FAST AND ROBUST OPTIMIZATION OF HIGH FIDELITY LOW THRUST TRANSFER ORBITS WITH CONSTRAINTS

David Mostaza-Prieto[(1)], **Georges Krier**[(2)]
[(1)]*SES Engineering, Château de Betzdorf, Luxembourg, david.mostaza.prieto@ses.com*
[(2)]*SES Engineering, Château de Betzdorf, Luxembourg, georges.krier@ses.com*

Abstract: *This paper presents the development and validation of an original method to optimize low and medium thrust trajectories between two orbits. The main difference with respect to previous approaches is a great improvement in robustness and speed. The method is able to solve any high fidelity minimum time or minimum fuel problem in a few seconds, without convergence issues and without the need for an initial guess. These features allow supporting both studies and real time operations, such as low-thrust transfer orbits to GEO. Several interesting results and findings regarding low-trust orbits are also provided.*

Keywords: *Low thrust, transfer orbit, trajectory optimization.*

1. Extended abstract

As low thrust transfer orbits to GEO are becoming operational, SES Engineering has identified the need for optimization software able to support studies and operations. Low thrust trajectories are characterized by long propagation times and many optimization variables. As a result, optimization programs are typically time-demanding and require a fair level of user expertise. Moreover, they normally need a “good” initial guess to converge, and is not always obvious how close this guess needs to be from the solution. Sometimes, under similar conditions, the optimization algorithm fails to find a solution, making the initial guess generation a sort of art as demanding as the optimization itself. The addition of constraints or discontinuities, such as allowing the trust to shut down, adds more difficulties to the problem, decreasing the robustness and convergence of the algorithms. All these facts make the use trajectory optimization programs challenging for real time operations or trade off studies. Since any deviation from optimality can impact the on-station lifetime of the satellite, supporting operational transfers to GEO requires a method able to provide a true optimum in any scenario, without falling into convergence issues and within a reasonable short time, in the order of seconds-minutes.

In order to fulfill these requirements, a comprehensive research has been conducted. Almost all the existing methods can be classified as Direct or Indirect (or a combination of both). Direct methods transform the optimal problem into a linear programing problem, requiring to parametrize the control function (thrust steering law) by a discrete and large number of optimization variables. The problem is typically solved by means of an NLP solver, which adjust the control variables in order to reduce a given cost function. Although it is easier to include constraints and these methods are more robust, they are also slower and less accurate. On top, the discretization of the control sometimes produces several minima, so the problem may converge towards solutions that are quite far from the global optimum. Therefore, we believe that indirect methods are better suited for the orbit to orbit continuous thrust transfer problem. They are typically faster and more precise, however, quite difficult to converge. We have focus our efforts in enhancing the convergence properties of a problem formulated as an indirect method. The result is an optimization program coded in FORTRAN (LOTTO) highly robust and able to provide results in a few seconds without an initial guess from the user. The following features can be included in the optimization:

- Minimum time problem (thrust always on)
- Minimum fuel problem (for fixed time, optimum coast periods)
- Minimum fuel problem for different thrust levels
- Eclipse shadowing (thrust reduction or thrust off)
- Earth potential (J2)
- Solar radiation pressure
- Sun-Moon effects
- Drag force
- Altitude constraints
- Longitude targeting
- Averaged and non-averaged dynamics

Formulated as an indirect method, the problem consists on finding the initial set of co-states (λ0) that allows deriving the control law that transfers the satellite from its initial sate into a given final orbit. This is basically a two point boundary value problem (2PBVP). Specific solvers are available, however it is known that the problem is sensitive and difficult to solve unless a very good initial guess is provided. Rather than focusing on the initial guess generation we have developed an iterative solving algorithm able to take advantage of the particularities of the problem. The algorithm is based on two main ideas, first, for any given values of initial co-sates, the integrated trajectory is optimal but it will finish in a different orbit. Second, a DV cost can be defined between this orbit and the target one. The way to find the required trajectory is to drive this cost towards 0. To accomplish that, LOTTO uses a robust heuristic search method similar to a simplex, which finds the solution of any transfer in a few iterations and without initial guess from the user.
One additional difficulty is the consideration of non-keplerian effects or constraints such as thruster off periods. We have observed that the problem is very sensitive to numerical noise and this is probably the root cause of the reported difficulties in the past when using indirect methods. However, this can be avoided by a careful study of these effects. Specifically, by avoiding approximations or discretization issues that could create non-smoothness or numeric noise, leading to a bad conditioned problem.
We will provide several study cases together with findings and recommendations, including:

- *Study of minimum fuel vs minimum time transfers to GEO and lifetime savings*: We have found how minimum fuel transfers can be extremely interesting. By extending a few days, there is a potential gain of years in on-station lifetime.
- *Comparison of averaged and non-averaged trajectories.*
- *In-orbit low thrust relocations.*
- *Complex cases including several effects.*