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ASTOS, a reconfigurable software for design of mega constellations, operation of Flying Laptop and end-of-life disposal

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ASTOS (Analysis, Simulation and Trajectory Optimization software for Space applications) allows the user to set up arbitrary space scenarios with multiple vehicles. The versatility and reconfigurable capability of ASTOS enables its application during all the mission phases: from feasibility to end-of-life disposal. The paper presents the capabilities of ASTOS modelling mega constellations like OneWeb, supporting the operations of the Flying Laptop small satellites from the University of Stuttgart (DE) and the re-entry of the European Automated Transfer Vehicle (ATV).

I. Introduction

The current paper presents the ASTOS software [1]; in particular its evolution from a dedicated and powerful trajectory optimization tool for ascent and re-entry vehicles to a flexible software able to handle several space scenarios along the complete mission life: from feasibility studies till disposal and post-flight analyses.

In line with this conference, several past and current examples are provided to show the application of the software to the operational phase of a mission as well as the inclusion of operational aspects during the design of it.

The range of scenarios is quite extended:

- Space launcher design performed by European Space Agency (ESA), Korea Aerospace Research Institute (KARI) and others.
- Preparation and execution of the operational phase of Flying Laptop [2] at the Institute of Space Systems (IRS) of the University of Stuttgart (DE).
- Automatic Transfer Vehicle (ATV) [3] end-of-life disposal with associated risk.
- Trajectory reconstruction of Sounding Hypersonic Atmospheric Re- entering Kapsule (SHARK) [4] on MAXUS 8 sounding rocket.
- Simulation of OneWeb constellation with pitching maneuver.
- Ground safety for satellite launcher applications.

The goal of this paper is to present the advantage of using a reconfigurable software during all the phases of a mission in term of reduced personal training and fast learning curve.

II. ASTOS

ASTOS originates from a European Space Agency (ESA) contract in 1989, which was dedicated to ascent trajectory optimization in the frame of the Future European Space Transportation Investigations Programme (FESTIP). At that time it was called ALTOS. In the following 10 years ASTOS was developed at the Stuttgart University into a powerful trajectory optimization software. Since 1999 ASTOS is sold to industry and agencies worldwide; it provides highly functional methods for optimal control and it is featured with most powerful solvers like the European nonlinear programming (NLP) solver WORHP [5]. Since 2006 the development and sales of the

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software is managed by Astos Solutions GmbH with its application expanded beyond optimization in the field of mission analysis, guidance, navigation and control (GNC) and system concept analysis.

The natural evolution has been the expansion in the operational phases, with several successful examples covering a wide range of space scenarios.

ASTOS allows the user to set up arbitrary space scenarios with multiple vehicles (e.g. constellations), ground stations, areas of interest and points of interest. Each vehicle or station may consist of several elements like sensors, actuators (e.g. thrusters, magnetorquers or wheels), tanks, structural components, batteries, solar generators, radiators, etc.

The versatility and reconfigurable capability of ASTOS enables its application during all the mission phases: from feasibility to end-of-life disposal. Moreover links to applications such as mission simulation, GNC via a Simulink interface and assembly, integration and test (AIT) are provided. One example of reconfiguration is provided in Fig. 1: enabling or disabling the features, the user can configure the software according to the need of the analyzed phase and scenario. The enabling/disabling of a feature shows/hides the respective entries: e.g. the “Optimization” affects the left tree as well as the actions buttons “Initialize”, “Optimize” and “Simulate xxx”. The effect of other features is instead distributed on more areas: e.g. “Data system” shows/hides the data generation, storage and transmission of each sensor as well as the specific vehicle part, i.e. “data buffer”.

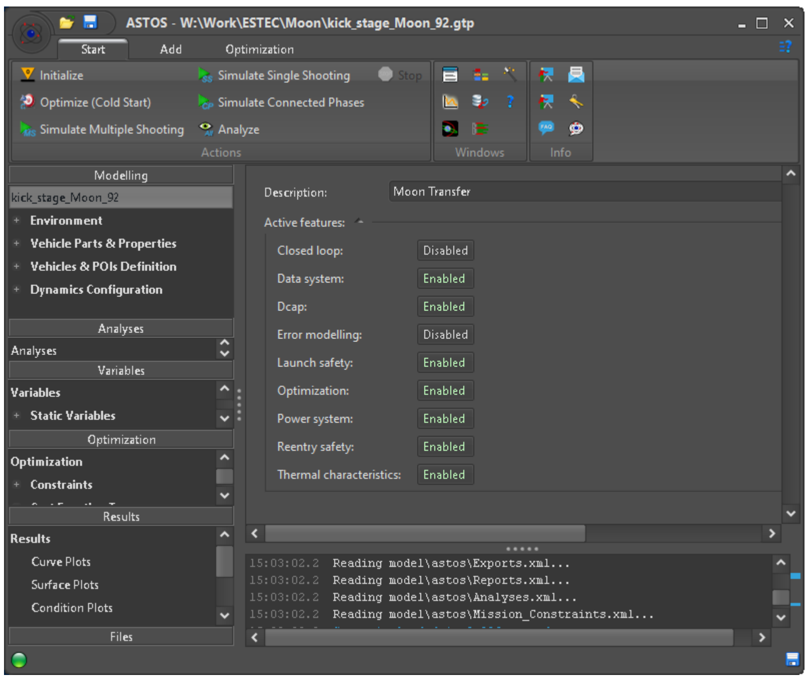

Fig. 1 ASTOS Main windows with features.

In ASTOS a set of customizable models with various complexity and realism is available for each of the abovementioned categories (model database). The same for environmental models like atmosphere, gravity field, magnetic field, hydrosphere, ephemerides and celestial body spin models. All the user input can be provided directly via a graphical user interface or via multiple links to MySQL databases and Microsoft Excel files. Additionally the adoption of XML for the input file allows the use of external scripts for the generation of the complete scenario without the use of the software GUI.

Ones configured, all these models can be reused throughout the scenario (template approach), see the “Components” list in the left tree of Fig. 2. Via a graphical “Vehicle Builder” (right panel in Fig. 2) a spacecraft or rocket can be built from the defined and configured elements, whereas the element’s aspects like positioning, their role or contribution in the power, thermal control or data management system or their graphical representation (e.g. for animations) can be configured.

The use of templates is even more important when considering the creation of a constellation made of identical satellites flying in different planes. This procedure is almost fully automatic, in the sense that the software requires only few inputs related to the constellation (e.g. Walker parameters) and the definition of a single satellite to be used multiple times.

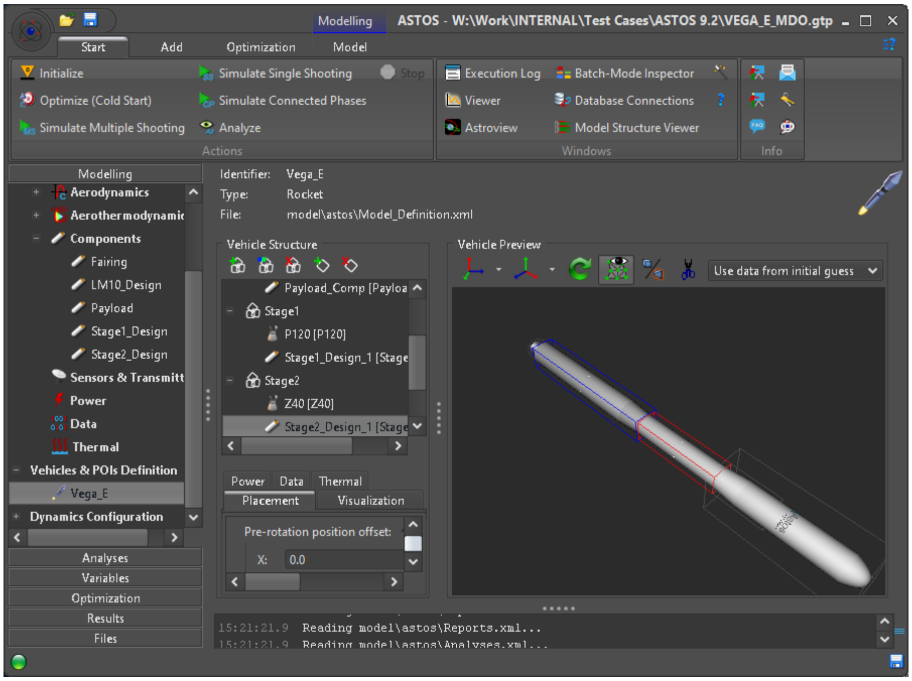

Fig. 2 ASTOS Vehicle builder and preview.

Via the dynamics configuration, initial states and the translational and rotational motion of each vehicle can be defined: e.g. equations of motion, attitude control laws; 3-degree of freedom (3-dof) or 6-dof propagation, whereas motion rules can be changed throughout the simulation time (multi-phase concept).

The further work flow of ASTOS depends on the application: it might consist just of a simulation and results inspection by means of the built-in plotting and 3D realistic animation tools or using one of the available export filters. But it can be more complex e.g. if the optimization or batch processing feature of ASTOS is used.

Several hundred output functions are provided already in a standard ASTOS simulation output file. However, further information can be exploited from the simulation result in post-processing step by means of a variety of available analyses: link budget, visibility, navigation, eclipses, fuel budget and operational life-time, end-of-life disposal, coverage, electrical power budget, data management/storage and orbit evolution.

In order to reduce the effort for the user, ASTOS can create automatically generated reports that can be customized by the user. For the mission performance analysis a report is generated that follows a structure as it is defined in the ESA Mission Analysis Guidelines for Earth Observation Missions [6].

The system concept analysis feature of ASTOS allows preliminary design and performance analysis of the power, the thermal control and data management systems of an orbital spacecraft. This new functionality is seamlessly integrated into ASTOS, i.e. each definable element of the scenario has now optional parameters that characterize their behavior under thermal, power or data aspects (e.g. heat production or power consumption). These generic elements are accomplished by new models dedicated to system concept analysis (e.g. batteries, solar arrays, data storages, radiators).

Fig. 3 shows the level of detail of the solar generator input panel with enabled the thermal characteristics. The possibility to activate the optimization of the scaling factor provides an automatic procedure to identify the dimension of the solar panels for the simulated mission. Since this is a real parameter, the optimal value computed by a gradient-based solver needs to be transformed in an integer: e.g. a scaling factor of 3.75 means 4 parallel cells.

The latest release significantly extends the capabilities of the ASTOS software and opens new markets for a software that started as an optimization tool for launcher trajectories more than 20 years ago. Nowadays ASTOS is able to perform design optimization, mission performance, system concept and safety analysis task. In order to mitigate the risk that the complexity of the tool impedes its usability, measures like the introduction of a wizard system were taken.

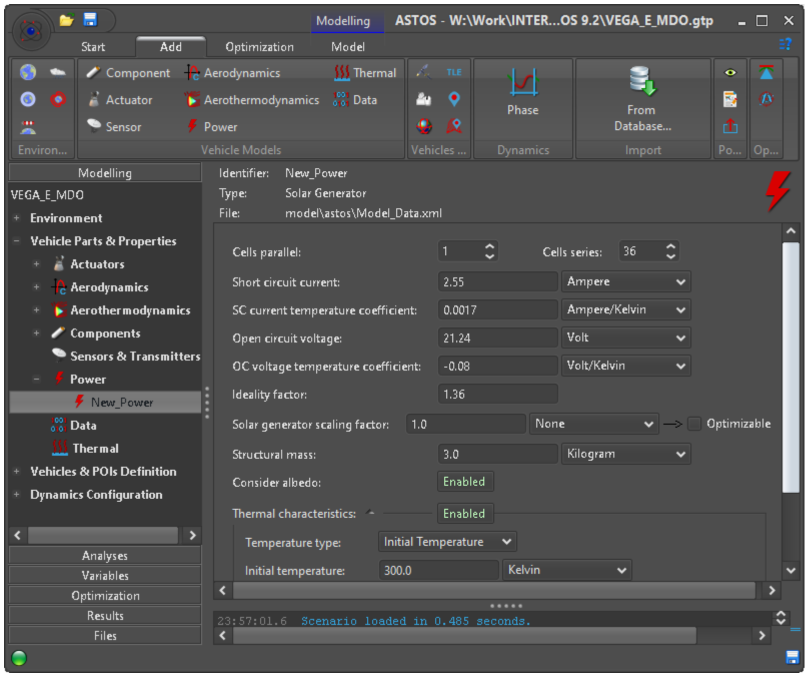

Fig. 3 Solar generator input panel.

III. Operational examples

A. Launcher design

The process of designing a vehicle via a step-wise approach is the most effective in the field of space launchers. The rationale is the progressive knowledge that the designer achieve during the process itself: starting with high-level requirements, then moving toward a preliminary design until the detailed design of each sub-system.

In order to follow this procedure, ASTOS presents several levels of design models in the most important fields: aerodynamics, mass budget and propulsion. This step-wise approach is not only driven by the missing knowledge of some details in the early phases of the design, but also by the performance of the optimization software. The duration of the process is affected by the complexity of the models involved; therefore in the early phases it is more efficient to use fast models and analyze several potential concepts. Once the most promising concept has been identified, detailed models could be applied to refine the design of the vehicle.

Considering operational aspects, the attention is drawn to the load-case computation performed by ASTOS in order to identify the required thickness of the structure composing the vehicle. In particular for the propellant tanks, an important aspect is the ullage pressure during the different phases of the mission. ASTOS allows the user to analyze all the different configurations of a tank:

- empty with low ullage pressure;
- empty with high ullage pressure (i.e. during integrity test).
- full with low ullage pressure;
- full with intermediate ullage pressure, e.g. during critical events like maximum dynamic pressure;
- variable filling ratio with high ullage pressure during the burn of the burn of the connected engine.

Fig. 4 presents the details of the tank pressure for a component. In this particular case the ullage pressure during the upper stage burn phase is defined for the upper stage tanks of VEGA E. In addition to the dynamics of the vehicle (e.g. attitude), it is possible to define the phase-specific dynamics of actuator (e.g. throttle), sensors (e.g. pointing laws) and components.

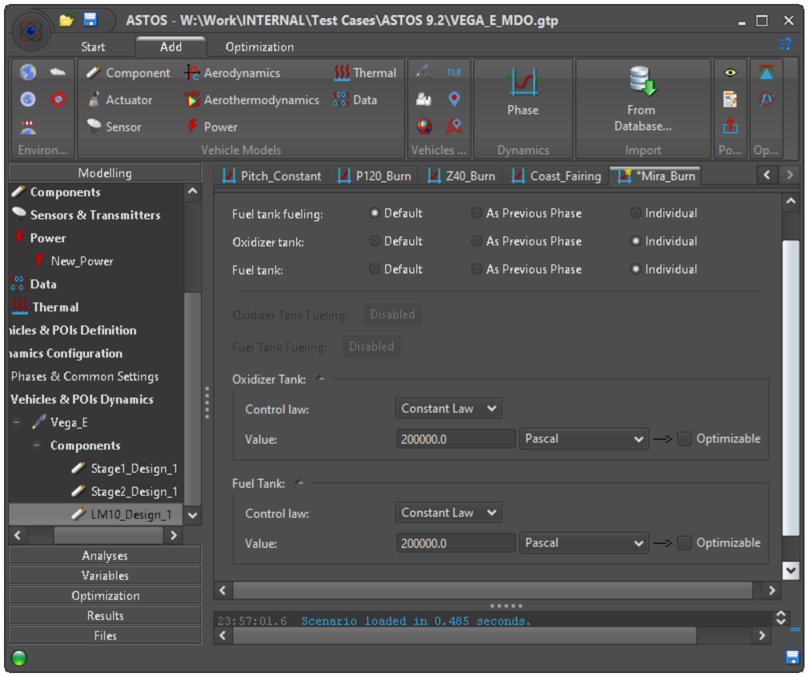

Fig. 4 Phase-specific definition of tank pressure.

B. Flying Laptop satellite

ASTOS is used and it has been used to support the operations of the Flying Laptop small satellites from the University of Stuttgart. The satellite has been launched the 14th July 2017 on Soyuz, but the mission analysis team adopted ASTOS more than two years in advance. The main objective was the flight dynamics: to generate the orbit information in different formats, time, azimuth and elevation coordinates for antenna control and acquisition/loss of signal (AOS/LOS) times for the purpose of mission planning. For this purpose the team introduced new observation targets and new orbit data. Moreover they edit the existing details on a regular basis to perform analysis and get the necessary outputs for additional post-process. So the tasks are constant and therefore a batch procedure has been established with ASTOS called by command line and automatic modification of model data via an external procedure. The main advantage of this procedure is the reduction of the user errors while inserting the input. A disadvantage is the need to update the scripts every time a modification is introduced in the XML format. This is normally the case with each new release of ASTOS; therefore a frequent interaction has been established between the developer team at Astos Solutions and the Flying Laptop team at IRS. Fig. 5 shows the control center located at the University of Stuttgart.

Technical details about the integration of ASTOS in the ground segment software of Flying Laptop has been already presented in past papers, e.g. [10].

Fig. 5 Flying Laptop control center at IRS.

C. Re-entry of ATV

Before the re-entry of ATV-1, ESA performed several risk analysis based on existing tools in Europe and in USA. The outcome was not satisfactory, therefore ESA supported the improvement of the existing capabilities of ASTOS to be able to address the complex fragment tree generated during the re-entry of ATV [7]. Each fragment is integrated considering its shape, material and initial temperature. Considering melting and demise, the surviving fragments are identified and used to compute the risk associated to the population density, air-traffic and ship-traffic in the impact area.

The air-planes observation campaign performed during the ATV-1 re-entry provided additional input for the improvement of ASTOS. A similar procedure has been applied to other re-entering objects: e.g. third stage of VEGA [8] and the International Space Station (ISS) [9].

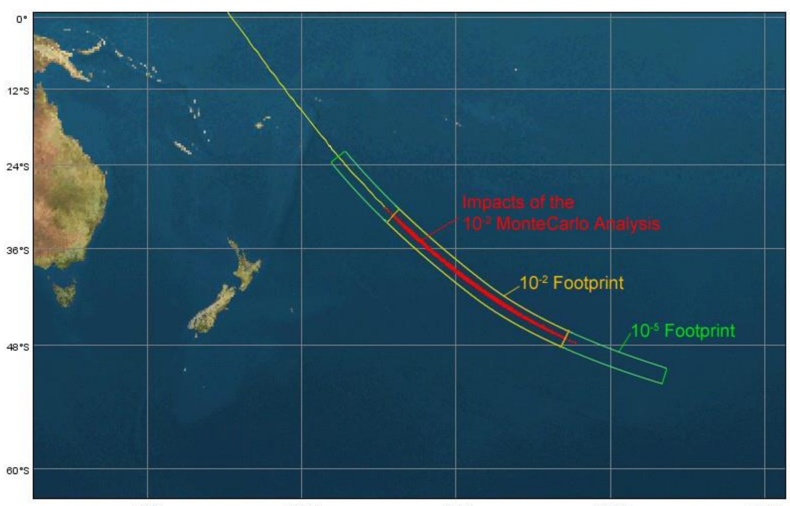

Fig. 6 Impact points (red dots) of ATV-1 with safety footprints.

D. SHARK on MAXUS 8

During the launch of MAXUS 8 in 2010, a small capsule – SHARK – was assembled in the interface between the payload and the stage. This capsule presented no parachute and therefore the recovery chances were low considering the snowy environment near Esrange (Sweden). ASTOS has been implemented to reconstruct the trajectory based on GPS receiver measurements and compute the impact location. The position computed by the software was less than 2 km far away from where the capsule has been recovered, quite impressive considering that the apogee of MAXUS is in the order of 700 km and the GPS signal was interrupted already during the ascent trajectory at an altitude around 100 km.

Fig. 7, left, presents the post-flight meeting at the Esrange control center in Sweden, with the comparison between the trajectory reconstructed by ASTOS and the GPS telemetry transmitted by MAXUS 8 during the flight. On the right the dispersion of the impact position of SHARK computed by ASTOS is shown (yellow crosses).

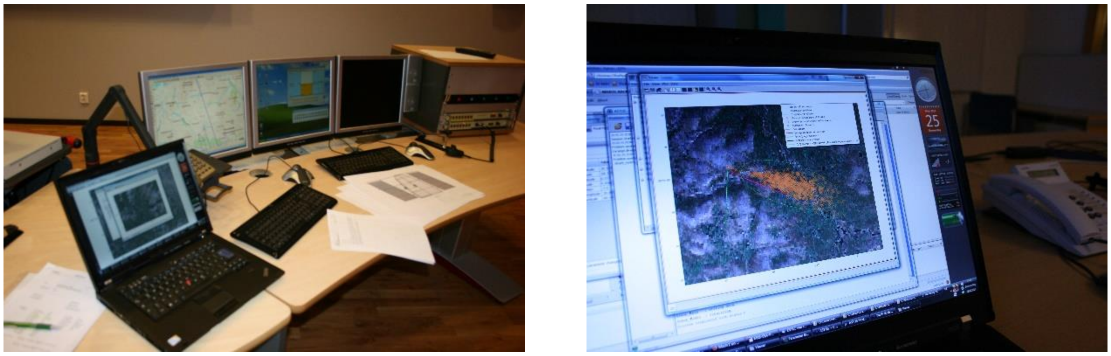

Fig. 7 Left: ASTOS at the Esrange control center; right: SHARK dispersion computed by ASTOS.

The trajectory reconstruction campaign has been run in parallel to the official launch campaign of MAXUS 8, including a complete wet dress rehearsal the day before the launch to check if the procedure was correctly considering the mission time-line. After some adjustments, the process run in a smooth way during the launch allowing the Astos Solution team to provide the coordinates and the dispersion ellipse to the search helicopter only 30 minutes after the lift-off. A combination of automatic data import, trajectory optimization and Monte-Carlo simulations via ASTOS batch mode was implemented to achieve this goal.

E. OneWeb constellation

ASTOS has the capability to model mega constellations like OneWeb (see Fig. 8) including the possibility to perform the pitch maneuver al low latitudes to reduce the interferences with telecommunication satellites in geostationary equatorial orbit (GEO).

The operational aspects are related to the possibility to load the satellite positions from updated two-line elements (TLE) data in order to simulate the "real" constellation and compare it with the ideal one. In that situation station-keeping maneuver are normally performed either autonomously or commanded by the ground control center to avoid or at least limit the areas not covered. These maneuvers can be inserted in the software to evaluate in advance the effect of them on the global coverage. As of today an automatic procedure is not yet inserted in the software, but it has been a common practice in the past to customize ASTOS according to the needs of the users.

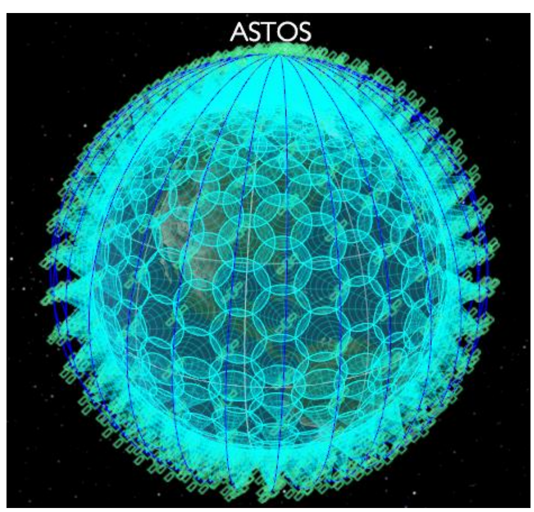

Fig. 8 OneWeb constellation.

F. Ground safety for launchers

As mentioned in section C, ASTOS provides several safety analyses to evaluate the human risk associated to re-entering fragments; it can compute the casualty and fatality index associated to a destructive re-entry or to a launcher failure. A model for automatic explosion and fragmentation is provided. The fragments are propagated considering atmosphere interaction: drag and demise. Once the impact positions are computed, these are used to evaluate the risk associated to nominal trajectory and not nominal events. Additionally several blast-wave models are implemented to compute the overpressure as function of the distance from the explosion.

These capabilities are extremely useful for the ground safety of launch vehicles, in particular as support for the ground handling of the vehicle stages and for the evaluation of the debris area in case of early termination of the mission.

The ground handling and storage of vehicle stage requires the identification of the blast radius for different configuration: e.g. when 4 lower composite are stored in a container. The output of this ASTOS analysis provides indication of the distance between different storages to avoid a chain reaction.

A typical worst case scenario for a controlled launcher is the thrust vector control (TVC) at saturation: the engine nozzle can be rotated to direct the thrust is a direction different from the main vehicle axis. This is required to compensate for integration misalignment and to perform the gravity-turn maneuver during ascent. The trajectory of a controlled launcher starts on the launch-pad with a vertical flight. After few seconds, e.g. 5 for solid propulsion rocket and 10-20 for liquid propulsion rocket, the vertical orientation of the vehicle is changed to define the direction of flight. In this maneuver the TVC is activated and the activation could lead to a malfunction: the nozzle is rotated to the highest allowed angle. This angle is normally between 5 and 10 degree, but the torque generated on the vehicle is enough to start a fast rotation (up to 50 degree/second). The procedure is this case is to activate the neutralization of the vehicle to terminate the flight, see Fig. 9.

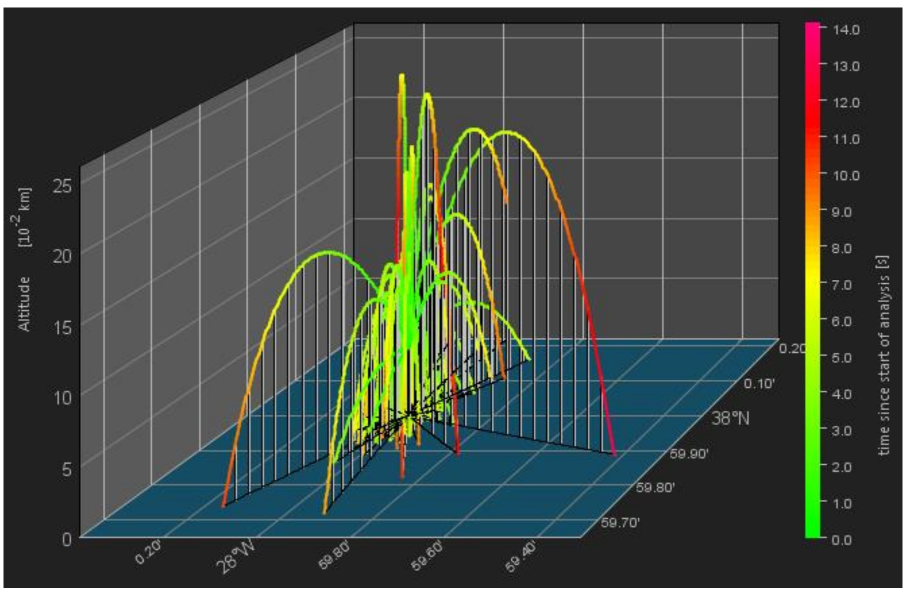

Fig. 9 Fragments after explosion in flight.

ASTOS can simulate the complete procedure with full consideration of the vehicle geometry as well as the 6-dof aerodynamics effects. An explosion can be triggered in the flight or when the vehicle heats the ground. In both cases the fragments are generated with random delta-V due to the explosion, integrated till ground and the associated risk and areas are computed.

IV. Conclusion

Although dedicated to the design phases of space missions, ASTOS can be used efficiently also during the operations of launchers, re-entry vehicle and satellites. The extended user community and the support of ESA guarantee for a high level of quality. Frequent verification and validation tasks are performed both internally and externally.

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