Operational Concept for Orbit Raising with Low Thrust

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The problem of designing a transfer trajectory joining two different and distant orbits when low thrust is the only control means is profusely treated in the literature of recent years. While this can be seen as a strictly mathematical problem, which needs to be solved under representative environmental models during satellite design related activities, the question of how this nominal / theoretical trajectory is flown / operated in a real scenario has been paid considerably less attention. The paper presents many of the links between the relevant operational design aspects of such phases: after a first general statement of the problem and the context in which it has to be solved, some of the most important trade-offs to be performed are discussed, some related analyses results are presented, and finally some derived conclusions are proposed.

Key Words: Flight Dynamics, Collision Avoidance, Low Thrust, Transfer to GEO

1. Introduction

Missions performing long orbit transfers with low-thrust electric propulsion systems have become increasingly popular in last years. A recent example of such mission is the ABS-3A mission, launched in March 2015: a fully-electric communications satellite in a geostationary orbit with a Boeing 702SP satellite bus[1)]. The satellite made the transfer from a super-synchronous transfer orbit to the final geostationary orbit using electric propulsion only.

Relying on a low-thrust electric propulsion system, such a transfer from a satellite's initial orbit to the final operational orbit can take between several months to one year. During this period, the satellite fires its thruster(s) almost continuously. There are several challenges associated with such transfers, not the least of which is the optimization of the transfer trajectory. The optimal transfer problem has been studied actively over the last decades and many solutions and related tools exist, most of which rely on solving some large optimization problem to determine optimal steering laws over the course of the transfer. Problems less studied are related to the operational implementation of such a transfer, which is the topic of this paper.

During the transfer with continuous low thrust, the orbit prediction errors are significantly larger than without such continuous thrust. These errors are dominated by the combination of orbit determination errors and errors arising from the propulsion system itself – the execution of the maneuvers differs slightly from the planned maneuvers; and these differences accumulate along time to create non-negligible trajectory dispersions. This paper shows the influence of these two dominant error sources.

Two particular challenges result from the errors due to orbit determination and maneuver execution. The first is that the planned trajectory differs from the actual trajectory. This introduces the need for re-planning, consisting of a re-optimization of the transfer trajectory with a certain frequency, as well as generating and uploading new thruster and steering commands to the satellite. The frequency of such re-planning is an important operational design parameter, as well as how the maneuver commands and updates are executed on-board the satellite. The usual approach is a time-tagged execution of such profiles, however, when an on-board orbit determination capability is present, such commands can also be "anomaly-tagged", reducing the impact of orbit prediction errors.

The second challenge is collision avoidance. Typically, launcher injection orbits have high apogees, at or above the apogee of the target operational orbit, where usually the density of other satellites is low and the risk of collisions is acceptable. However, the perigee is usually in the Low Earth Orbit (LEO) regime. During a low thrust transfer, it may take the satellite several weeks to raise its perigee to an altitude above LEO (~2000 km). The density of objects in the LEO regime is significant, providing a need for conjunction analysis and collision avoidance strategies.

These challenges are addressed in this paper. An analysis of the orbit prediction errors is performed and the results of this analysis are treated in the discussion of a concept for collision avoidance for orbit raising using a low thrust propulsion system.

The paper starts with a description of the key flight dynamics functionalities that are required during the transfer. Following is a discussion of the implementation options, indicating where important trade-offs are required. The accuracy of propagation, as well as the collision avoidance considerations are analyzed in more detail, after which a short conclusion is included.

2. Functional Description

Any Flight Dynamics system used by the on-ground operators of a space mission must have as main objective the computation of the dynamic state of the satellite along time, accurately enough to allow for a feasible and reliable execution of the designed Mission Plan. Further, it has to do this in a timely manner to allow for an adaptation of the satellite tasks composing that Plan (f.i., maneuvers) to cope with the unpredictable events the satellite trajectory is subject to during this phase:

- Detected high risk of collision with other objects in-orbit.
- Thrusters stops due to malfunctions or too high dispersions.
- Etc.

To properly deal with these responsibilities, following functionalities can be distinguished within the Flight Dynamics application:

- Guidance function;
- Navigation function;
- Control function;
- Propagation function;
- Collision Avoidance function;
- FDIR function;

These functions are graphically shown in Fig. 1 below, where some of the relationships between these functions are already highlighted.

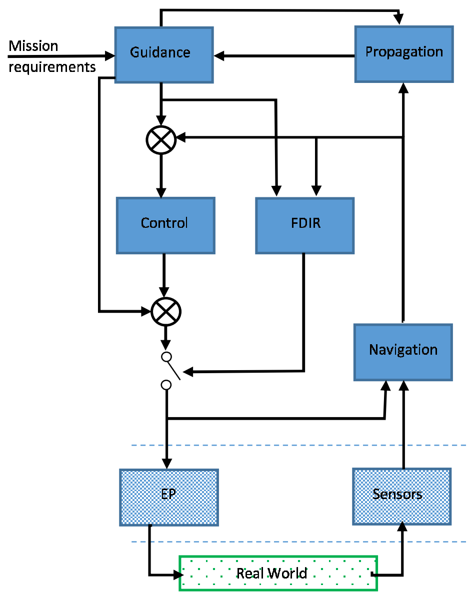

Fig. 1. Functional description of a Flight Dynamics system for transfer of Low Thrust satellites

2.1 Guidance function

The Guidance function calculates the trajectory to be followed by the satellite during the transfer phase, and the maneuvering profile required to reproduce it. This trajectory is computed in accordance to a set of mission objectives: either minimize transfer time, or maximize mass in final orbit (or a combination of both). Together with this trajectory, the Guidance function would also provide the maneuver profiles and the nominal attitude required to reproduce that dynamic evolution of the state vector.

The low thrust transfer problem can be formulated as a full optimal control problem and as such, it can be regarded as a large-scale optimization problem to determine the thrust and attitude profiles over time. For being a computationally demanding activity, it must run on-ground. The resulting guidance profiles are time-tagged or anomaly-tagged commands that the satellite executes as feedforward profiles. The most suitable implementation option is subject to a trade-off.

2.2 Navigation function

Based on measured data, the Navigation function determines the satellite state (mainly position & velocity, for what regards this transfer phase, but also attitude & attitude rate). Further, it is also in charge of estimating any other variable deemed relevant for the execution of the guidance profile. In the low thrust transfer scenario, it is commonly the case that the thrust components must be known or measured somehow in order to feed the estimation filter, where the off-line commanded acceleration coming from guidance profile provides the lowest level of accuracy for such variables.

The needed measurements can arise from ground-station tracking or an on-board GNSS receiver, possibly aided by the processing of some other measurements. The Navigation function can be implemented on-ground, on the satellite, or both on-ground and on the satellite, and is subject to a trade-off.

2.3 Control function

The control function is executed onboard by the AOCS subsystem in a feedback control scheme. The desired satellite and thruster attitude is obtained from the Guidance function, which provides the needed thrust direction along time. The control function achieves the desired attitude and switches the thruster(s) on/off.

For being the function really closing the loop for attitude control purposes, it is executed fully autonomous on-board and hence not included as a functional entity in the Flight Dynamics operations.

2.4 Propagation function

The Propagation function takes as an input a satellite state determined by the Navigation function, as well as the thrust profiles from the guidance function. It propagates both state vector and covariance matrix. The Propagation function is required in the ground segment as well as on-board the satellite.

2.5 Collision Avoidance function

The Collision Avoidance function takes the propagated trajectory and possibly covariance matrices and checks for collisions with external objects. An external service provider is usually required to perform an initial screening. Based on the result of the screening, each close approach is assessed in detail. This can be done on the basis of miss distances or the calculation of the probability of collision.

If a close approach exceeds certain risk parameters, action is required. If a detected threat allows for it, the preferred emergency action should be to switch the electric propulsion thrusters off for a certain period of time (to be computed & assessed by this Collision Avoidance function). The emergency action is always calculated on-ground. When and whether or not to execute the emergency action can be determined autonomously on-board or on-ground and is another trade-off.

2.6 FDIR function

The FDI(R) function primarily compares the trajectory flown with the desired state from the guidance function. If the deviations from the desired state exceed a certain threshold, electric propulsion is switched off until either recovery is performed, or after intervention from ground. This FDI(R) functionality is by definition implemented on-board, but recovery action can be performed from ground.

3. Implementation and Trade-offs

One of the main particularities of a transfer phase executed by a low thrust actuator is that, due to the low level of the acceleration, the satellite needs to propel itself quasi-continuously, with only quite short intervals during which the thrusters may (or must) be off. The satellite power balance (i.e., eclipses) forces some of these intervals, some other might come from operational reasons (f.i., eventual ranging campaigns) or from other needs imposed by different sub-systems (AOCS constraints violation, EP malfunction, etc.).

This fact has important consequences on at least two of the functions explained in paragraph above:

- On one side, the **Navigation** function needs to adapt to the continuously changing orbit of the satellite. Classical approaches based on ground ranging are not directly applicable, and would require a reliable alternative to feed the system with an accurate enough estimation of the satellite trajectory.

The main solution adopted for this purpose is the use of GNSS receivers onboard, which would process GNSS raw measurements in real-time, or store the GNSS measurements over some interval long enough to allow for the required level of state estimation accuracy. The post-processing of these raw data might then happen on-board (GNSS measurements would be processed with the help of a Kalman-like filter, for instance) or on ground (after downloading the corresponding data packages).

- On the other side, the accuracy of the **Propagation** function is greatly impacted by the level of predictability that could be assigned to the EP thrusting errors. Since time between contacts to ground ranges from several hours to few days, the solution provided by the Propagation function might quickly degrade if dispersions (i.e., unpredictable errors) as a result of low thrust, orbit determination, or mismodeling are big enough.

The propagation function is an important input for the **collision avoidance** function, and both these functions are discussed in more detail in the next two paragraphs.

3.1 Propagation Accuracy

The accuracy of propagation plays an important role in deciding the necessary frequency of ground station contact and the frequency of re-planning the desired trajectory and thrust profiles. It also provides an important input for the design of the collision avoidance function.

The propagation accuracy is affected by three sources of dispersions:

- Orbit determination errors
- Maneuver execution errors
- Modeling errors

The first two sources completely dominate the achievable orbit prediction accuracy: the impact of these errors is investigated for an exemplary orbit. An approximate Ariane 5 GTO was used for the analysis with the following orbital parameters:

- Semi-major axis: 24338 km
- Eccentricity: 0.73
- Inclination: 6°
- Right Ascension of Ascending Node: 0°
- Argument of Perigee: 180°
- True anomaly: 0°

The errors resulting from an orbit determination are dominantly in the radial and tangential direction. Figure 2 shows the evolution of the standard deviation of orbit determination errors in the radial, tangential, normal plane, over a period of two days. The peaks in the figure correspond to perigee passages. The analyzed orbit determination performance is comparable to GEO navigation performance obtained with a GNSS receiver[2)].

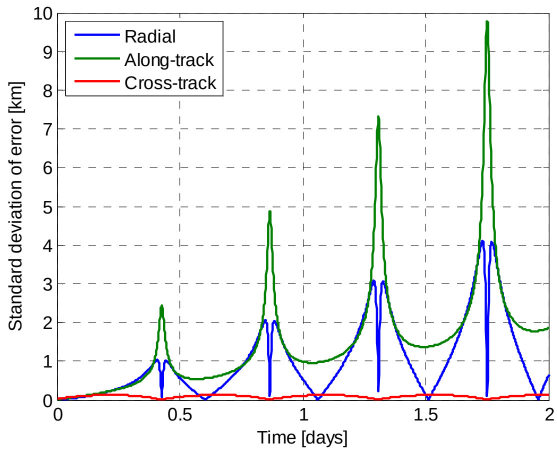

Fig. 2. Dispersions accumulated in radial, along-track and normal direction due to navigation errors in the order of 25 m & 2.5 cm/s, 1σ, based on a full covariance matrix

In addition to orbit determination errors, errors in the execution of maneuvers have an even larger impact on orbit prediction errors. Figures 3 and 4 show the evolution of the errors due to thrust uncertainty in respectively magnitude and direction, over a period of two days. As evident from the Figure 2, already after two days, extremely large orbit prediction errors in the tangential direction are observed.

These orbit prediction errors have several important consequences. The first is that the execution of the thrust profile becomes more erroneous as the orbit prediction errors accumulate. More, if considering the inertial attitude commands, it is clear that any deviation from the intended position can cause the satellite to thrust in increasingly erroneous directions. Having the satellite attitude defined in the radial, tangential and normal reference frame provides an improvement. A further and more significant improvement can be achieved by executing the thrust profile as set of anomaly-tagged commands: the position of the satellite along the orbit is used as an independent variable to determine the firing direction from the thrust commands.

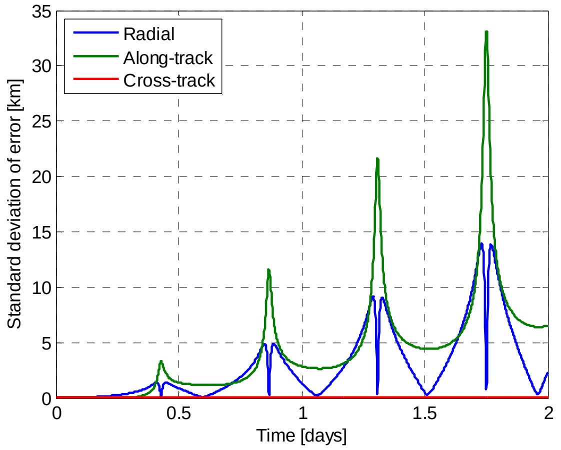

Fig. 3. Dispersions accumulated in radial, along-track and normal direction due to thrusting errors in the order of 0.5%, 1σ thrust level

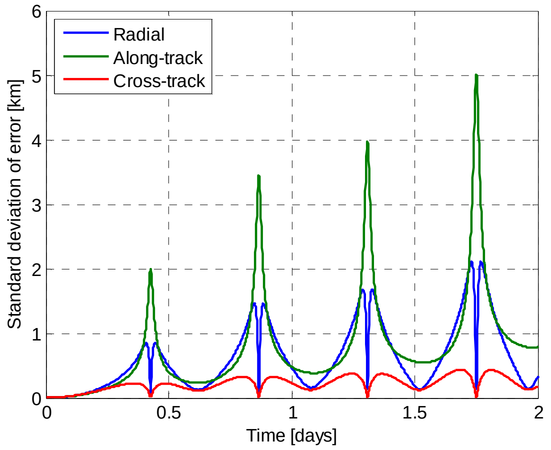

Fig. 4. Dispersions accumulated in radial, along-track and normal direction due to thrusting errors in the order of 0.5°, 1σ off-pointing

Since particular orbit maneuvers are more efficient at certain places inside an orbit (e.g. inclination changes are most efficiently achieved at the node crossings), an improvement in accuracy can be obtained for anomaly-tagged commands: the along-track error still accumulates, but it no longer causes the thrust profile to become increasingly sub-optimal. The advantage of this approach is that less frequent trajectory re-planning on-ground is required. The disadvantage, on the other hand, is that increased on-board autonomy is required, and the execution of the thrust profile requires a valid GNSS solution at all times.

The orbit prediction errors further have an important consequence for the design of a collision avoidance function, as discussed in the following.

3.2 Collision Avoidance

Close conjunctions with external objects pose a major risk to the satellite and collisions must be avoided with the highest priority. The general process for conjunction analysis and collision avoidance considered in this work includes a regular screening by an external organization (e.g. JSpOC). Conjunctions exceeding certain thresholds on miss distances are flagged and communicated to the satellite operator. The usual thresholds for LEO objects are 200 m radial, and 1000 m overall miss distance, however, these thresholds need to be enlarged significantly for a satellite subject to continuous low thrust. The flagged conjunctions are further analyzed by the satellite operator to identify the collision risk and decide on appropriate action to mitigate the risk.

The state prediction accuracy is an important input to decide if, when and how to take action. As seen before, the state prediction accuracy decreases rapidly in time. A decision to perform a collision avoidance maneuver could be made solely based on miss distances between the satellite and an external object. The larger the uncertainty in the satellite state, the higher we should set the thresholds for miss distances in order to safely mitigate collision risk. When using a probability of collision figure to decide, the same reasoning applies when a maximum probability of collision figure is used[3].

Figure 5 provides the results of an analysis for the classic Ariane 5 GTO to GEO trajectory. The analysis consisted of calculating the expected number of required collision avoidance maneuvers as a function of a threshold in radial direction, and a threshold in distance in the relative velocity direction for flagging an event requiring a collision avoidance maneuver. An open database of approximately 15k objects in Earth orbit was used. Although not visible from the figure, over 90% of the flagged events take place in the first few weeks of the transfer, when the perigee is still below 2000 km.

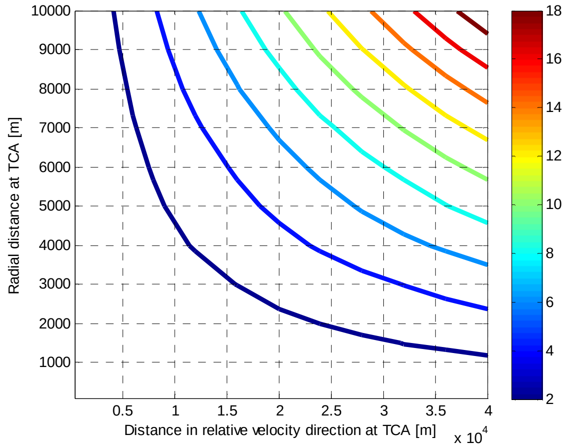

Fig. 5. Expected number of collision avoidance maneuvers as function of the radial distance and distance in the relative velocity direction at TCA.

Combining the results from Figures 3-5 we can conclude that the earlier a decision on a collision avoidance maneuver is taken, the larger the required thresholds on separation distances should be, resulting in a larger number of collision avoidance maneuvers along the trajectory. If the miss distance is smaller than the state uncertainty, we cannot be sure that no collisions occur, and hence, with larger state uncertainty, larger miss distance thresholds are required to safely mitigate collision risk. If the decision on the execution of a collision avoidance maneuver can be delayed until shortly before the conjunction, a significantly smaller number of collision avoidance maneuver is required. Based on the results of the expected propagation accuracy, a trade-off can be performed between the point in time that a decision on a collision avoidance maneuver is taken and the expected number of such events that occur along the transfer.

Taking an early decision allows for a ground-in-the-loop architecture with (relatively) sparse ground station contacts. However, many collision avoidance actions may be required along the transfer, negatively impacting the duration of the transfer. Also the calculation of collision avoidance maneuvers may be more complicated in this scenario, as a collision avoidance action is more likely to result in a close conjunction with another object.

Taking a late decision, on the other hand, requires either continuous ground-station contact or a form of onboard autonomy in deciding whether to execute a collision avoidance maneuver (the actual maneuver can still be computed on-ground). The former significantly increases operational costs, whereas the latter introduces additional development costs and provides a definitive need for an on-board GNSS receiver. Additionally, increasing onboard autonomy is usually associated with increased complexity and hence risk.

There is another important factor separating early and late collision avoidance maneuvers. An early maneuver has the advantage that a larger separation distance can be achieved using a smaller maneuver size, whereas a much larger maneuver is required for a late maneuver. The preferred course of action for a low-thrust transfer is to simply switch off the engine for a certain amount of time in case of high collision risk.

We provide the results of an exemplary analysis that was performed to identify the impact of switching the engine off for 30 minutes on the radial and tangential position difference at the time of closest approach (TCA). The analysis considered a continuous acceleration of approximately 0.2 mm/s^2 acting on the spacecraft during the transfer, with a thrust profile characteristic of a low-thrust transfer.

Figures 6 and 7 show the impact when the engine is switched off respectively 2 and 12 hours before TCA, in each case for a period of only 30 minutes. The investigation considers a TCA at various true anomalies (as shown on the y-axis). The green bars in the figures correspond to altitudes below 2500 km, which is where most of the conjunctions occur.

Although only one example case is shown, the figures clearly show that an action as simple as switching off the engine can lead to significantly increased separation distances at TCA and such course of action appropriately avoids close approaches in most cases. It also shows that also a late decision (only 2 hours before TCA in this example) can lead to a large enough separation distance (i.e. the state prediction uncertainty is much smaller 2 hours into the future). An early decision (12 hours before TCA) leads to a much larger separation distance, which corresponds well to the need for a larger separation distance, to counteract the limited orbit prediction accuracy.

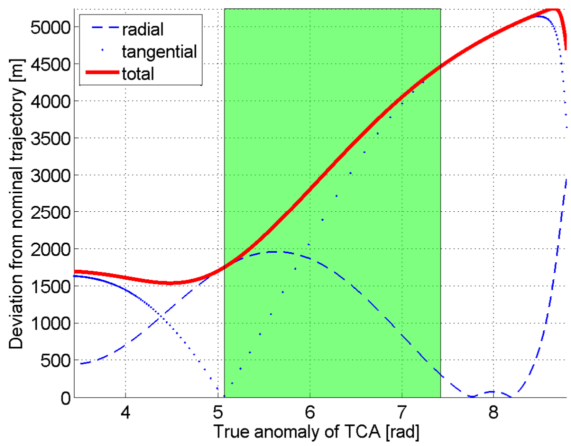

Fig. 6. Impact of switching the engine off for 30 minutes for various true anomalies. The deviation after exactly 2 hours is shown

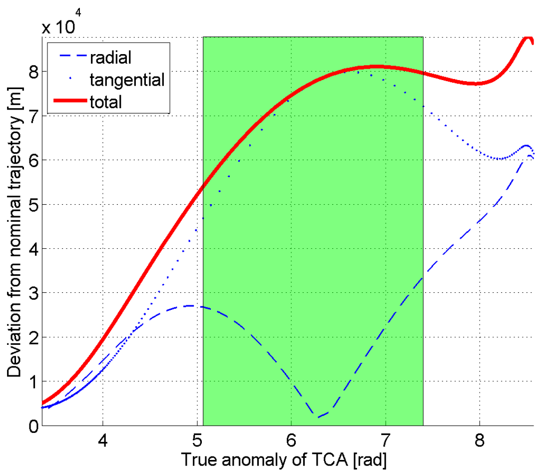

Fig. 7. Impact of switching the engine off for 30 minutes for various true anomalies. The deviation after exactly 12 hours is shown

4. Conclusions

This paper has discussed several considerations to support the design of an operational concept for flight dynamics of a low thrust transfer. The flight dynamics concept consists of several functionalities and each of the functionalities has been discussed on a general level. Several trade-offs are required to arrive at a particular operational concept for a low thrust transfer.

Two important drivers for the design of the operational concept were identified: on the one hand the orbit determination and prediction accuracy plays an important role. It is a key factor to decide the frequency of ground-station contact with the satellite, as well as the frequency of re-planning the trajectory and steering laws. The accuracy is driven by the navigation concept on the one hand, and the thrust uncertainty on the other hand.

In terms of collision avoidance, several considerations have been discussed, most notably the point in time at which a decision to execute a collision avoidance maneuver is taken, as well as whether to take this decision on-ground or autonomously onboard the satellite.

The exemplary analysis showed that both approaches can result in valid concepts, to be decided on in a trade-off. Since the actual size of the state prediction accuracy, the actual acceleration on the spacecraft, as well as the particular transfer scenario play an important role in the corresponding analysis, neither method is unambiguously better than the other method, and the particularities should be considered on a case-by-case basis.

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