LOTNAV: A LOW-THRUST INTERPLANETARY NAVIGATION TOOL

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ABSTRACT

LOTNAV has, for more than 10 years, been the reference tool for ESA in the design of finite-thrust and ballistic interplanetary spacecraft trajectories and in the preliminary assessment of navigation and guidance issues on the computed trajectories. Within DEIMOS Space, LOTNAV has recently undergone a considerable update effort to enhance its modularity, its flexibility and to extend its applicability to new navigation problems.

The aim of this paper is to present LOTNAV capabilities and its most important updated features (i.e. the inclusion of ephemeris data directly from SPICE, new launcher models, use of GNSS signal in the navigation analysis, etc.). A number of test cases on low-thrust missions are also presented along with the utilities composing the LOTNAV tool.

1. INTRODUCTION

The Low-Thrust Interplanetary Navigation Tool, a.k.a. LOTNAV, is a mission analysis assessment tool developed under ESA contract by an international consortium led by DEIMOS Space S.L.U., which serves a number of purposes:

- First, it allows reproducing optimised low-thrust trajectory profiles including encounters with massive and minor bodies
- Second, it can simulate a number of measurement systems to allow carrying out orbit determination activities
- It also allows carrying out covariance analyses to obtain achievable values of the spacecraft state knowledge (formal and consider) after trajectory determination
- In addition, it permits the simulation of a full Monte Carlo process on the navigation activities such that previous orbit determination results can be checked out and results on low-thrust guidance obtained
- And finally, it allows interfacing with other global trajectory optimisation tools to permit trajectory re-optimisation after possible failure scenarios

The present paper describes all the modules included within LOTNAV together with the results of some of the analyses performed. It can also be said that the tool is prepared to be executed in a number of different platforms.

2. TRAJECTORY GENERATION MODULE

One of the main fields of activities in the development of the LOTNAV tool has been related to the reconstruction of low-thrust trajectories. The Trajectory Generation Module is the one that allows carrying out this goal.

The module is composed of a Trajectory Reconstruction Utility that actually performs such tasks, a Trajectory Exploitation Utility for plots generation and the Trajectory Sectioning Utility for trajectory segmentation. This segmentation allows performing different navigation strategies to different arcs of the trajectory.

2.1. Trajectory Reconstruction Utility

The present utility is the core tool to allow the reconstruction of low-thrust and/or impulsive interplanetary trajectories within the Trajectory Generation Module. This utility is composed of three different submodules that help solving different problems

The first submodule, Initial Value Problem Solver, allows direct propagation of trajectory after the definition of a number of propagation arcs with possibly different dynamics assumptions. Different stop conditions can be set in the propagation such as stopping at a determine date, when reaching the sphere of influence of the body or when acquiring the escape energy level, especially useful when leaving a planet with electrical propulsion.

The other two submodules allow solving a full interplanetary low-thrust Multiple Point Boundary Value Problem (MPBVP) in two steps. In the first step, the Boundary Value Problem Solver (BVPS) permits the user to obtain optimised trajectory profiles with low-thrust segments and multiple encounters with either massive or minor celestial bodies. In this module it is assumed that encounters with massive bodies are such that they are punctual in time (no spheres of influence accounted for). Apart from the original parameter optimisation package OPXRQP, new versions of LOTNAV include also the SNOPT library that can be selected by the user to perform the optimisation. The main objective of the optimisation process is to maximise the spacecraft mass at the end of the simulation also complying with a number of constraints.

The number and nature of these constraints is constantly under evolution to fulfil the needs of the new projects.

Parameters defining the trajectory refer to:

- Initial conditions: which includes departing from a fixed state, from an orbit around a major or minor body and also escape conditions from Earth taking into account the performance of any launcher included in the LAUnchers LIBrary tool (LAULIB) developed by DEIMOS.
- Flyby conditions at celestial body encounters.
- Deep Space Manoeuvres size and epoch.
- Low-thrust conditions: taking into account several electric engines from a database to compute the thrust level, mass flow rate and thrusting direction.
- Final conditions: including arriving to a fixed state as well as getting to major or minor body.

All epochs defining the trajectory events can enter the optimisation process together with the previous conditions. The thrust law vector at each thrust arc is parameterised as quadratic polynomials, which are added to previously establish nominal profiles (e.g. constant thrust angles).

In the second step, a so called Refined Boundary Value Problem Solver (RBVPS) allows attaining a full solution to the low-thrust optimisation problem also accounting for the gravitational effect of the massive bodies visited, performing propagation within their spheres of influence. The solution obtained in the BVPS is utilised as initial guess in the optimisation process in the RBVPS.

The following models of the force interactions acting on the spacecraft are available in the tool:

- Central body gravity field, with expansion in spherical harmonics
- Gravity of third bodies assumed as mass points
- Low-thrust forces with a variety of engine models and power system models feeding the engines
- Solar radiation pressure as a Lambertian reflection model
- Atmospheric drag forces
- Residual forces

2.1.1. Ephemerides: SPICE

Ephemerides of the bodies involved in the optimisation can be obtained from an internal ephemerides file based on JPL and MPC data to speed up the calculations. However, last version of the software includes also the possibility to use different SPICE kernels, which provides more precise ephemerides at the cost of slower interpolation. The use of SPICE is available for all LOTNAV modules.

2.1.2. Launchers LIBrary (LAULIB)

During the past years, DEIMOS has developed a database with the performance of different launcher vehicles depending on C3 and declination of the escape trajectory. LOTNAV makes use of this library to optimise the departure conditions of an interplanetary trajectory taking into account the performance of the launcher such to maximise the mass delivered at the target. LAULIB is constantly updated to include the latest available performance values of all the considered launcher vehicles.

2.1.3. Trajectory Reconstruction Utility

A number of low-thrust trajectories from ESA and NASA have been successfully regenerated using the Trajectory Reconstruction Utility. As an example, the trajectory that was computed for Marco Polo M5 for a mission to the asteroid 2001SK162 is presented in Fig. 1.

In such a profile, the S/C is set to a trajectory that performs an Earth fly-by before departing for a rendezvous with the asteroid. It stays there for 30 days before coming back to Earth, this time without the need of any fly-bys.

2.2. Trajectory Exploitation Utility

This utility allows obtaining a large number of output plots from the computed trajectory profile such as the one presented in Fig. 1. Next are the possible outputs that the user can obtain:

- Projection of the spacecraft trajectory and the orbit of a number of bodies in different reference frames
- Time evolution of distance and distance rates to a number of bodies
- Time evolution of a number of angles of interest for trajectory analysis purposes
- Time evolution of the thrust variables and the spacecraft mass
- Time evolution of the orbital elements
- Satellite ground-track on different bodies

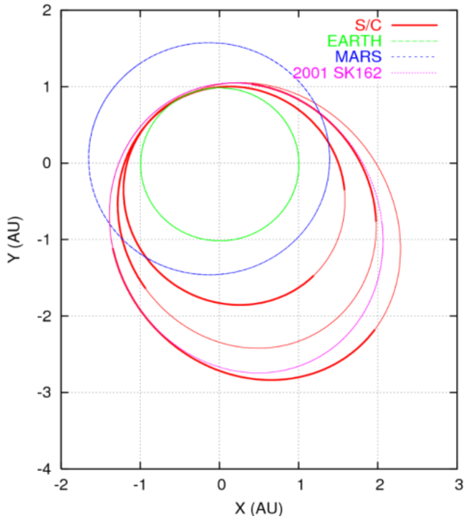

Fig. 1. Mission to 2001SK162 performing an Earth fly-by and using low-thrust propulsion

2.3. Trajectory Sectioning Utility

The Trajectory Sectioning Utility allows sectioning the spacecraft trajectory in the number of arcs required by the user to perform an additional navigation analysis in different segments of the mission.

3. MEASUREMENTS GENERATION MODULE

3.1. Measurements Generation Utility

Current utility allows generating a number of system observables for navigation analyses. The implemented measurement systems include radiometric measurements from selected ground stations and on-board measurement systems. Following is the list of available measurements:

- Range and range rate from a number of ground stations (GS), defined in an external data file
- DOR and ΔDOR from a number of GS baselines
- On-board optical measurements of celestial bodies
- On-board accelerometer measurements
- On-board radar measurements of a nearby object
- Feature tracking and landmark measurements
- GNSS measurements
- For the particular case of feature tracking and landmark measurements, a specific LOTNAV version was created to be integrated in a full GNC simulator for the NEOShield-2 mission [1].

The implemented models are congruent with the assessment level given to the tool. The utility permits flexible scheduling gathering measurements with different types of constraints for the observables calculation, such as required minimum elevation for a successful contact on ground stations, or the minimum distance to a target body from which altimeter measurements can be accepted. As an example, the range measurements from Madrid ground station to a S/C in low Lunar orbit is shown in Fig. 2.

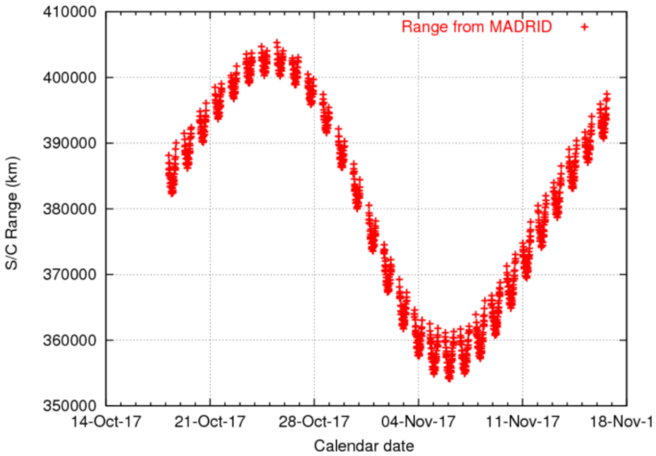

Fig. 2. Range measurements from Madrid ground station to a S/C in low Lunar orbit

3.2. Measurements Exploitation Utility

This utility allows obtaining the output plots of the obtained system observables such as the one presented in Fig. 2.

4. COVARIANCE ANALYSIS MODULE

The covariance analysis process performed in LOTNAV over the orbit determination (OD) process allows obtaining results on achievable accuracy in the knowledge of the spacecraft state and a number of further estimation parameters.

The estimation process is based on the use of a Square Root Information Filter (SRIF) as presented in [2]. Trajectory determination levels are obtained in time intervals where a batch of measurements is processed altogether to obtain the update in the knowledge of the system state. The use of SRIF allows obtaining an estimated deviation in the state vector at the beginning of the mapping time interval. This is done by mixing the a priori information with the information provided by the associated dynamics and the measurements in a mapping time interval. Then, the augmented state and the covariance matrix are propagated to the next mapping time.

The formulation of the proposed approach with SRIF allows to include in the estimation process not only the modelling of the dynamic variables as defined by their equations, but also the effect of exponentially correlated random variables (ECRVs) and consider biases. This permits performing both a formal and a consider estimation analysis.

4.1. Partial Derivatives Computation Utility

Present software utility allows the computation of the required derivatives of the dynamics and the observables, which will be required in the estimation process. The measurements matrix built with the partial derivatives of the observables with respect to the estimation variables is used to perform the update in the knowledge covariance matrix. The dynamic partial derivatives are used to build the transition matrix that allows mapping the covariance into the next time interval.

The computed derivatives are introduced into a data file that is used in an ulterior run of the covariance analysis process.

4.2. Covariance Analysis Utility

This is actually the software utility that allows computing the theoretical achievable levels of accuracy in the knowledge of the spacecraft state vector and of all the estimated variables. The user can assume that a number of consider biases can affect the estimation process (e.g. biases in the ground station locations, in the measurements themselves, etc.) and also some correlated process noises (e.g. solar radiation pressure forces, residual forces, the thrust force itself). A similar approach was utilised also for low-thrust trajectories in the frame of the recently launched BepiColombo mission.

An example is hereafter provided using a reference mission with and Earth and Venus swing-by. The arc analysed here covers from the Earth departure to the Earth swing-by. The Venus flyby event occurs between both.

The conditions applied in the computations are:

- Mapping is performed once every two days in the long arcs and once every 0.25 days for short arcs (in the SOI of the planets)
- Initial uncertainty at Earth launch in components of position of 10 km, in velocity 1 m/s and mass 0.1 kg
- Thrust variables are assumed as ECRVs with uncertainty at 1%, 0.6°, autocorrelation time of 1 d
- Residual acceleration assumed as an ECRV of 10-11 km/s^2, autocorrelation time of 1 day
- Range and range-rate measurements from ground stations in Perth and Madrid
- Range noise at 10 m random and 2 m bias
- Range rate at 0.3 mm/s random and no bias
- Ground station position errors at 1 m in X and Y position and 2 m in Z position

Two cases were computed: in the first one the thrust vector was assumed to perform perfectly, thus the thrust modulus and the thrust angles were assumed to behave with perfectly known dynamics. In the second case, the thrust was assumed to be affected by a correlated noise with the statistics provided before.

Results are given in Fig. 3 and Fig. 4 where the achievable levels in the knowledge of the state vector along the proposed trajectory profile can be observed. The two plots are shown in logarithmic scale to allow a better visualisation of the compared results. Fig. 3 presents the results in terms of knowledge in total velocity for the two mentioned cases. It is clearly visible the change in knowledge every time the noisy thrust vector is switched on in comparison with the perfect thrust. In this last case only faint changes are observed due to the slight change in the dynamics and thus do not produce a noticeable change in knowledge. The peak in the coast segment is due to the Venus swing-by.

Similar results can be observed in Fig. 4 for the achievable knowledge in total position but less drastic due to the available information provided by the range measurements. The crack observed in the curves during the coast segment is due to the focusing effect introduced by the swing-by dynamics in Venus.

4.3. Covariance Exploitation Utility

Present utility allows obtaining output plots on the achievable knowledge in the estimation variables such as the ones presented in Fig. 3 and Fig. 4.

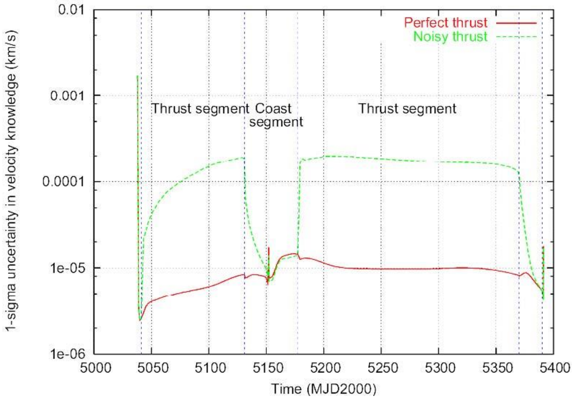

Fig. 3. 1-σ achievable knowledge in spacecraft velocity for cases with perfect and noisy thrust

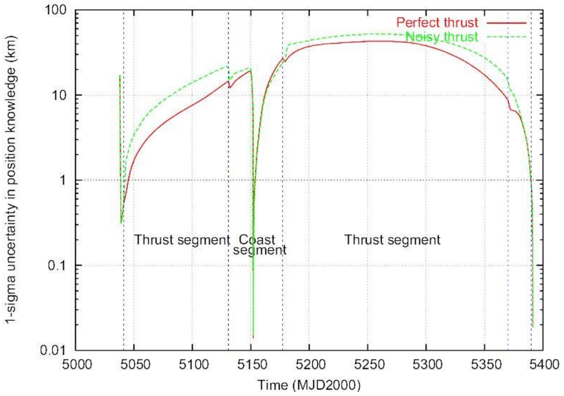

Fig. 4. 1-σ achievable knowledge in spacecraft position for cases with perfect thrust and noisy thrust

5. SIMULATION MODULE

5.1. Monte Carlo Utility

Once a covariance analysis is performed on the achievable results of the orbit determination process, it is also possible to carry out a full simulation process with the Monte Carlo Utility. The present utility allows conducting a number of simulations of the orbit determination process actually estimating the spacecraft state. The behaviour of the real world measurements is done by adding a stochastic component to them. These measurements feed the OD process to obtain best estimates of the estimation variables together with the update in the knowledge covariance. The process is repeated by iterating with the last obtained estimates such that the averaged measurement residual can be minimised.

In addition to obtaining orbit determination performances with the Simulation Module, it is also possible to perform the simulation of trajectory correction manoeuvres. Targets can be set at any point in the future and in particular at some swingby point in an approaching body. Two options are possible to correct the trajectory to meet the target selected:

- Introducing chemical burns (e.g. using the AOCS engines to correct for some dispersion)
- Performing feedback guidance on the low-thrust controls as established in [5].

The first case is the classical way to introduce corrections in the trajectory, actually modifying the spacecraft velocity such to meet the target point. The implemented procedure is based on a linear fixed time guidance approach.

Thanks to the latest developments in the tool, LOTNAV can also apply errors when performing chemical trajectory correction manoeuvres, in both modulus and direction. In this way the navigation results can take into account extra real world errors of the manoeuvres performance.

In the second case a linear-quadratic controller is used to compute the deviations in the low-thrust modulus and the low-thrust vector angles at certain discretisation points such to allow meeting the target conditions. In this case, both position and velocity can be matched at the end of the guidance simulation period. This process can be repeated as many times as a solution from the estimates is available.

The advantage of this method is that it allows determining the navigation budget for corrections when using low-thrust, which cannot be generally obtained by any closed analytical formulation, as it can be done for the discrete manoeuvre changes.

An example is included during for ESA’s BepiColombo cruise (applied to a previous trajectory design). The selected scenario is a trajectory segment with a 30-day thrust arc some time before the first swing-by of Mercury. 200 simulations were performed with the following assumptions:

- Mapping is performed once a day
- Initial uncertainty in all components of position of 10,000 km, in velocity 10 m/s and in mass 0.1 kg
- Thrust variables were assumed as ECRVs at 2%, 1.2^{o}, autocorrelation time of 10 days
- Solar radiation pressure as ECRV with 10% error in size and autocorrelation time of 10 days
- Residual acceleration assumed as an ECRV of 10-11 km/s^2, autocorrelation time of 1 days
- Radiometric assumptions as for the Solar Orbiter example
- Guidance assumptions are the following:
- Discretisation of the thrust controls in sub-intervals of 1 day
- Guidance is performed each time OD is performed with the exception of the first three days to allow enough improvement in the knowledge
- Target is fixed at the end of the 30-day period

Results are given in Fig. 5 and Fig. 6. In the first figure the achievable accuracy in the determination of the total position after the covariance analysis is plot against the results of the Monte Carlo simulation. Comparison is in fact quite accurate.

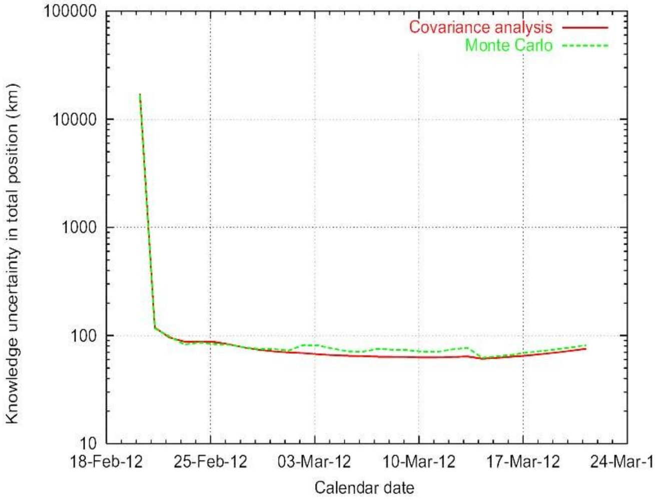

Fig. 5: Monte Carlo results for BepiColombo on knowledge uncertainty in the total position

Fig. 6 shows the result in the comparison of the dispersion evolution for the covariance analysis (which does not include guidance and it then disperses without control) and for the Monte Carlo. It is possible to see in this last case how the changes in the thrust controls allow bringing the spacecraft position almost to the achieved knowledge. Same plots were obtained for the spacecraft velocity.

It is also possible to obtain plots of the computed statistics on the thrust utilisation for trajectory correction and the fuel mass spent with such purpose. Fig. 7 shows such a fuel mass consumption plot in the proposed case.

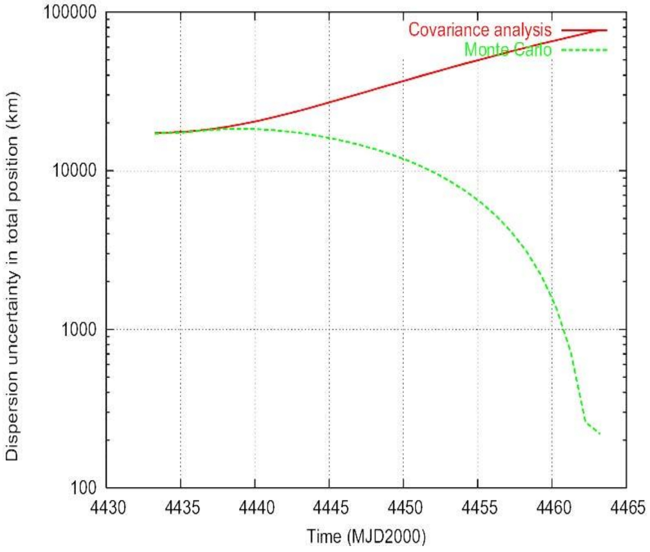

Fig. 6: Monte Carlo results for BepiColombo on dispersion uncertainty in total position.

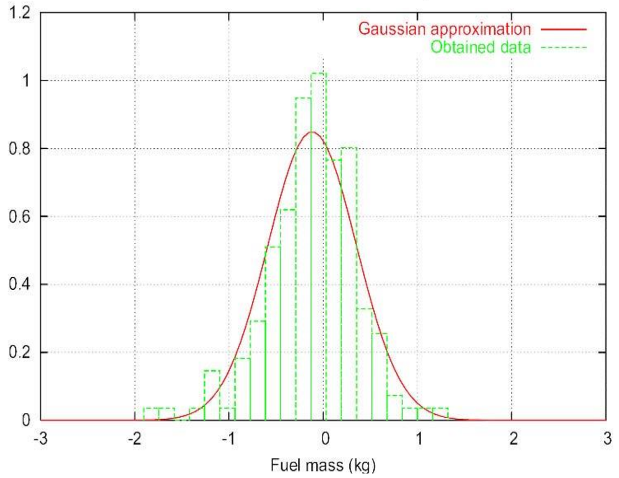

Fig. 7: Monte Carlo results for BepiColombo on fuel consumption

Some cases have been also executed to show the performances on a terminal approach to a swing-by body. In such cases, also plots of final dispersion in the B-plane and the pericentre plane can be obtained. Such is in Fig. 8 the case for a simulation prior to a Mercury swing-by for one of the BepiColombo trajectory options. In this case the trajectory segment prior to the encounter was of thrust. The dispersion shape is clearly observable having some of the cases very close to the Mercury surface but without any crashing on it.

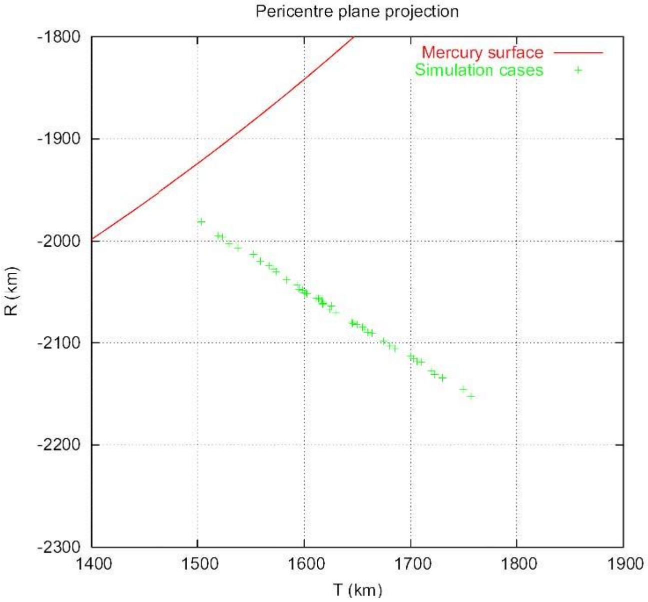

Fig. 8. Monte Carlo results for BepiColombo on final dispersion in the pericentre plane of GAM 2 in Mercury

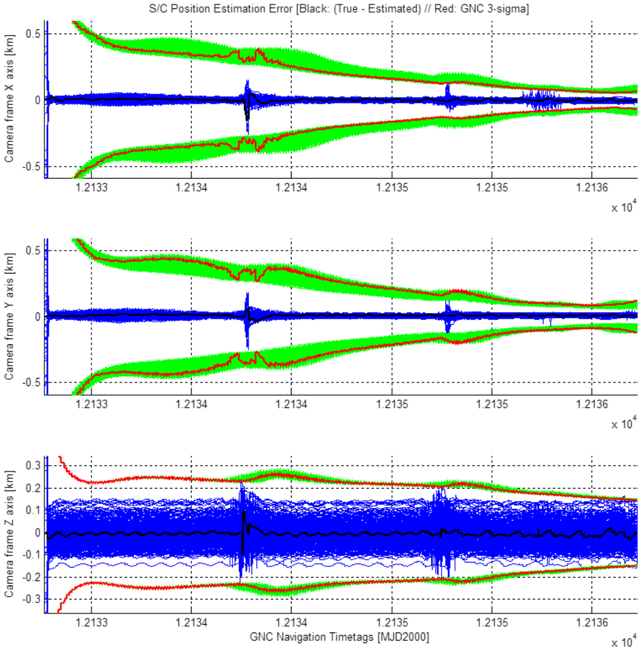

Fig. 9: Results of Monte Carlo analysis for NEOShield-2 Close Approach phase mixing on-ground and on-board measurements [1]

As mentioned before, different LOTNAV versions have been developed for concrete projects and different target platforms, thanks to a complete new compilation environment to make the tool much more flexible. As an example, in Fig. 9 the results of the Monte Carlo analysis NEOShield-2 close approach phase are presented. In this particular case, the navigation analysis merged range and Doppler measurements from three different ground stations next to relative Line of Sight and altimeter data to the target asteroid. LOTNAV outputs were post-processed with the simulator post-processing tool to show the results in the S/C camera frame.

5.2. Statistical Analysis Utility

Present utility allows filtering of all the Monte Carlo results which are out of a given confidence interval set by the user. By this process it is possible to obtain the corrected statistics of the Monte Carlo essay once the ruled-out cases are eliminated from the statistics. An iterative scheme is established to perform such process.

5.3. Simulation Exploitation Utility

Present utility allows obtaining output plots on the achievable knowledge in the estimation variables, the dispersion evolution with guidance, the controls utilisation and fuel mass consumption after the simulation is performed by the Monte Carlo Utility and filtered by the Statistical Analysis Utility.

6. TRAJECTORY REOPTIMISATION

The last LOTNAV module allows interfacing the tool with the full low-thrust optimisation tool DITAN [6]. Two interfaces are included in this module: the first one allows preparing a trajectory output from DITAN to be executed in LOTNAV. Thus an optimised trajectory computed in DITAN is analysed arc by arc and the required input by LOTNAV is generated by the interfacing utility.

The second utility allows defining a number of failure cases in a trajectory profile defined by DITAN such that the new conditions can be fed back to DITAN for re-optimisation. The implemented failure cases are:

- Ignition delay of the propulsion engine
- Engine flame-out
- Non-nominal performance of the low-thrust engine
- Non-nominal launch into escape orbit
- Non-nominal planetary flyby

All previous conditions are treated by the interface such that the user can select any of those failure conditions on the nominal trajectory profile. The interface utility then computes the new conditions of the optimisation problem for further re-optimisation.

7. CONCLUSIONS

Next set of conclusions can be enumerated after the development of LOTNAV:

- LOTNAV is a living tool, in constant development and improvements to include new functionalities and update the ones already covered with the latest data available.
- The work performed during the last years lead to a more modularised tool that allows the user to integrate different modules in external simulators.
- A versatile multi-platform navigation tool for mission analysis assessment studies was developed
- A powerful mission reconstruction module is available to allow producing trajectory profiles of application to navigation. This can be also used as a stand-alone tool for mission definition as already shown in support to some ESA studies
- The covariance analysis capability allows performing quick and thorough analysis of achievable OD performances
- A Simulation Module allows characterising the guidance requirements of a mission together with the validation of the OD results
- Some application tools have been developed to interface with other reference tools for mission re-optimisation
- Mission design and navigation capabilities have been applied to numerous ESA projects as: BepiColombo, Solar Orbiter, ExoMars, Marco Polo, Phobos Sample return, Mars Sample Return, etc. and many other mission studies
- LOTNAV has also been applied with high success in several editions of the GTOC

8. ACKNOWLEDGEMENT

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