

# SOUNDING ROCKET TRAJECTORY SIMULATION AND OPTIMIZATION WITH ASTOS

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## ABSTRACT

With a long experience in the simulation and optimization of atmospheric trajectories (launcher and re-entry vehicles), ASTOS [1], the AeroSpace Trajectory Optimization Software, has been applied to the sounding rocket environment. An extensive library [2] of differential equations (3-DOF and 6-DOF), vehicle models (propulsion, aerodynamics, etc.), constraints and cost functions is available to the user, in a friendly graphical user interface (GUI).

As a demonstration test-case, the simulation of the SHEFEX II (SHarp Edge Flight EXperiment) mission is presented. In collaboration with DLR MORABA (Mobile Rocket Base), the available aerodynamics and propulsion data has been inserted in ASTOS to reproduce (through simulation) and improve (through optimization) the trajectory. Furthermore the paper depicts the post-processing features of the software: the results can be displayed both numerically and graphically, the first for a precise evaluation of the trajectory data and the latter to provide a straightforward overview of the mission. Safety aspects are covered by a dispersion analysis of the impact position that completes the paper.

## 1. ASTOS SOFTWARE TOOL

ASTOS is a simulation and optimization environment to simulate and optimize trajectories for a variety of complex, multi-phase optimal control problems. In the last twenty years it has been successfully applied in several industrial or ESA projects in the field of launcher, re-entry and exploration missions. Just to provide some examples: Ariane5, Vega, ATV, Hopper, Skylon, Fly-back Booster, X38, Capree, ATPE, USV, Smart-Olev, LEO, Astex, IXV, ARD, Expert, et. al.

ASTOS consists of fast and powerful optimization programs, PROMIS, CAMTOS, SOCS and TROPIC, that handle large and highly discretised problems, a user interface with multiple-plot capability and an integrated graphical iteration monitor to review the optimization process and plot the state and control histories at intermediate steps during the optimization.

ASTOS comprises an extensive model library, which allows launcher and re-entry trajectory optimization without programming work.

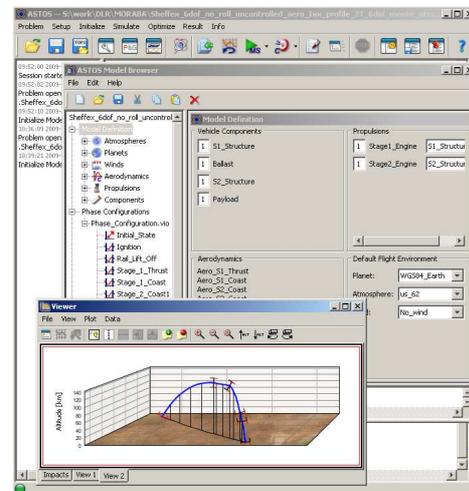


Figure 1. ASTOS multi screenshot

### 1.1. Batch Mode capability

The "Batch Mode Inspector" (since ASTOS version 6.0) enables the user to perform Monte Carlo analyses without third-party tools and to plot the results directly by means of ASTOS plotting capabilities. The user can associate a batch variable to each model uncertainty.

Then, in the Batch Mode Inspector, he can build the structure of the processes with which the batch variables are used in order to run the model automatically over a given parameter space. The structure consists of various batch elements freely chosen by the user. These can be actions like Initialize, Simulate, Optimize or post-processing elements that prepare the data taken from the simulation for further analysis.

The batch variables may be modified by Loop and Random elements. Loop will change a batch variable monotonously from an initial value to a final one using a given increment. Instead, with the Random element it is possible to compute random numbers with Gaussian or uniform distribution. Uniform distribution variables are defined by a lower and upper bound, Gaussian by

their mean value and the standard deviation. Further details are described in [1].

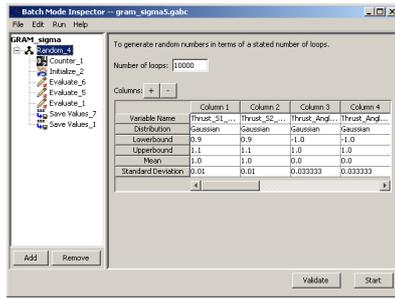


Figure 2. Batch mode inspector

## 2. SHEFEX

The Sharp Edge Flight Experiment is a DLR (German Aerospace Centre) program to investigate aerodynamic behaviour and thermal protection problems and develop solutions for re-entry vehicles at hypersonic velocities, using unconventional shapes comprising multi-facetted surfaces with sharp edges. Sounding rockets provide a useful facility to obtain experimental flight data for period of several orders greater than possible with shock tunnels. The first SHEFEX sounding rocket launch, comprising an experiment with an asymmetric form at re-entry velocities of Mach 6-7, was launched from the Andoya Rocket Range (ARR), Norway, in October 2005. The success of this mission led to the definition and approval of the SHEFEX 2 mission.



Figure 3. Artistic impression of SHEFEX2

SHEFEX 2 was originally conceived as a payload with small passive stabilizing fins, to be flown on a VSB-30 with a conventional parabolic trajectory which would have provided velocities in the order of Mach 8. The greater velocity, together with a re-entry elevation angle in the order of 75 degrees, would have resulted in a short experiment time. An alternative solution was then found in the VS-40 motor combination together with a precession control of the spinning second stage to provide a conventional trajectory of the first stage together with a suppressed trajectory of the exo-atmospheric burning second stage. The result is a flatter re-entry angle of about 35 degrees and a velocity of Mach 10, which still provides in the order of 60 seconds of experiment time between 100 and 20 kilometres altitude.

The results are a vehicle and a payload that are the most complex and challenging projects MORABA has constructed and launched to date.

## 3. TRAJECTORY SIMULATION

As described in section 2, the SHEFEX 2 mission will be launched by a two stage sounding rocket. The workflow to simulate a trajectory in ASTOS is intuitive and in line with the logic of the mission design engineer. The first steps are performed in the Model Browser, the GUI that links all the models of the ASTOS library.

### 3.1. Modelling the Vehicle

- Define the environment either from a list of already available models or linking external data from txt or Excel files
- Define the vehicle components: stages with structural and propellant mass, payload, fairing, etc.
- Define the propulsion systems: thrust, mass-flow or Isp profile; jet damping
- Define the aerodynamic models used in the course of the mission through coefficient and inertia tables
- Define the list of phases based on the thrust and coast arcs



Figure 4. SHEFEX case in Model Browser

The most important task of the model definition is the phase list: it is required to define a new phase every time a “discontinuity” is present in the physical vehicle. A discontinuity could be a new aerodynamic configuration, the jettisoning of a module or an important point of the mission. In the specific case of the SHEFEX 2 missions:

- Starting the engine with the vehicle still fixed at the ramp.
- The vehicle is moving along the inclined rail due to the thrust force.
- Thrust arc of the first stage until burn-out.
- Coast arc until the separation of the first stage.
- Coast arc until the ignition of the second stage, required to compute the re-pointing manoeuvre.

- Re-pointing manoeuvre to produce a suppressed trajectory (see section 2).
- Thrust arc of the second stage till burn-out and separation.
- Coast arc until 100 km altitude.
- Experiment phase until 20km altitude.
- Re-entry until ground impact.

### 3.2. Simulation and visualization

As soon as the mission is modelled, the simulation can be easily performed with the pressing of a button in the GUI of ASTOS.

Also the trajectory visualization is managed through the graphical interface: hundreds of auxiliary functions are automatically computed by ASTOS and can be arranged in the “Viewer” according to the user requirements.

### 3.3. ASTOS computation verification

ASTOS has been extensively used for the computation of launcher trajectory where the simulation and optimization of a point mass (3DOF) is accurate enough in firsts phases of a mission design.

According to this experience, a 3DOF simulation has been performed and the results compared with a 6DOF simulation (Fig.5).

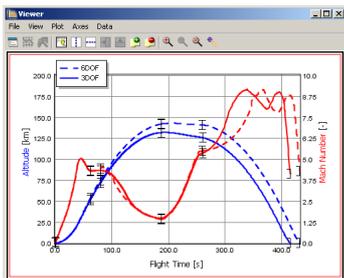


Figure 5. Comparison 3-6DOF simulation

The comparison shows that the 3DOF and the 6DOF simulations are quite different: a simple 3DOF simulation seems not accurate enough for this sounding rocket mission. A second comparison is performed between the ASTOS simulation (6DOF) and the reference trajectory computed by MORABA [3].

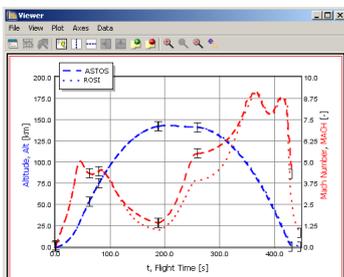


Figure 6. ASTOS verification

The altitude profile is almost identical (Figure 6). Several other auxiliary functions have been compared and the matching between the ASTOS computation and the MORABA reference trajectory is very good. This result validates the ASTOS 6DOF computation for sounding rocket applications.

### 3.4. Atmosphere effect

An accurate analysis of the ASTOS results (Figure 6) reveals an important difference in the Mach profile when the vehicle is flying at high altitude (above 100 km). The Mach number is the ratio between the vehicle speed and the speed of sound; the speed of sound is computed by the atmosphere model as function of the altitude. The altitude and the vehicle speed profiles are almost identical between ASTOS and the reference tool: the atmosphere model is the “guilty” party.

Both ASTOS and the reference tool are using the US Standard 62 model [4], but it seems that the interpretation of this model for high altitudes is not univocal.

This result directs the attention to the importance of the atmosphere model for the correct simulation of sounding rocket trajectories.

The influence of the atmosphere can be estimated by a comparison between simulations performed with the several models present in the ASTOS library.

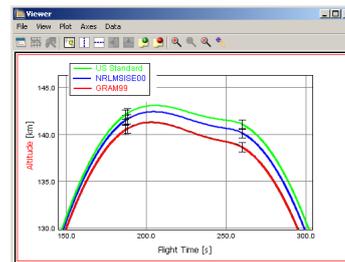


Figure 7. Atmosphere influence

The Figure 7 presents the altitude profile zoomed in the max-apogee area of the trajectory. The different atmosphere models produce a difference in the order of 2-3 km.

## 4. IMPACT DISPERSION ANALYSIS

In chapter 3.4 the influence of the atmosphere has been assessed in relation to the altitude profile of the trajectory, but one of the most critical aspects of a sounding rocket simulation is the computation of the impact point. This position is required for technical and safety issues: among others the placement of a mobile tracking station, the payload recovery and the verification that the rocket will not exit from the impact area.

The batch mode capability of ASTOS (see chapter 1.1) can be merged with the extensive data available from the GRAM99 atmospheric model [5] to compute a

dispersion analysis function of the atmosphere characteristics: density and temperature (Figure 8). In fact the GRAM99 model contains not only information on the atmosphere functions (density, pressure, temperature, composition), but also the dispersion of these functions (i.e. the one sigma value).

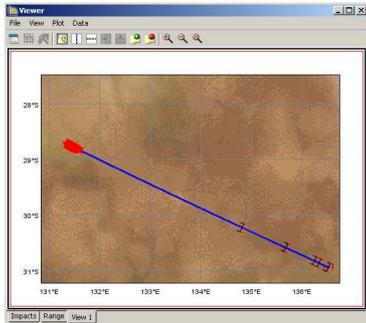


Figure 8. Atmospheric dispersion analysis

Having assessed the power and flexibility of the batch mode in this first exercise, a more comprehensive Monte Carlo analysis has been conducted on a wider spectrum.

The atmosphere uncertainties are not the only source of dispersion in the computation of the impact position; other variables cannot be precisely identified or measured in a sounding rocket mission either.

- Launch ramp elevation
- Launch azimuth
- Drag coefficients
- Vehicle mass
- Thrust value
- Thrust misalignment

Based on the experience of MORABA, the dispersion values for all these variables have been inserted in the batch mode of ASTOS (Figure 2). A set of simulations has been performed and automatically post-processed to provide an indication of the impact region and extension.

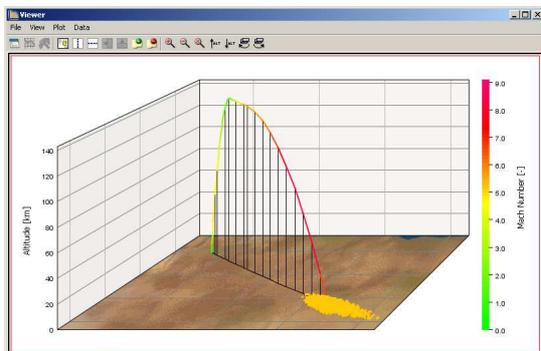


Figure 9. 3D trajectory and impact positions

The visualization capability of ASTOS can be appreciated in Figure 9, where the altitude and Mach number information are plotted over a physical map of the Earth surface. In the field of the safety assessment, the possibility to use a map of the Earth population density as a background can be appreciated. This map was produced with the upmost recent data at the present date from GPWv3 [6].

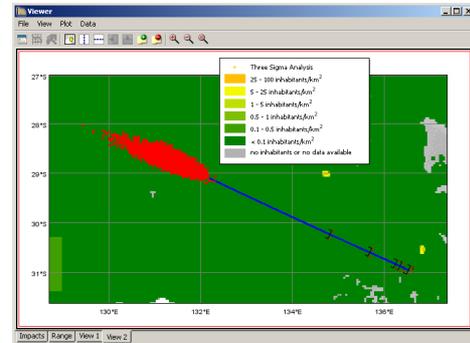


Figure 10. Impact positions on population map

As post processing analysis ASTOS computes the distribution profile of the output variables selected by the user. In Figure 11 the distribution of the trajectory range is presented.

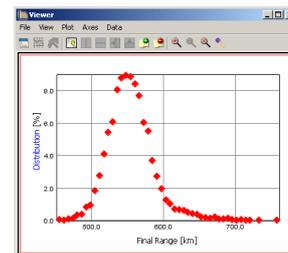


Figure 11. Range distribution

The analysis computed shows an asymmetric Gaussian bell with the peak at the nominal value (550km). This Monte Carlo analysis is based on 10000 simulations; the computation time on a Pentium 2.4GHz was 20 hours.

## 5. OPTIMIZATION

ASTOS was designed in 1989 for trajectory optimization; since then many simulation features have been added to the tool, but the optimization field is still the playground of this software.

Just to clarify one important point:

- For simulation the models should be as complex as possible
- For optimization the models should be as complex as required

The important phase of the mission, from the scientific point of view, is the hypersonic re-entry of SHEFFEX2. The optimization goal is therefore to maximize the time

the rocket stays at an altitude range between 100km and 20km with Mach number higher than 7.  
The problem characteristics are summarized in Table 1.

Open parameters	Constraints
Initial pitch Duration of coast arcs Pitching maneuver	Range Required time after jettison of first and second stage
<b>Goal:</b> Maximize the experiment duration	

Table 1. Optimization summary

The reference trajectory has been provided by MORABA [3], but the mission design of SHEFEX2 is not concluded yet, so it is probable that the “flying” trajectory will differ from the one presented in this paper.

### 5.1. Results

Even if the modifiable parameters are few, the optimization has tailored the trajectory to a completely different altitude profile (Figure 12).

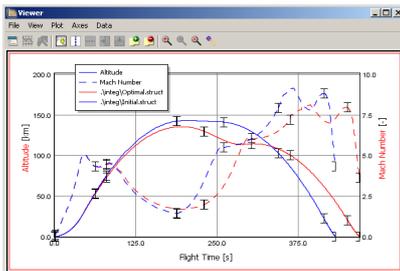


Figure 12. Optimized vs. reference trajectory

The launch pad elevation is slightly lower (1.5 degree), the coast arc before the second stage ignition is longer. These modifications produce a lower apogee and increase the flatness of the Mach profile in the experiment arc (Figure 12).

The optimized trajectory allows an experiment time of 86 seconds, it was 69 in the reference trajectory.

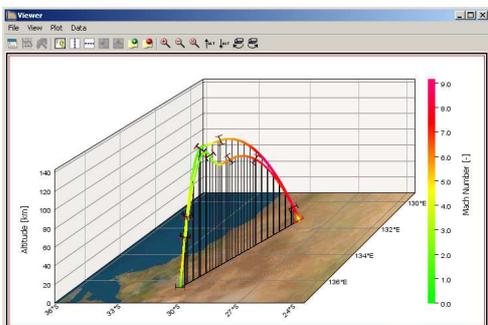


Figure 13. 3D map plot, optimized vs. reference

Figure 13 presents a 3D visualization of the two trajectories, the reference and the optimized, from a different point of view (North-West). Even if the duration of the optimized trajectory (the lower one) is longer (see Figure 12), the range constraint has not been violated (see Figure 13).

The increased experiment duration presents one evident side-effect: the maximum Mach number reached decreases from 9 to 8.

This is a classical situation in the design of a mission: it is not possible to gain in all the aspects of the trajectory. Of course it would be possible to change the weight of the cost function and to add more constraints in order to obtain a different result.

This makes the optimization an interactive process where the engineer and the computer work together to reach the best compromise in the mission design.

## 6. CONCLUSION

ASTOS is a software tool for trajectory simulation and optimization completely data driven through GUI.

The simulation results are in line with the MORABA reference tool.

The batch mode capability of ASTOS can be used to perform an interesting impact dispersion analysis.

The optimized trajectory can increase the experiment time by 25% without any violation of the mission constraints.

The computation time for a trajectory simulation (less than 10 seconds) is in line with the ground segment requirements.

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