Using Solar-sail Induced Dynamics to Increase the Warning Time for Solar Storms Heading Towards Earth

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Abstract:

Coronal Mass Ejections (CMEs), commonly referred to as solar storms, that are on an Earth-intersecting trajectory, may lead to the breakdown of power grid transformers, the malfunctioning of Earth-orbiting spacecraft, and disruptions in navigation and communication systems, among many other effects. The financial impact of a solar storm is predicted to be in the order of trillions of euros and the probability of such an event occurring within the next decade is 12% (Riley, 2012; Eastwood, et al., 2018). With society relying ever-more on technology, the impact of a solar storm is ever-increasing. It is therefore essential that operators of vital infrastructure are notified of an approaching storm in a timely manner such that they can take adequate measures to mitigate the impact. Such notifications are currently provided by in-situ detection of the solar storm by spacecraft at or near the Sun-Earth L_1 point. Because of the time difference between the solar-storm arrival on Earth and the arrival of the spacecraft warning signal, a warning time of only 30 to 60 minutes is currently achieved.

To increase the warning time, the spacecraft should be placed further upstream of the CME propagation path, i.e., closer to the Sun. This paper aims to do exactly that, by designing periodic trajectories that travel upstream of the CME propagation path by using a solar sail as sole propulsion device. The CME propagation path and its axis is outlined in Fig. 1. A solar sail reflects photons off a lightweight and highly reflective membrane, thereby generating continuous thrust. Due to the propellant-less nature of a solar sail, the aimed-for trajectories can be maintained throughout the operational lifetime of the mission. The periodic solar-sail trajectories are obtained by solving the accompanying optimal control problem using pseudospectral collocation. Initial guesses for the collocation method are found by generating solar-sail assisted heteroclinic connections between artificial equilibrium points in the vicinity of the solar-sail displaced L_1 and L_5 points. The optimised trajectories trade-off three mission performance metrics: 1) the *average* increase in warning time along the trajectory; 2) the *maximum* increase in warning time along the trajectory; and 3) the probability of detection (which is modelled through the distance to the CME-axis).

The results show that, with near-term solar-sail technology (a lightness number of 0.05), the maximum warning time along the trajectory can be increased to approximately 15 - 30 hours without compromising on the other two performance metrices. This trajectory is displayed in Fig. 2. In addition, an inverse relationship exists between maximising the average increase in warning time and the probability of CME detection: the better the average warning time, the smaller the probability of detection. Finally, the paper investigates a range of sensitivity analyses (e.g., on the lightness number and CME size) to successfully prove the robustness of the methodology and the effect of assumptions made.

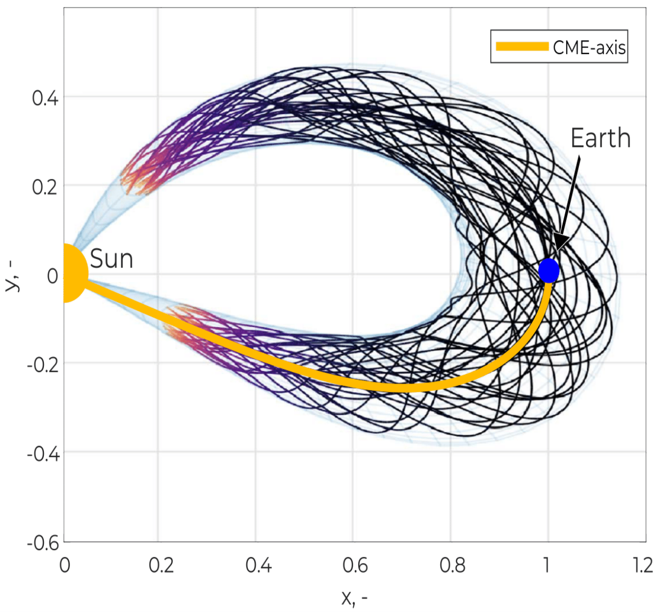

Figure 1. CME propagation path and axis.

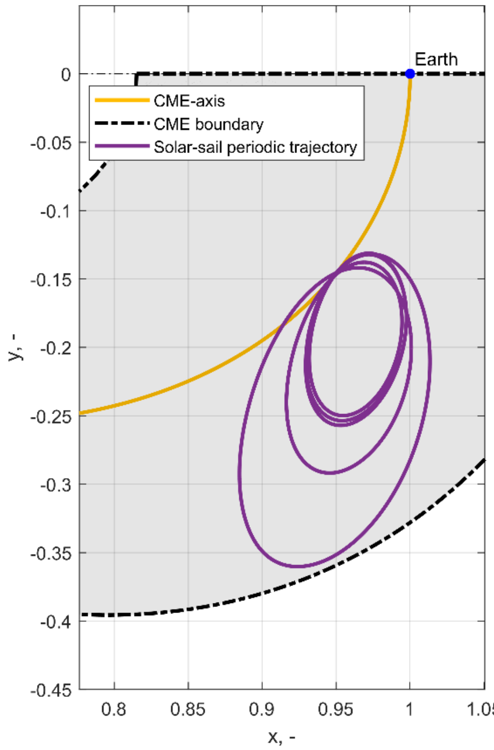

Figure 2. Optimised solar-sail periodic trajectory.

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