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Trajectory Optimization of a Low-Thrust Geostationary Orbit Insertion Maneuver for Spacecraft Total Ionizing Dose Reduction

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We consider the problem of optimal low-thrust spacecraft geostationary orbit (GEO) insertion from initial circular orbit with 800 km height and 51.6 degrees inclination. Minimal time for electric propulsion insertion of considered nuclear powered heavy spacecraft [1] is about 117 days. Significant amount of this time (~90 days) the spacecraft spends in regions with harsh space radiation environment inside the Van Allen radiation belts. To reduce an absorbed total ionizing dose (TID) for onboard electronic systems we propose a method of changing shape of the insertion trajectory and examine efficiency of this method. The main idea of the proposed method is to consider TID as a part of state variables set and to add the equation for TID change over the time to the equations of motion. Then if we add to the low-thrust optimal time GEO insertion problem [2] with the new set of state variables a condition of fixed TID at the end of transfer, one could obtain trajectories with lower final TID values. The obtained optimal control problem was solved using the maximum principle for one orbit time-averaged equations of motion. For numerical solution of corresponding boundary value problems we used the numerical continuation method with the predictor-corrector scheme. Numerical integration of considered ODEs was performed using the DOP853 integrator code.

The dose calculation for obtained trajectories we performed with CmdLineAe9Ap9 [3] software and Python scripts using AE8/AP8 MIN, AE8/AP8 MAX and AE9/AP9 electron and proton flux models of the Van Allen Radiation belts. In order to tackle discontinuities in right parts of ODEs we constructed a two-step spline approximation scheme of dose rate function. The first step is cubic smoothing spline approximation for noise level reduction of the CmdLineAe9Ap9 dose rate data. The second step consists of high-order (11th or higher) usual spline interpolation of the smoothing spline values. High-order order spline is needed to meet smoothness conditions of the right parts for Dormand-Prince ODE integration method.

We managed to reduce the final TID values by 25-38% (depending on the flux model) of final TID value on the minimal time GEO insertion trajectory. The duration of GEO insertion transfer is increased by no more than 7% of the minimal insertion duration. The additional required characteristic velocity for obtained trajectories is 320-560 m/s (depending on the flux model) with respect to the minimal time insertion trajectory.

References
[1] Legostaev V. P. et al., Prospects for and Efficiency in Application of Space Nuclear Power Plants and Nuclear Electrorocket Propulsion Systems, Space Engineering and Technology, 2013, No. 1., P. 4-15. (in Russian).
[2] Petukhov V. G. Optimization of Multi-Orbit Transfers Between Noncoplanar Elliptic Orbits, Cosmic Research, 2004, Vol. 42, No. 3, P. 250-268.
[3] https://www.vdl.afrl.af.mil/programs/ae9ap9/downloads.php

Summary

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