

Radiation Optimum Solar-Electric-Propulsion Transfer from GTO to GEO

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ABSTRACT

While electric propulsion is already used for station keeping purposes, the current technological improvements make the implementation of full electric propulsion (“full-EP”) telecom satellites realistic in the near future. ESA has performed a CDF study where solar electric propulsion is applied to reach GEO. The results of the Rendezvous and Refuelling Demonstrator study can be found in RD[1]. As a matter of fact also in the US a lot of analysis is currently performed in this area. In RD[2] transfers are investigated with a minimum radiation dose accumulated during the transfer. Radiation is a major concern for such transfers that typically last 6 months.

The total fluence on the spacecraft which is accumulated during the transfer cannot be reduced by a large extent because the minimum time solution already aims at a fast orbit raise which automatically reduces the radiation doses. In literature no radiation minimisation for a low-thrust GTO to GEO transfer was found. However for a LEO to GEO transfer with an inclination change of 15° such an analysis was performed in RD[2] and a reduction of the radiation of 3.9 % was calculated. For an inclination change of 0° no reduction of the radiation can be achieved at all.

A strict mathematical minimisation of the radiation fluence is very complicated. However, with state-of-the-art desktop computers, very complex optimisation problems can nowadays be solved in a reasonable amount of time. The software developed for Smart-1 to optimise the multi-revolution low-thrust transfer from one orbit to another (RD[3]) was re-programmed as a subroutine which can be called in an optimisation package like SNOPT (RD[4]).

The idea is to split the transfer trajectory in two parts. $X = (hp^i, ha^i, i^i)$ is the intermediate orbit where the two parts of the trajectory match. X is determined by the perigee radius hp^i , the apogee radius ha^i and the inclination i^i . Let $T_1(X)$ be the minimum time transfer solution from GTO to X (for GTO an inclination of 6° is assumed) and $T_2(X)$ be the minimum time transfer solution from X to GEO. These optimum transfers are calculated in a subroutine together with an approximation of the radiation.

The radiation is approximated by integration over time of a function f_{rad} depending on altitude h :

$$f_{rad} = 3.3 \cdot 10^7 \exp(- (h - 11700)^2 / 2 \cdot 10^7)$$

The function f_{rad} was determined by a fit to the 1 MeV flux calculated with SPENVIS for a GTO to GEO transfer.

Having a subroutine that determines the transfer time and the fluence of the solutions $T_1(X)$ and $T_2(X)$ it is now possible to determine X for which

$$\text{Fluence}(T_1(X)) + \text{Fluence}(T_2(X)) = \text{minimum}$$

SNOPT is used to solve this minimisation problem, because it has a fast convergence in spite of a low number of function calls. One difficulty in this optimisation problem is the choice of the required precision for solving $T_1(X)$ and $T_2(X)$. If the required precision is too high, this causes

excessive CPU-times, if it is too low, the numerical differentiation which SNOPT performs to find the gradients does not work, because the results of the function calls (which is a full optimisation problem) are not reliable enough and give wrong gradients. Some experimenting with the tolerance values was necessary but in the end the following solution was found:

$$X = (24140 \text{ km}, 73360 \text{ km}, 1.763^\circ)$$

The total transfer time is only 10 % more but the 1 MeV proton fluence is reduced by 9.5 %. The key difference in the two scenarios is the faster increase in the apogee height in case of the radiation minimisation. Having a higher apogee leads to a faster passage through the radiation belts. Another effect is the increased orbital period which reduces the total number of passages through the radiation belts. After 100 days the perigee radius is in both cases at about 22000 km (altitude=15600 km), but the spacecraft has completed only 152 orbits in the minimum radiation scenario whereas it has completed 161 revolutions in the minimum time scenario.

- RD[1] CDF Study Report R2D3: Rendezvous and Refuelling Demonstrator, CDF-104(A), June 2010.
- RD[2] A. Dutta et al., Minimizing Total Radiation Fluence during Time-Constrained Electric Orbit-Raising, 23rd International Symposium on Space Flight Dynamics, Pasadena, CA, October 29 - November 2, 2012.
- RD[3] R. Jehn and J.-L. Cano, Optimum Low-Thrust Transfer Between Two Orbits, Mission Analysis Working Paper No. 414, ESA/ESOC, March 1999.
- RD[4] Gill, P.E., Murray, W. & Saunders, A. User's Guide for SNOPT Version 7: Software for Large-Scale Nonlinear Programming, University of California, San Diego, USA, February 2006.