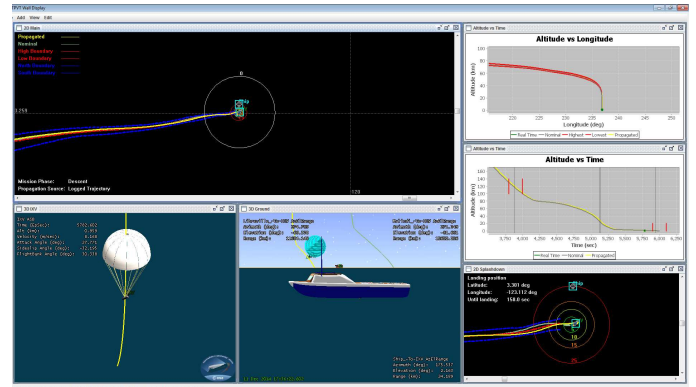
Figure 9 Display of the descent phase, featurinh 3D model of the parachute. (screenshot from trainings)

4. ARCHITECTURE

In order to ensure a fluid functionality of the functions and features described in the previous paragraph, the tool had to be designed in a way to split the whole process in multiple independent threads in order to allow task parallelization. The propagator takes a considerable fraction of a second to complete the trajectory, meanwhile the interpolator must keep providing the DO output continuously and precisely at 10Hz frequency. At the same time the TPVT must monitor the SMF server for new data packets, filterer if necessary, update position and attitude provided to visualizator, and also handle the inputs from graphic user interface.

The TPVT calls the propagator module called TPM by passing it the vehicle's state vector in ECEF frame, and the corresponding MET value.
As an output, the TPM module returns an updated trajectory profile, where it updates the trajectory only after the MET value passed together with the initial state vector.
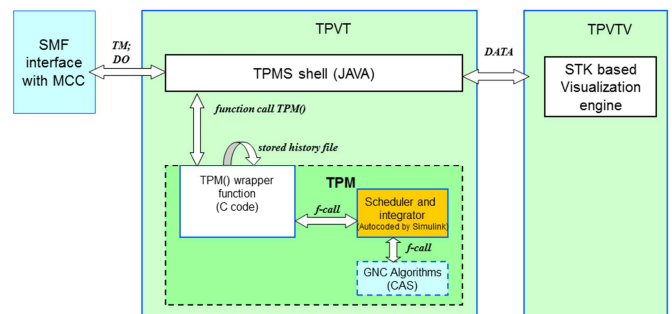

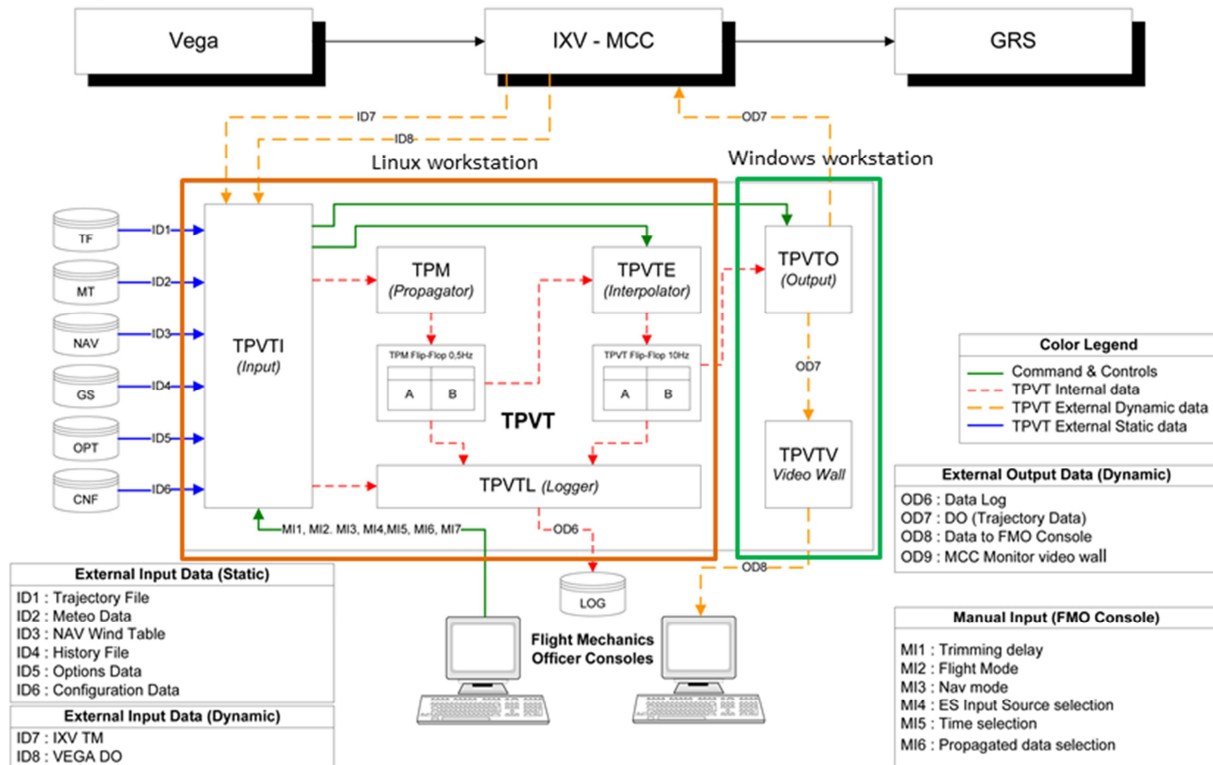
Figure 10 TPVT shell architecture

Figure 11 Overall architecture and data flow

5. PROPAGATOR MODULE

Equations of Motion have been defined in ECEF frame, that is not inertial. So the Coriolis and centripetal components have to be included. It was very convenient to use ECEF frame as it is also used by VEGA DO data, IXV GPS, IXV navigation solution (output) and as an input for the ground station DO PC.

The equation of motion is the following:

$$\frac{d\vec{v}}{dt} = \vec{a} - 2(\vec{\omega} \times \vec{v}) - \vec{\omega} \times (\vec{\omega} \times \vec{r}) \qquad \text{and} \qquad \frac{d\vec{r}}{dt} = \vec{v}$$

The attitude of the vehicle is according to the mission events and schedule.

5.1 Environment model

The environment model, mainly atmosphere and winds, has to be as representative as possible, but implementation of complicated model structures was undesired. Therefor the environment profiles were generated externally and imported into the tool via GUI.

The set of necessary atmospheric parameters is defined as follows:

- air density (kg/m³)
- speed of sound (m/s)
- wind velocity (3-elements vector in NED frame, m/s), with vertical component always assumed to be 0

This set is computed on the basis of the current geodetic altitude (m) in the Atmosphere model. Two independent sources of data are considered inside the model:

- the nominal atmosphere: pre-defined standard atmosphere in the geographic location of the IXV nominal mission scenario's reentry phase based on the NRLMSISE00 model;
- the measured atmosphere: data from radio soundings (for the lowest part of the atmosphere).

- The both models are bridged by a simple linear law to avoid sudden jumps and acceleration peaks:

As for the gravity model, a simple WGS84 ellipsoid model has been adopted for gravity and geodetic position calculations, it is simple and accurate enough for short missions.
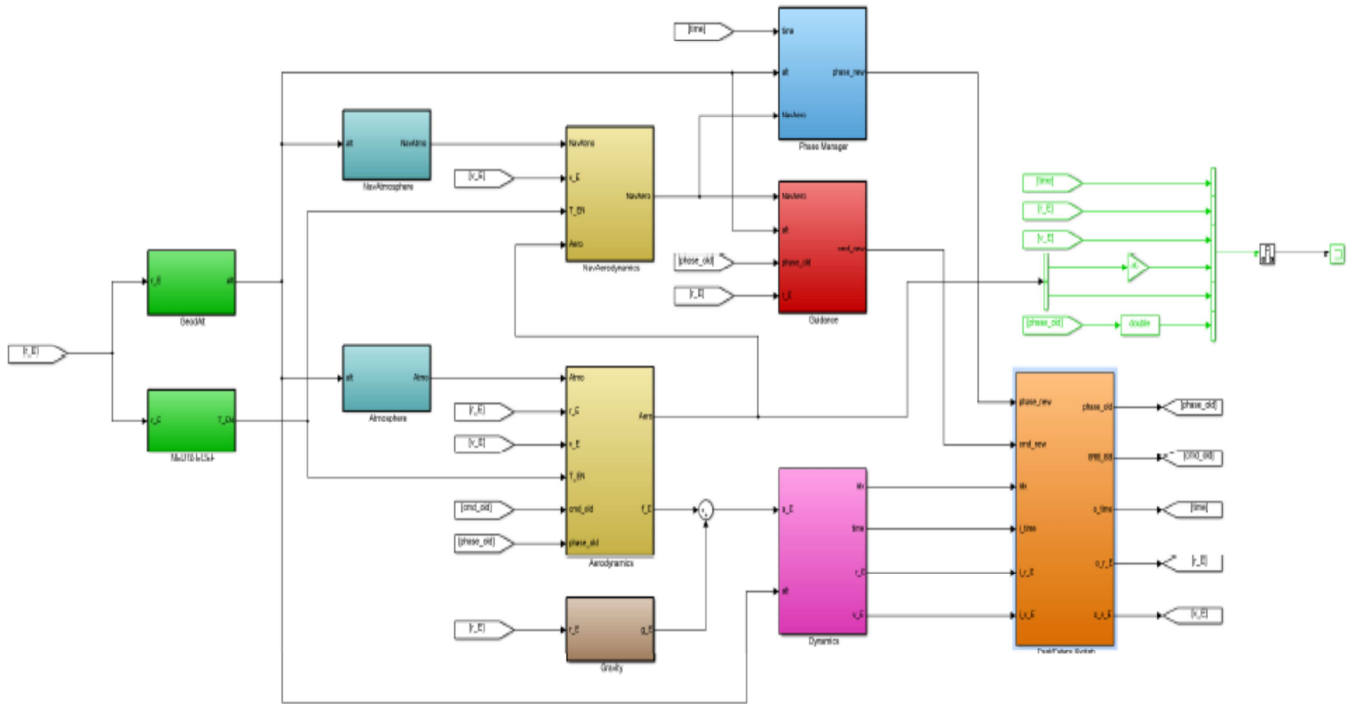
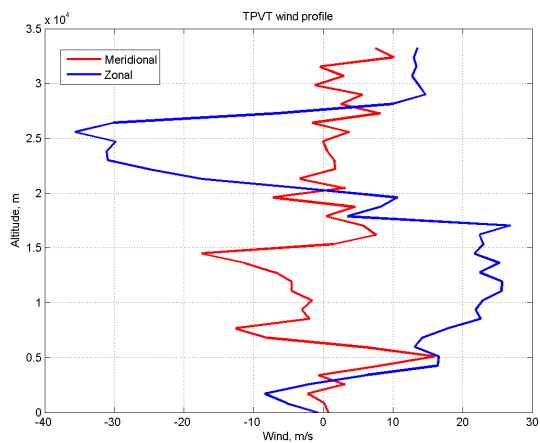**Figure 12 Illustration of the Simulink structure of the TPM module**

Figure 13 Atmospheric wind profile uploaded into the propagator 4 hours before the launch
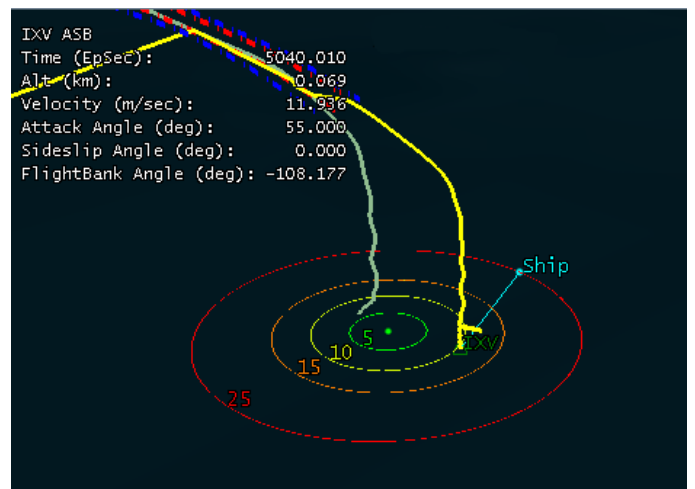

Figure 14 The effect of atmospheric winds - difference between nominal and propagated (yellow) trajectory when due to wind drift in case of high, zoom-in of 3D window (from training session)

5.2 Vehicle's model

Like for the environment models, the representativeness of the vehicle's properties has to be balanced between the complexity of their corresponding mathematical description. The following parameters have been used:

- Vehicle's mass, assumed to be constant, aligned with the predicted mass based on predicted average ablative TPS erosion and RCS fuel consumption calculated before the mission.

- Simplified model of vehicle's aerodynamics, IXV aerodynamic shape is very complex, and so are the describing models used for the vehicle'0s development. In the propagator the aerodynamics were expressed as 2 look-up tables of CA and CN.

- Simplified model of the parachute for all 3 stages, featuring timed staging, and a simple linear inflation law just to avoid abrupt changes of state in the simulation. The parachute force computation assumes the parachute's drag force is always aligned with the opposite of the relative airspeed vector with respect to the vehicle.

- Correct modelling of the vehicle's Attitude performance under parachute is even more important than the inflation or drag of the canopy itself. As the vehicle can freely rotate around the longitudinal axis of the parachute, it's lift vector can act upwards or downmwards making the initial descent profile less or more steep. The resulting difference in altitude can lead to more than 500s difference of descent time under main parachute, which can be multiple kilometres of position error due to the drift by horizontal winds. The model has been developed on the base of TASI 12DOF multi body simulator results. The observed behaviour of the vehicle under the supersonic drogue chute was in line with the expected behaviour as foreseen by the multi body model, and as implemented un the propagator. For the sake simplicity the model was expressed as multiple-segment exponential profile describing the rotation rate as function of time. The rate was integrated in order to obtain the bank angle.
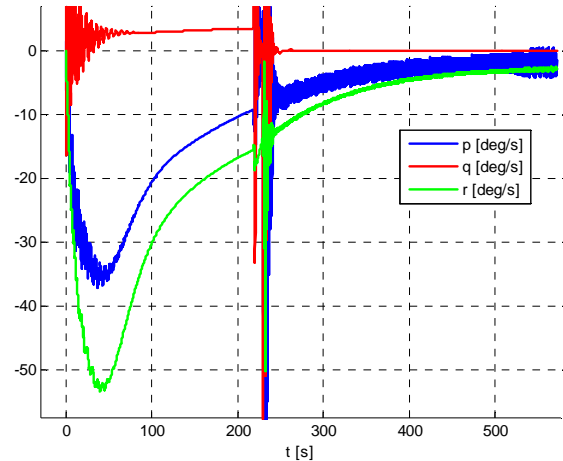

Figure 15 Example of maximum attitude rates in body frame from Multi Body simulations (max lateral CoG misalignment). T=0 corresponds to DRS triggering.
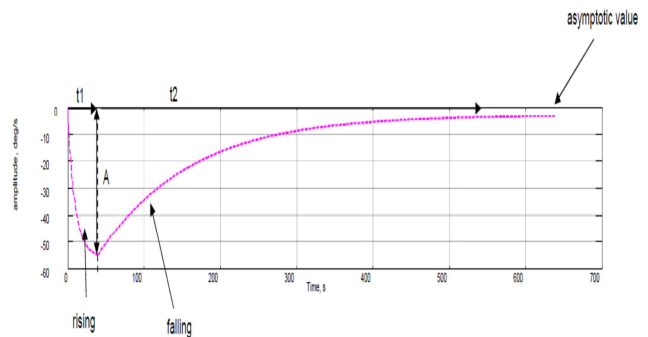

Figure 16 Model used to approximate the bank rate under supersonic drogue

5.3 Guidance

The TPM module features exactly the same guidance algorithms and navigation algorithms as the real IXV vehicle onboard, therefore the same behaviour was expected as for the vehicle. As the angle of attack follows a pre-defined trim profile with respect to mach number, and the angle of sideslip tends to 0 degrees, the principal output of the guidance algorithm was the bank angle profile with respect to the time.
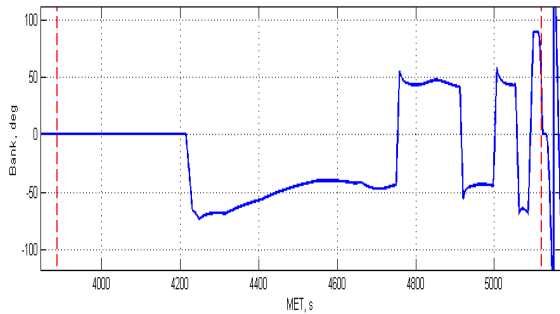
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Figure 17 Generated bank angle for the re-entry phase (limited by red dotted lines) on the last telemetry packet before loss of signal from Malindi ground station.

6. TOOL'S PERFORMANCE ANALYSIS

During the mission the TPVT prediction was the best estimation of the trajectory available, hence there was no it's propagation accuracy was not estimated in real time. During the development the propagation accuracy was assessed based only on predictions by other higher fidelity models. Only the preliminary post flight analysis allowed to assess the real performance of the TPVT during the mission and quantify the propagation error.

The propagated splashdown point accuracy has been checked and reported here for the following points of propagation:

1) 1st VEGA DO packet

2) last VEGA DO packet, before IXV TM became available

3) first packet after separation

4) last packet before Malindi LoS

5) 1st packet after NAVAL AoS

6) 1st packet after DRS triggering

7) Last received packet

The results are plotted as "travel" of the estimated splashdown point coordinates, and as a variation of the azimuth-elevation profiles, as seen from the recovery ship.
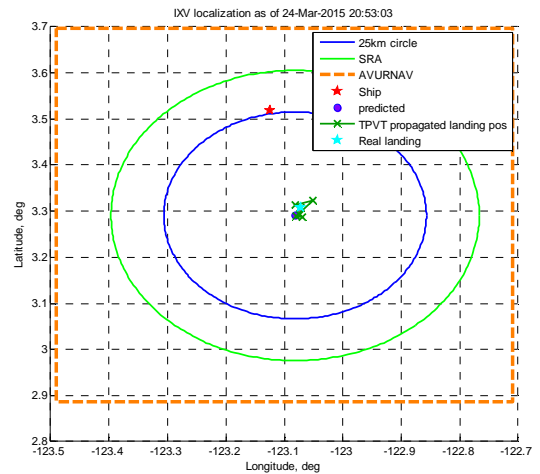

Figure 18 Predicted splashdown position together with the 25km circle (accuracy requirement), SRA and NOTAM/AVURNAV area
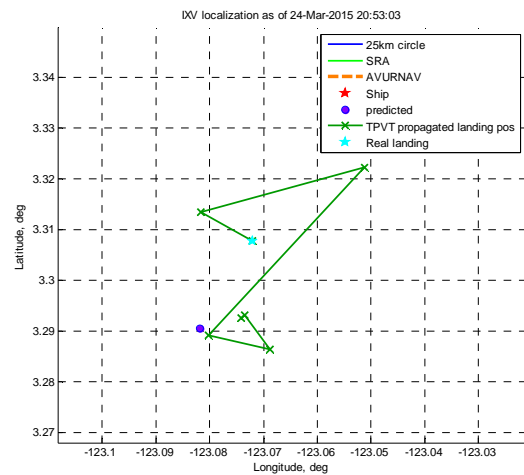

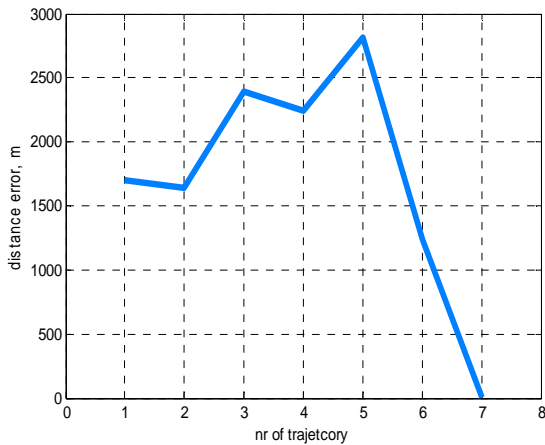**Figure 19 Zoom-in of predicted splashdown position "travel" together with the mission evolution.**

Figure 20 Variation of the position error expre4ssed as distance to the real splashdown point.
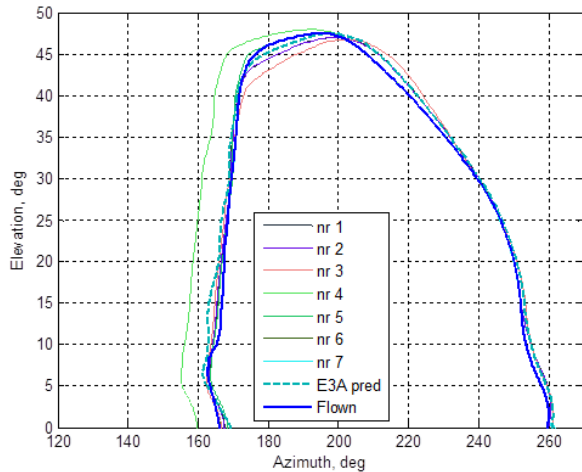

Figure 21 Elevation-azimuth plot for all the 7 checked propagation points.

7. CONCLUSIONS

Dedicated tool has been developed and utilized for the IXV mission monitoring. The trajectories have been propagated from the AVUM cut-off and during the visibility windows. The graphical representation of the trajectory allowed MCC operators, especially OD and OM to access the information they needed without using a voice loop request.

TPVT provided a very good estimate of the splashdown position and would have given a high probability to recover the vehicle even position should the transmission had been lost earlier somewhere during the descent phase, which fortunately was not the case. The mission went nominally and vehicle was successfully recovered thanks to quick localization.