UNIVERSITY
of
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Department of Aerospace Engineering

Solar Sail Requirements for a Combined Solar Wind and South Pole Data Relay Mission

Consultants Report to the National Oceanic and Atmospheric Administration

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1. Introduction

In this report an analysis of the sail requirements for a combined solar wind and south pole data relay mission are investigated. The combined mission reflects a possible architecture for delivery of solar wind monitoring and data relay from the south pole. The study uses data provided in:

Starchville, T., "South Pole Access from Sun-Earth L_1 and Below Ecliptic", Aerospace Corp. Memo 2004(7949)-3

which identifies the required displacement away from the ecliptic plane to provide continuous data relay from the south pole, while also providing solar wind monitoring. A position 615,000 km below the Sun-Earth L_1 point is proposed to satisfy both of the mission requirements.

It is found here that the proposed location directly below the Sun-Earth L_1 point is on the boundary of allowable equilibria for the circular restricted three-body model used. It is recommended that a modified position slightly sunward of the L_1 point be considered to allow a modest solar sail to perform the mission. The new position is also somewhat further from the ecliptic plane (650,000 km) in order to provide continuous data relay from the south pole.

2. Non-Keplerian Orbits

Solar sails can enable unique families of highly non-Keplerian orbits. Of particular interest are equilibrium points displaced sunward of the L_1 Lagrange point or displaced above the L_1 point, high above the ecliptic plane on the day-side of the Earth. Locations sunward of L_1 provide an ideal location to provide early warning of solar storms, which is the concept for the NOAA Geostorm mission. Locations high above L_1 provide a vantage point above the ecliptic plane for whole Earth imaging of the polar regions or for high latitude communications (**Figure 2.1)**. In addition, a combined mission may be possible which allows solar wind monitoring, while providing continuous data relay from the south pole.

An analysis of the dynamics of such orbits shows that there are allowed and forbidden regions for artificial equilibria in the neighbourhood of the Sun-Earth libration points. In particular, for an ideal solar sail, there is a large volume of space between the L_1 point and the Earth which cannot support artificial equilibria (**Figure 2.2**). Similarly, analysis for a non-ideal solar sail shows that the forbidden regions grow in volume and connect (**Figure 2.3**). The effect of this on potential operating points for a combined solar wind and south pole data relay mission will now be considered.

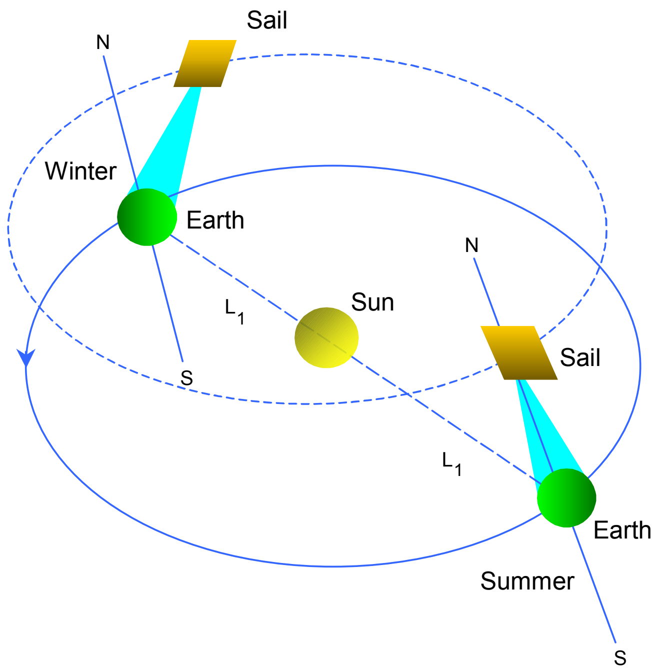

Figure 2.1 Schematic levitated L_1 orbit

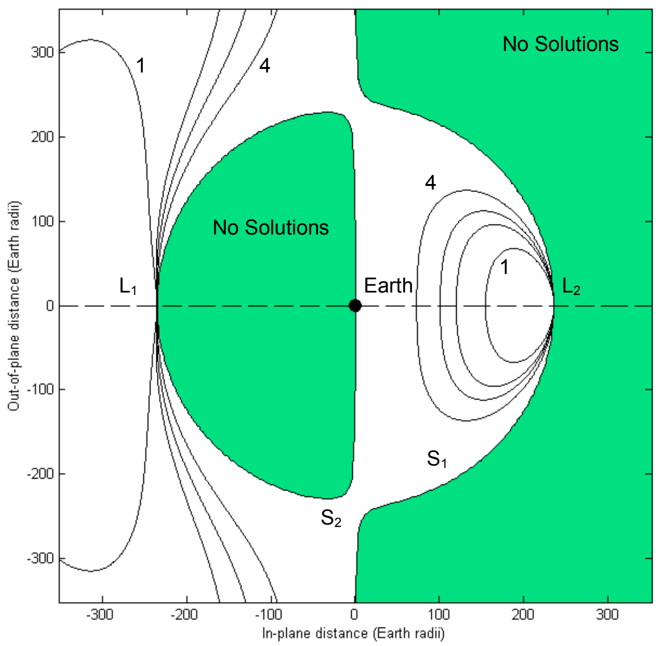

Figure 2.2 Contours of sail loading in the x-z plane with reflectivity η=1. Contours (gm^{-2}): [1] 30 [2] 15 [3] 10 [4] 5

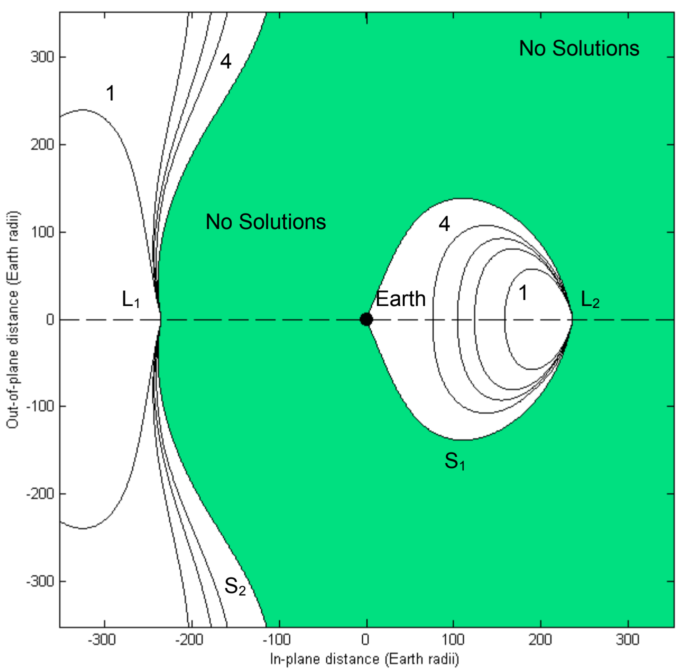

Figure 2.3 Contours of sail loading in the x-z plane with reflectivity η=0.9. Contours (gm^{-2}): [1] 30 [2] 15 [3] 10 [4] 5

3. Combined Mission Analysis

In order to provide a south pole data relay function, the solar sail must be displaced below the ecliptic plane in order to provide sufficient elevation above the horizon at the south pole for telecommunications (**Figure 3.1**). Clearly, as the displacement distance is increased the duration of continuous data relay will also increase. The analysis by Starchville [2004] shows that in order to provide continuous data relay throughout the entire year, an out-of-ecliptic angle θ_1 of 0.21° is required. This corresponds to an angle θ_2 of order 22° relative to the Earth, providing a displacement –z of 615,000 km below the Sun-Earth L_1 point.

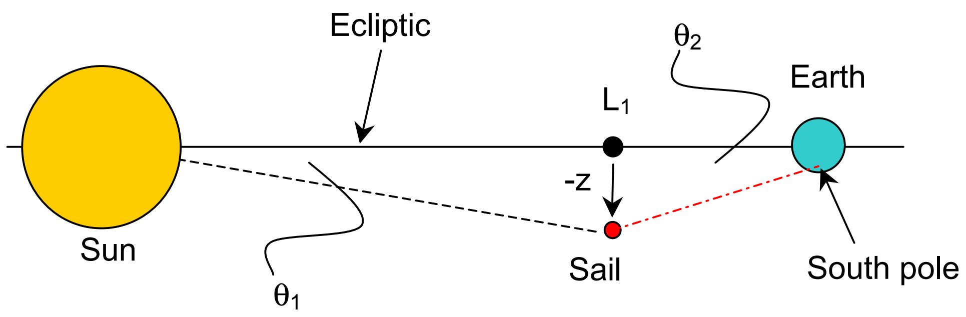

Figure 3.1 Schematic geometry of a south pole data relay mission (Starchville, 2004)

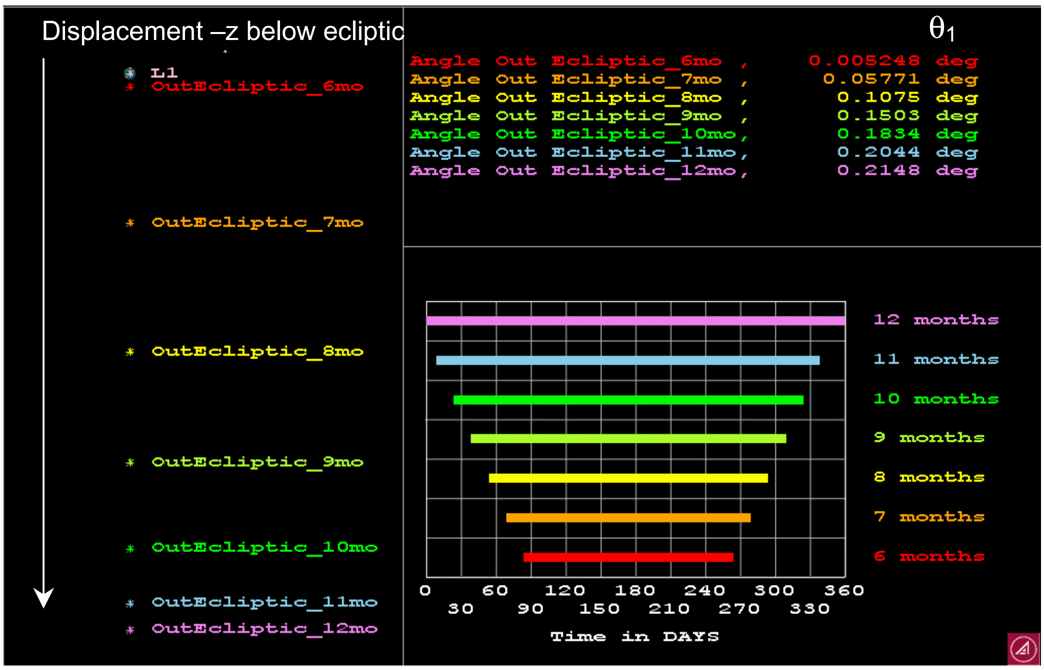

Figure 3.2 Requirements for a south pole data relay mission (Starchville, 2004)

Using a restricted three-body model, the requirements for such an out-of-plane location can be determined. Firstly, the sail reflective efficiency is assumed to be 0.85, as used in previous studies. The allowed and forbidden regions for artificial equilibria in the neighbourhood of the Sun-Earth L_1 point can now be determined (**Figure 3.3**). It can be seen that the required operating point is extremely close to the boundary between the allowed and forbidden regions. This poses difficulties with the use of the operating point for solar sails. In particular, as the boundary is approached the required sail performance rises sharply, as can be seen from the contour values (**Table 3.1**).

In order to overcome this problem, it is recommended that an operating point on the minimum elevation line between contours 2 and 3 be considered. This ensures the use of a modest performance solar sail and provides year-round south pole data relay, although the out-of-plane displacement is increased somewhat which will impact on the solar wind monitoring component of the combined mission. New operating points are detailed in **Table 3.2** which show that the out-of-plane displacement is increased from 615,000 km, although the required sail performance is of order 0.23-0.3 mm s^{-2}, with a sail pitch angle of 42-53^{o} relative to the Sun-line. It should be noted that this is a rather large pitch angle and may raise telecommunication issues due to the relative alignment of the Earth and the plane of the sail.

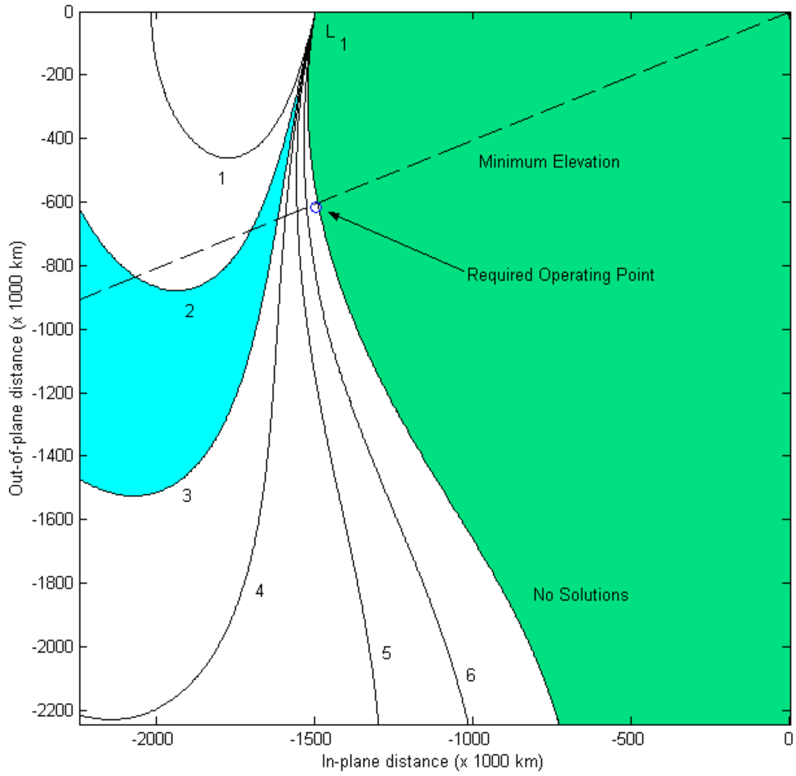

Figure 3.3 Solar sail performance requirements for displacements below ecliptic plane (- - - - minimum elevation for al-year south pole visibility, o – operating point 615,000 km below L_1)

Contour	Sail loading ($g\ m^{-2}$)	Sail acceleration ($mm\ s^{-2}$)
1	60	0.15
2	40	0.23
3	30	0.30
4	25	0.36
5	15	0.61
6	5	1.82

Table 3.1 Solar sail performance contours

Sail loading ($g\ m^{-2}$)	Contour	Sail acceleration ($mm\ s^{-2}$)	Sail pitch angle (deg)	Displacement distance –z (km)
30	3	0.30	-52.9	653,300
40	2	0.23	-42.0	687,400

Table 3.2 Solar sail performance data at new operating point