ADVANCED ELECTRIC ORBIT-RAISING OPTIMIZATION AND ANALYSIS WITH LOTOS 2

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ABSTRACT

In the newest version of the low-thrust optimization and analysis tool LOTOS (Low-thrust Orbit transfer Trajectory Optimization Software) many new features are available. The tool is not limited to electric orbit-raisings anymore; it also supports hybrid transfers where chemical maneuvers are followed by the low-thrust transfer. Another new feature of the software, for example, is the support of spacecraft operations. This mode identifies the spacecraft location on a pre-computed reference trajectory and uses its attitude profile for re-optimization. Such a processing is required due to deviations of the real-flown spacecraft trajectory from the nominal one.

A full overview of the software capabilities and features is given in this paper, such as hybrid transfers, 6 degrees of freedom attitude control and verification of trajectories. Highlights of the Graphical User Interface (GUI) are presented as well. It includes automatic user defined post-processing and customizable reports to support mission analysis engineers and to relieve them from repeating tasks. For example, reports provide full access to all data of the user defined scenario and may include tables and plots as well.

Index Terms— Electric Orbit-Raising, Hybrid Transfers, Re-Optimization of Orbit Transfers, Operational Chain, Non-Linear Programming, Batch-Processing, Post-Processing, Reports, Database

1. INTRODUCTION

Telecommunication satellites located in the Geostationary Equatorial Orbit (GEO) are typically not directly placed there by the launch vehicle. The satellites are often injected in a Geostationary Transfer Orbit (GTO) and then transferred to the GEO using their own onboard propulsion system. State of the art for the GTO to GEO transfer is still the chemical propulsion. Just recently few satellites transferred or are transferring to GEO using Electric Propulsion (EP) (see Figure 1).

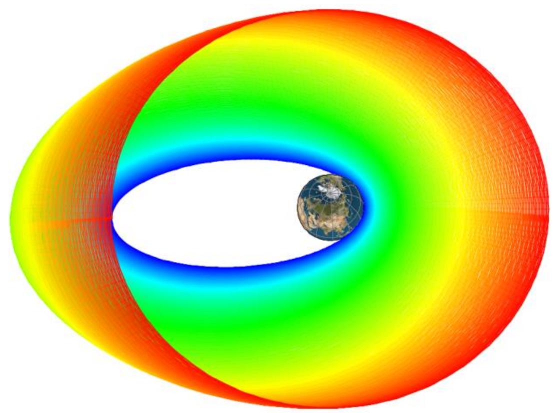


Figure 1. Illustration of a typical low-thrust orbit transfer from GTO (blue) to GEO (red) lasting about 6 months. The top-down view shows more than 250 revolutions around the Earth.

It is very attractive to exploit their high specific impulse reducing the propellant mass of the orbit transfer. Since the total spacecraft mass is reduced this yields launch vehicle cost reductions. Further, Electric Orbit-Raising (EOR) is now available for most telecommunication satellite platforms or at least under development.

But electric orbit-raising requires much more complex maneuver sequences than what is needed for pure chemical transfers. Since EP provides only small thrust magnitudes in comparison to chemical propulsion, the transfer lasts many months. A careful planning of the spacecraft attitude maneuvers is required in advance to fulfill this mission. In recent years, many software tools have been developed for the preliminary assessment of low-thrust orbit transfers. Unfortunately, most tools lack both maturity and accuracy necessary to fully exploit the capabilities of electric orbit-raising. For example, during the transfer any crossing of the GEO ring poses a certain collision risk with high value assets. Thus, the precomputed transfer trajectory has to avoid crossings of the GEO belt. Further, ground station visibility might be considered for transfer planning as well as limitations and constraints related to different spacecraft subsystems, such as eclipse handling, power generation, storage and consumption, or EP firing limitations in general. Other possible limitations are related to the attitude of the spacecraft or consider environmental aspects like the radiation dose.

Using Non-Linear Programming (NLP) to optimize the attitude profile in combination with detailed modelling of complex mission constraints and limitations of the spacecraft model is essential, especially under consideration of tight accuracy and fidelity requirements for achieving optimality in sense of propellant consumption and transfer duration. Besides optimization, many aspects have to be analyzed in more details. It encompasses subsystem issues for example of the Attitude and Orbit Control System (AOCS) as well as station visibilities.

Some of the aforementioned software features were already presented [5]. Now the latest improvements of the LOTOS software [1] are presented. First, the next chapter provides an overview of the general software functionalities. This is followed by a description of the spacecraft dynamics and the environmental modelling required for low-thrust orbit transfers. Next, the support of spacecraft operations is detailed. Finally, after presenting the report functionality, the conclusions are summarized.

2. SOFTWARE OVERVIEW

In comparison to the previous software version [5], many new features and improvements were made in LOTOS 2 (see Figure 2). It is an advanced tool for electric orbit-raising scenarios and allows optimization, simulation, verification and analysis of orbit transfer trajectories with electric (low-thrust) propulsion. Since initial and final orbit are user defined, the software tool is not just limited to typical orbit raising scenarios of telecommunication satellites but offers a wide range of possible applications for low-thrust transfers such as constellation deployment and graveyarding. The software facilitates:

- Optimization of reference trajectories
- Re-optimization of updated trajectories for spacecraft operations and autonomous transfers
- Hybrid transfers
- Verification of trajectories
- Full 6DoF attitude control
- Slew rate optimization
- Graphical User Interface for full control of user customizable scenarios
- Post-processing analyses related to transfer performance and spacecraft subsystem aspects
- Automatic mission analysis reports
- Database
- Built-in batch-processing
- Command line interface for use at control centers

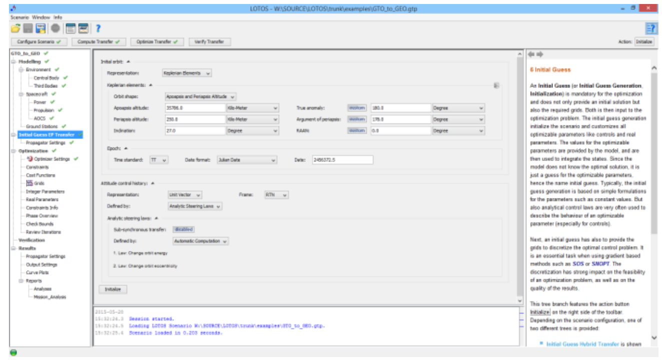


Figure 2. Main window of the orbit transfer optimization and analysis software LOTOS. On the left the navigation tree is shown to access all configuration panels with one example shown in the center. Input is expected to define the whole scenario properties. The right panel shows content sensitive help to aid the user.

Some but not all of the aforementioned key features are briefly presented in the following paragraphs. Two highlights, the support of spacecraft operations and the report functionality, are discussed in separately in chapter 4 and chapter 5, respectively.

2.1 Verification of trajectories

Once the trajectory is optimized the computed maneuver plan has to be verified to meet all constraints and requested conditions, because there are further aspects for electric-orbit raisings that might be crucial [6]. A verification of the computed or optimized control histories checks whether key transfer properties are met. For example, the spacecraft has to reach the desired final orbit. An overview provides details how accurate optimization and propagation of the control histories are with regard final orbit constraints. An assessment rates the quality of the met trajectory conditions.

2.2 Post-processing analyses

Typical output is provided by the software by means of functions and scalars. For example, the position, velocity and attitude of the spacecraft are available as output functions in different representations and coordinate frames. Another typical output function, at least when ground stations are involved in the scenario, is the visibility between ground station and spacecraft. An example for this aspect is illustrated in Figure 3. Unfortunately it is quite some effort to know how many ground station contacts occur, how long they typically last, and what the shortest and longest contact times are. For the mission analysis engineer it is important to have these numbers on hand. Now, the integrated post-processing is computing all aforementioned data for the user.

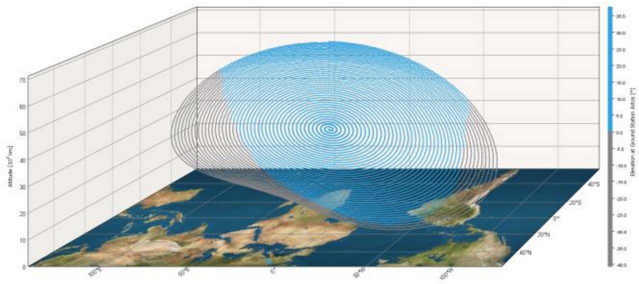


Figure 3. Synchronous orbit transfer (grey) to GEO with ground station in Stuttgart, Germany, and its visibility from the spacecraft (blue). The south-north map illustrates how an observer at the ground station actually "sees" the spacecraft trajectory.

All calculated quantities are added to the output data. Thus, the need for additional post-processing software is removed. Besides the output data can be easily included in a mission analysis report (see chapter 5 for more details).

But not only ground station analyses are valuable, especially aspects of the spacecraft subsystems are of very high interest for mission analysis:

- crossings of the GEO ring
- attitude
- slew rates
- torques
- eclipses
- thruster firings
- wheel momentum
- star trackers
- ground station visibility

For instance, a typical spacecraft is equipped with star trackers for navigation purpose. It should be known whether the optimized attitude profile results in blinding of one or even two star trackers. The included post-processing analysis identifies all star tracker blindings and outputs their total number as well as other relevant data.

2.3 Database

One of the most time consuming tasks is a proper setup of the optimal control problem. For low-thrust orbit transfer optimal control problem many different aspect have to be specified and defined. For example, the whole environment, (celestial bodies, radiation, etc.) has to be modelled. Furthermore all spacecraft properties are requested as input including many properties of the satellite and its sub-systems.

Since most of the data is usually identical it is very convenient providing the user an interface for easy and quick access of frequently used parameters and settings. For this purpose LOTOS provides access to a database. Predefined database entries can be easily expanded by the user since all data is managed through an XML (extended markup language) file. Database categories include:

- initial and final orbit
- environment such as radiation belt and stationary ring
- central body: shape, gravity, spin
- spacecraft properties
- spacecraft subsystems (power, propulsion, AOCS)
- ground stations
- cost function set

2.4 Hybrid Transfers

Sometimes the mass of a spacecraft is quite high in comparison to the thrust magnitude of the equipped electric propulsion system demanding a very long orbit transfer. In such situation mission designers and spacecraft engineers might think about an additional chemical orbit boost before the low-thrust orbit-raising starts. For fast assessments and efficient mission planning LOTOS 2 supports the evaluation of hybrid transfer scenarios. Up to three user customizable chemical burns are supported. Each burn can be located either in periapsis or apoapsis passage and has a maximum user definable burn duration. Besides the optimization of the duration of each burn, an additional out-of-plane component can be included in the burns for changes of the inclination. Thrust magnitude and specific impulse of the chemical propulsion are expected user input.

Two constraints are provided to limit the maximum total transfer duration or to define a minimum periapsis radius required after the chemical orbit-raising. The second constraint is very handy to minimize the dwell time in the hazardous radiation belt. For easy first iterations of possible transfer scenarios, the hybrid transfer feature can be used with the built-in batch-mode inspector for detailed studies minimizing the user interaction.

3. ASTRODYNAMICS

This chapter briefly describes the motion and attitude of a spacecraft and its representation. It is known from Newton's law of gravitation that any two objects of mass m and M attract each other. Assuming the larger mass M is fixed in the inertial space and furthermore $m \ll M$, the acceleration is defined by

$$\ddot{\mathbf{r}} = -\frac{\mu}{\|\mathbf{r}\|^3}\mathbf{r} + \mathbf{a} \quad (1)$$

where μ is the standard gravitational parameter of mass M, $\mathbf{r}$ is the position vector from M to m and $\mathbf{a}$ is the disturbing acceleration vector. With the acceleration vector every disturbing effect such as third body gravitational perturbations can be described, but also the low-thrust acceleration caused by the onboard propulsion system.

3.1 Translational states

As suggested in [2], the software uses a set of modified equinoctial orbit elements to describe position and velocity:

- Equinoctial element p is the semi-latus rectum
- Equinoctial element f and g represent the eccentricity vector
- Equinoctial element h and k represent the inclination vector
- Equinoctial element L is the true longitude of the spacecraft position

This set of orbital elements is very convenient for trajectory optimization because the results are more precisely and the convergence is better than the Keplerian elements. Besides, two singularities for zero inclination and zero eccentricity are removed. The modified equinoctial elements are defined by the Keplerian elements according to

$$p = a(1 - e^2) \tag{2}$$

$$f = e\cos(\omega + \Omega) \tag{3}$$

$$g = e\sin(\omega + \Omega) \tag{4}$$

$$h = \tan\left(\frac{i}{2}\right)\cos\Omega \tag{5}$$

$$k = \tan\left(\frac{i}{2}\right)\sin\Omega \tag{6}$$

$$L = \Omega + \omega + \nu \tag{7}$$

For reasons of compactness the inverse transformations as well as equations of motion are found in [2, 7].

3.2 Rotational states

The angular velocity vector is the rotation vector of the spacecraft body axes with respect to the inertial frame and given as

$$\boldsymbol{\omega} = \begin{pmatrix} \omega_x \\ \omega_y \\ \omega_z \end{pmatrix} \tag{8}$$

And the spacecraft attitude in the inertial frame, for example the International Celestial Reference Frame (ICRF), using Euler angles and rates is defined by

- Yaw angle ψ_i and its angular rate $\dot{\psi}_i$
- Pitch angle θ_i and its angular rate $\dot{\theta}_i$
- Roll angle φ_i and its angular rate $\dot{\varphi}_i$.

According to [3], the relationship between body rates and Euler angles is described by

$$\omega_x = \dot{\varphi}_i - \dot{\psi}_i \sin\theta_i \tag{9}$$

$$\omega_y = \dot{\theta}_i \cos\varphi_i + \dot{\psi}_i \cos\theta_i \sin\varphi_i \tag{10}$$

$$\omega_z = -\dot{\theta}_i \sin\varphi_i + \dot{\psi}_i \cos\theta_i \cos\varphi_i \tag{11}$$

For the rotational states the optimal control problem is formulated with controlled body rates. It means, the three body rate components become controls i.e. a function of the independent variable. On the other hand, the actual attitude is formulated as states and the requires the following dynamics

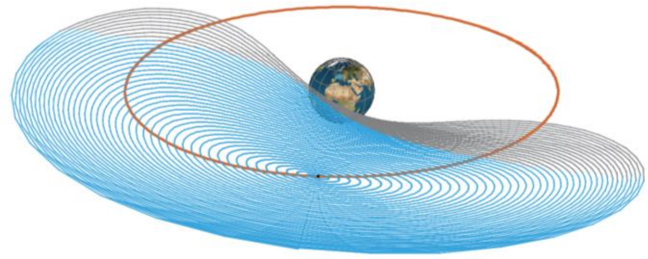


Figure 4. Synchronous orbit transfer (grey) in Earth-rotating frame with ground station visibility (blue) and GEO ring (brown).

$$\dot{\psi}_i = \frac{\sin\varphi_i}{\cos\theta_i}\omega_y + \frac{\cos\varphi_i}{\cos\theta_i}\omega_z \tag{12}$$

$$\dot{\theta}_i = \cos\varphi_i\,\omega_y - \sin\varphi_i\,\omega_z \tag{13}$$

$$\dot{\varphi}_i = \omega_x + \sin\varphi_i \tan\theta_i\,\omega_y + \cos\varphi_i \tan\theta_i\,\omega_z \tag{14}$$

3.3 Environment

Environmental effects are several natural forces affecting the dynamics of the spacecraft. For example, the motion of the spacecraft within a gravity field is not only governed by the point mass gravity of the central body. Also its inhomogeneity has to be considered. In particular the oblateness of the Earth is mandatory to be modelled for low-thrust orbit transfers. Other gravitational perturbations are third bodies i.e. Sun and Moon, for example.

Non-conservative forces like the atmospheric drag have to be considered as well. Its impact on the trajectory is strong for altitudes below 1,000 km, what is the case when starting in a low-Earth orbit or a GTO. Above 1,000 km of altitudes the atmospheric drag is small and dominated by other perturbations such as the solar radiation pressure. A typical spacecraft with electric propulsion for the orbit transfer has large solar panels to feed thrusters with solar energy. Solar radiation pressure becomes strong with small masses and large reference areas.

Further environmental aspects to be considered are eclipses, radiation and other objects such as satellites. A detailed eclipse model is required to know exactly how much solar energy is produced for the electric propulsion system. If the energy provided to the thrusters is too low the thruster has to be shut off. Since eclipses might last up to 40% of the orbital period, of course this has strong impact on the transfer trajectory. An example is illustrated in Figure 5. Radiation can be considered in two different ways. First, only the time spent in the radiation belt has to be considered. Or second, in more detailed evaluations, the total radiation dose is computed. Both options are supported by LOTOS. Obviously, the latter requires much more computational efforts while the first is perfectly suited for quick assessments.

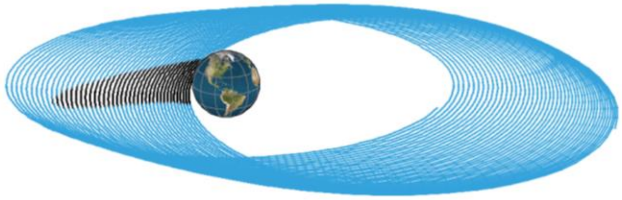


Figure 5. Eclipses (black) during a multi-revolution low-thrust transfer (blue) illustrated in inertial frame.

Last but not least, other assets need to be taken into account during the transfer avoiding possible collisions. In particular, telecommunication satellites in the GEO ring have to be considered. A protected region is defined by the user for the stationary ring (GEO ring). The software computes the passes of the spacecraft through this region and when optimizing the orbit transfer the number of crossings can be reduced. But also other satellites and objects pose a certain collision risk during the transfer. A conjunction analysis is required to identify the collision risk [5]. One critical aspect is that low-thrust transfers typically last several months. But propagating two-line element data of other objects for more than several days is very challenging.

4. SPACECRAFT OPERATIONS

After the successful launch of the spacecraft the operational phase of the orbit transfer starts. Its goal is to safely bring the satellite from its initial transfer orbit to the desired target location in geostationary ring. Because of the low-thrust character and the long duration of the transfer, a periodic operational process is proposed. It can be on daily, weekly, bi-weekly or monthly basis, or anything between. This cyclic concept was already applied for earlier investigations on re-optimization of perturbed GTO-GEO transfers [4] and presented in more details in [7].

One example of a periodic cycle for ground-based navigation involving the spacecraft operations center and software computing electric orbit-raisings is illustrated in Figure 6. In general, an operational chain may involve the following components:

- Orbit determination
- Reference trajectory
- Update of the spacecraft state
- Re-optimization of the trajectory to retrieve the maneuver plan
- Further verification and analysis tasks
- Processing of maneuver plan and upload to satellite
- Wait one period while the spacecraft travels

The reference trajectory is the re-optimized one of the previous cycle, or, in case of the first cycle, the whole trajectory.

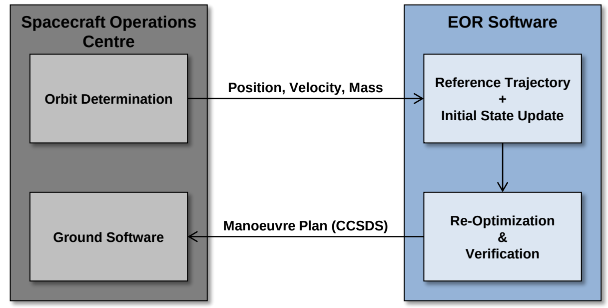


Figure 6. One example of an operational chain for a ground-based navigation concept. The spacecraft operations center (left) is responsible for orbit determination and upload of the optimized maneuver plan to the spacecraft. The optimization software for the EOR scenarios handles the reference trajectory and its re-optimization considering the updated spacecraft states.

In every cycle the components of the chain are accomplished. A low-thrust orbit transfer consists of several cycles between initial and target orbit. In other words, the whole trajectory is segmented into smaller parts where each single part covers one period. Since the processing of the components, except the last one, shall be in short time it requires a very good and efficient interaction of the involved hardware, software and personal. An example of a cyclic re-optimization is shown in Figure 7 for cycle #2. The shown trajectory lasts more than 6 months and consists of total number of 28 segments.

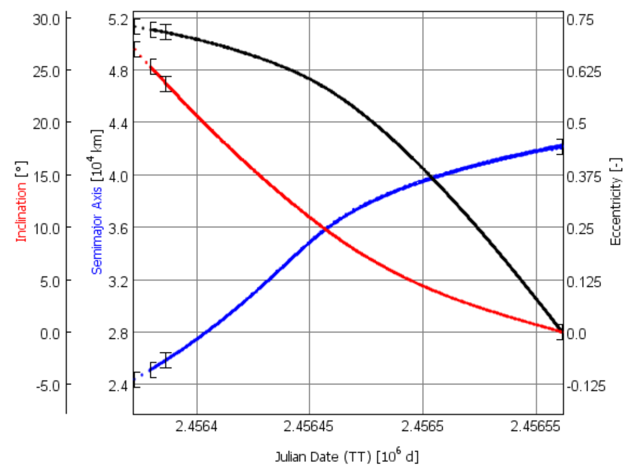


Figure 7. Evolution of orbital elements semimajor axis (blue), eccentricity (black) and inclination (red) after re-optimization of the trajectory. The dotted lines at the beginning of the transfer indicate the already travelled part of trajectory (cycle #1). Directly next to it the second cycle can be identified within the symbols "[" and "][".

The given example considers that the spacecraft already travelled 7 days to GEO (indicated by the dotted line), the duration of cycle #1. For the orbit determination, a spacecraft state (position, velocity, mass) was extracted from the reference trajectory after 7 days of transfer duration and perturbed to simulate a real spacecraft deviation from the nominal trajectory. Using the perturbed initial state of cycle #2 as actual spacecraft state the software LOTOS identifies the location on the reference trajectory which is closest to the actual one automatically. The remaining transfer is then re-optimized by direct transcription of the optimal control problem into a nonlinear programming problem by discretization.

5. REPORTS

Once the spacecraft orbit transfer is computed or has been optimized, all relevant output data is evaluated and post-processed automatically by the software. In the next step the mission analysis engineer is typically requested to include all relevant data in a kind of report. This usually means copy and paste of plots and numeric data. Of course, this is a pool of possible errors. Besides, after re-running the software numbers might have changed because of a different scenario setup and the engineer has to copy and paste again all numbers. Such repetitive tasks are waste of resources. LOTOS provides a built-in functionality to relieve the software user of it and to simplify workflows.

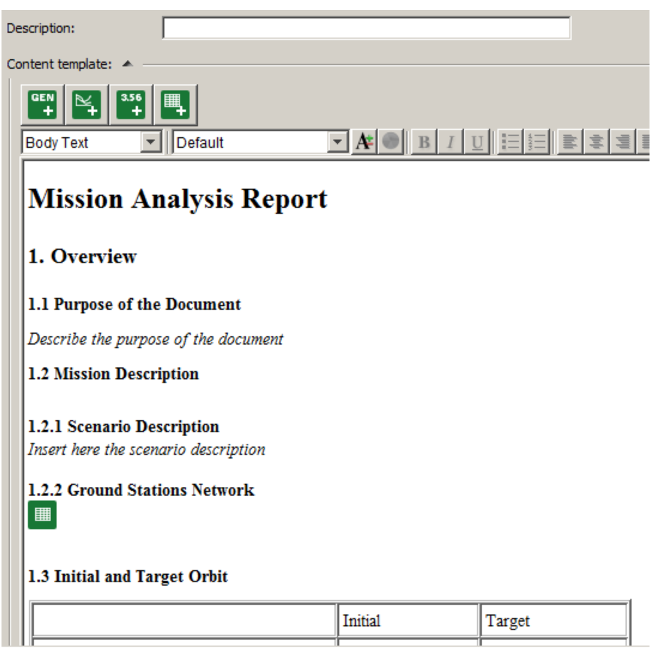
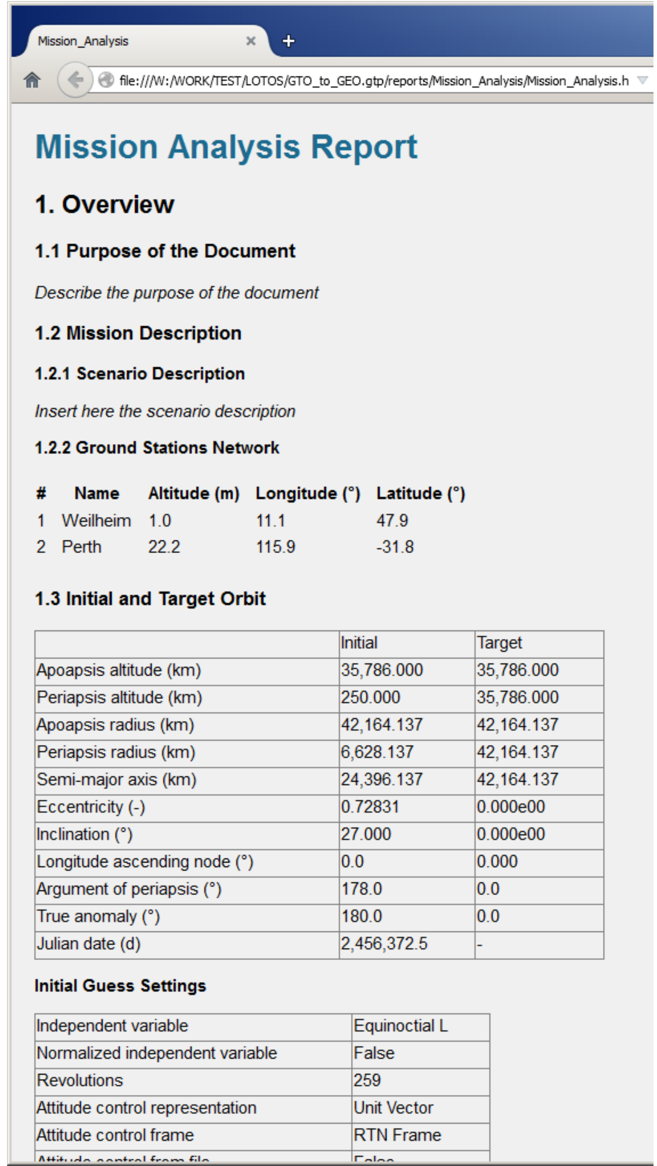


Figure 8. Example of a report template used to generate the report. A template might include text, figures, tables and data of the scenario (e.g. user defined initial orbit).



Mission Analysis Report

1. Overview

1.1 Purpose of the Document

Describe the purpose of the document

1.2 Mission Description

1.2.1 Scenario Description

Insert here the scenario description

1.2.2 Ground Stations Network

#	Name	Altitude (m)	Longitude (°)	Latitude (°)
1	Weilheim	1.0	11.1	47.9
2	Perth	22.2	115.9	-31.8

1.3 Initial and Target Orbit

	Initial	Target
Apoapsis altitude (km)	35,786.000	35,786.000
Periapsis altitude (km)	250.000	35,786.000
Apoapsis radius (km)	42,164.137	42,164.137
Periapsis radius (km)	6,628.137	42,164.137
Semi-major axis (km)	24,396.137	42,164.137
Eccentricity (-)	0.72831	0.000e00
Inclination (°)	27.000	0.000e00
Longitude ascending node (°)	0.0	0.000
Argument of periapsis (°)	178.0	0.0
True anomaly (°)	180.0	0.0
Julian date (d)	2,456,372.5	-

Initial Guess Settings

Independent variable	Equinoctial L
Normalized independent variable	False
Revolutions	259
Attitude control representation	Unit Vector
Attitude control frame	RTN Frame

Figure 9. Example of a mission analysis report generated by LOTOS. This report lists the defined ground stations as well as the properties of the initial and target orbit. Also some settings of the initial guess creation are shown.

This report feature processes the requested data using the provided output of the software. The user has only to create its own report template (see Figure 8) in LOTOS where certain text is added as well as figures, tables, and numbers. The template editor also supports an export mode to access the template source code written in XML. In a next step the template is used to create the report in HTML (hypertext markup language). An example is shown in Figure 9. The software automatically inserts the right numbers and data where defined. Full access is given to the user defined scenario data.

6. CONCLUSIONS

LOTOS 2 is an advanced tool for trajectory optimization and analysis of electric orbit-raising scenarios and hybrid transfers, where the chemical orbit-raising is followed by an electric orbit-raising. It allows simulation, optimization, verification and analysis of orbit transfer trajectories with electric (low-thrust) propulsion. For preparation and support of the spacecraft operations during the orbit transfer, LOTOS features the re-optimization of pre-computed attitude histories and optimal trajectories which has to be performed after an update of the spacecraft state by means of orbit determination. The software is not just limited to typical GTO-GEO transfers but offers a wide range of possible applications for low-thrust transfers including constellation deployment and graveyarding of telecommunication satellites located in GEO.

Possible optimization scenarios with user defined initial and final orbit include time and fuel optimal transfers, minimization of radiation, avoidance of GEO ring crossings, thruster shutdown during eclipses, and slew rate limitations. Furthermore the software provides the user with very convenient features such as integrated post-processing analyses, automatic mission analysis reports and a user-customizable database.

7. REFERENCES

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