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SOLAR SAIL GEOSTORM WARNING MISSION DESIGN

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ABSTRACT

In the solar sail community, a Geostorm warning mission is regarded as one of the best choices for the first application of solar sail technology. In a Geostorm warning mission, a spacecraft is placed between Sun and Earth so that any harmful solar events (coronal mass ejections) are detected before Earth experiences them. Radio signals sent to Earth from the monitoring station provide a warning period, since electronic signals travel faster than solar wind. The closer the location of the monitoring station is to Sun the more warning time is gained. Such a station is required to maintain the Sun-Probe-Earth lineup geometry approximately for the duration of the mission. The maintenance of such an orbit location will entail prohibitive amounts of propellants with rockets, chemical or electric propulsion systems. A solar sailcraft is ideally suited for this purpose because it uses no fuel and simply needs to set the sail to face the Sun fully at all times. Practical aspects of designing this mission are discussed in this paper.

INTRODUCTION

The concept of a Geostorm warning station came about with the understanding that solar pressure, by imparting a radially outward force, in effect reduces the solar gravitational acceleration on a sailcraft. In this reduced pseudo-solar-gravity field the motion of a sailcraft around the sun is made slower, which enables us to place a sailcraft that stays inside of Earth orbit but revolves about the sun at the same rate as Earth. Thus

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satisfying the orbital requirements of a Geostorm warning mission. These orbits are named as Sub-L1 orbits in this paper.

This conceptually simple idea of "placing a sail-craft say at X AU and face the sun" actually is more complicated in real mission planning. This is caused by the relatively immature sail technology available, budgetary constraints and the desire to avert total loss of mission in a risky first attempt. *A* currently envisioned "low-cost" mission starts with an injection into an Earth-Sun L1-halo orbit using piggyback launch. In the event that the sail fails to function in that orbit, the sail module will be discarded and the monitoring mission is performed at L1 albeit with a somewhat shorter warning time. After the confirmation of the sailing capability, the sailcraft is maneuvered into a Sub-L1 orbit using the sail thrust. This scenario includes several complicating factors, as shown below.

1) Sail technology limitations: An early technology sail is expected to give small net sail acceleration at 1 AU (a_0) possibly below 0.3 mm/s^2. The implication of a small a_0 is that the solar distance at which it can keep pace with Earth motion is very close to 1 AU; e.g. 0.95 to 0.98 AU. In that Sun-Probe-Earth geometry, the gravitational perturbations of Earth and Moon are significant together with some perturbations of Venus so that a N-body sail trajectory optimizer is required. Additionally, the sail attitude attainable with confidence is 45° or less in cone angle (angle between sail normal and Sun direction). This in turn creates significant thrust inefficiency and complicates sailing algorithms formulation.
2) Cost constraints: Current NASA vision of the mission is to perform the mission with a cost of less than $100 M. This dictates a low cost launch option such as *a* piggyback and imposes a severe mass restriction, low a_0 (small sail area) and launch flexibility.
3) Salvaging option: The thought that the sail deployment may fail prompted the need to start a sail mission from Sun-Earth L1 halo orbit. In the event that sail operation were not successful the spacecraft can remain in L1 halo orbit and still be useful as a Geostorm warning station. This dictates a chemical rocket transfer to a GENESIS-like[4] halo orbit first and then a sail-driven transfer from the halo orbit.
4) Sub-L1 orbit maintenance: Similar to an Sun-Earth L1 libration point, a Sub-L1 point is inherently very unstable and requires some level of sail steering to limit the sailcraft drifts to within an acceptable domain during the mission duration of one or more years. Since the "SAIL"[1], the trajectory optimization software authored by C.G. Sauer, is formulated with minimum-time steering law for given boundary conditions, it is not ideal for assessing the orbit maintenance requirements.

This paper presents first the a_0 (sail acceleration level at 1 AU) requirements for the Geostorm stations located at various solar ranges. Subsequently, the paper focuses on a 0.98-AU Sub-L1 station and discusses the orbit maintenance methods and issues. Finally, a description of the currently envisioned mission[2] encompassing GTO to (L1-

halo) to (Sub L1) and (Orbit maintenance) is described. The resulting thrust profile and thoughts on trajectory optimization and navigation are also included.

SAILCRAFT PERFORMANCE ASSUMPTIONS

Generation and maintenance of sailcraft orbits are affected by assumptions involving astrodynamics, sail hardware performance characterization and the sail-steering law. This paper dwells mainly on orbital aspects of Sub-L1 stations and ignores the very important but poorly understood or modeled sail hardware properties.

Astrodynamic Assumptions

The analyses to follow are based on a N-body formulation including Sun, Earth, Moon and Venus. Sub-L1 point, when near Earth, is very sensitive to various perturbations and requires accurate dynamic models. As stated earlier, current sail technology allow a delivery of a station not far from Earth and this assumption is necessary.

Solar Sail Performance Assumptions

In order to clearly separate the astrodynamic effects from the effects of complex sail properties, a perfectly reflecting sail based on single number a_0 is used throughout the paper. Relationships between the sail technology (often represented by sail loading), the size of the sail, its optical properties, shape distortion, and time-dependent degradations are complex and are ignored. Table 1 is a representative expectation of the state-of-art for a near term geostorm mission. Recent 0.98 AU geostorm warning station design[2] is based on the 14 g/m^2 technology assumption and a net spacecraft mass of 50-100 kg.

Table 1: Example Sailcraft Acceleration vs. Net Spacecraft Mass

Assumption: Sail loading = 10 g/m^2, Sail Area = (100 m)^2, Sail reflectivity = 0.8	
Spacecraft (Net) Mass (kg)	a_0 (mm/s^2)
50	0.539
75	0.462
100	0.404
Assumption: Sail loading = 14 g/m^2, Sail Area = (100 m)^2, Sail reflectivity = 0.8	
50	0.426
75	0.376
100	0.337

Solar Sail Steering Law

Up until a few years ago, applications of solar sailing have been in the heliocentric inter-planetary arena where little concern existed for the N-body effects or small-scale station keeping. The main thrust then was to get to the target the soonest

possible. So it is natural that the sail trajectory code "SAIL" is a minimum time trajectory optimizer. To facilitate the design of geostorm monitoring missions, modifications are made to include N-body and the boundary condition format convenient here. Boundary points in this paper are often relative to Earth in a Sun-Earth rotating coordinate. For example, to stay at 0.98 AU between Sun and Earth means that (Xs=-0.02 AU, Ys=0, Zs=0, and Vxs=Vys=Vzs=0), where subscript "s" implies the state in this rotating coordinate frame. The code is adequate for a sailing transfer, say from L1-halo to Sub-L1 in minimum time, but is not ideal in creating the most effective station keeping thrust profile. Nonetheless, some interesting Sub-L1 maintenance strategies are created using SAIL.

SAIL a0 REQUIREMENT vs. SOLAR RANGE

If Earth orbit were circular and without Moon and Venus perturbations, a single Sub-L1 location as a function of a_0 can be computed in a similar manner that Sun-Earth L1 is conceived in a restricted three-body analysis. Even so, one must note that differing solar gravity works on Earth and on the sailcraft in that formulation. In reality, the Sub-L1 location will depend on the specific date (or where Earth is) and a_0 and cannot stay stationary, even if sail is normally facing the sun perfectly all the time.

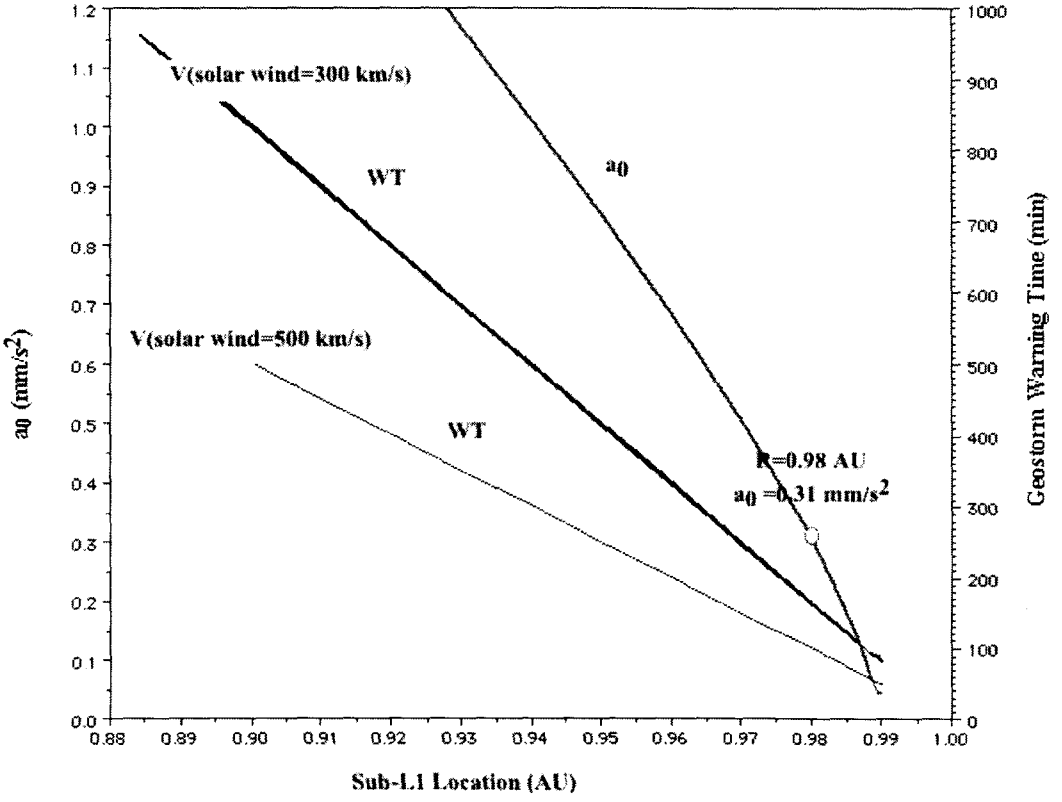


Figure 1: a_0 and Warning Time vs. Sub-L1 Solar Range

The data generated in Figure 1 assumes that the Sub-L1 point condition is satisfied on 2009 February 24th and thirty days later. In other words, the a_0 given below allows us to stay in an orbit loop starting and ending at the desired Sub-L1 location. For a 0.98-AU Sub-L1 station, a_0 of 0.31 mm/s^2 is indicated. The geostorm warning time is also given in the figure for the reader's reference. There, the solar wind speeds of 300 km/s and 500 km/s are assumed.

0.98-AU Sub-L1 ORBIT MAINTENANCE

The discussions from here on will be to promote an understanding of a 0.98-AU Sub-L1 mission. The initial mission requirement would be to deliver a sailcraft to 0.98 AU between Earth and Sun and with a zero orbital velocity relative to Earth in the Earth-Sun rotating frame. In practice, a purely Sub-L1 condition is not needed or desired because of various (communications etc.) operational problems arising from such a geometry. For the purpose of geostorm warning, station drift from Sub-L1 within a few hundred RE (Earth Radii) are probably acceptable but it will be educational to understand how we could and could not control to stay near the Sub-L1 point. This understanding may have interesting implications on the possibility of formation flying using multiple sailcrafts. Unlike other propulsion systems where it is possible to apply the thrust in all directions, sail imparts force only in a radially outward direction. This is a handicap of solar sailing and causes loss of timely controls and undesirable delay in flight time when the geometry is poor.

Orbit Maintenance Methods

In an attempt to restrict the sailcraft excursions from the Sub-L1 point, two ways of orbit confinements are tested. This is conducted within the current capability of the SAIL code. The methods and the results are shown below.

Method 1-Constant Sail Angle: This is a method conceived by C.G. Sauer[3] and aimed to confine the excursion from Sub-L1 using a fixed pair of sail cone & clock angles for a given period of time. Where cone is an angle between sail normal and Earth-Sun line, and clock is the clockwise angle with ecliptic north as zero reference. This strategy is convenient in that sail attitude relative to sun may be fixed for a considerable length of time although the size of the dispersion envelope may not be very small. Figure 2 is an illustration of the result using this method. In the first loop (Loop-1) orbit, three control variables (flight time, cone and clock angles) are used to bring the sailcraft back to the starting position, i.e. **X**s=(-3.e6, 0, 0) km relative to Earth. Since sail acceleration is fixed at 0.31 mm/s^2, the time that can return the sailcraft to the starting position is the minimum time required in a SAIL minimum-time steering law. When the sailcraft arrives at the Sub-L1 point, the relative velocity to Earth in the Erath-Sun rotating coordinates will no longer be zero. This is because we have only three degrees of freedom for targeting. In the second loop (Loop-2), the starting velocity is equal to the end velocity of the Loop-1. This targeting procedure is repeated for Loop-3 and Loop-4. Note that in Loop-3, the orbit loop <u>could not be closed</u> but at the Sun-Earth line crossing (i.e. Ys=0), Xs is inside of 0.98 AU, favorable for geostorm warning purpose. In this 3.3-year mission time the

sail angles has been revised about every 300 days. As indicated in the figure, cone angles are small but had to be biased away from zero to stay near Sub-L1. The clock angles stayed close to 90° indicating that thrusting is in near ecliptic plane. The excursions from the central point is as indicated in the figure. The drift is mainly toward Sun (-23.7 RE) and in the anti-earth-velocity direction (-57 RE).

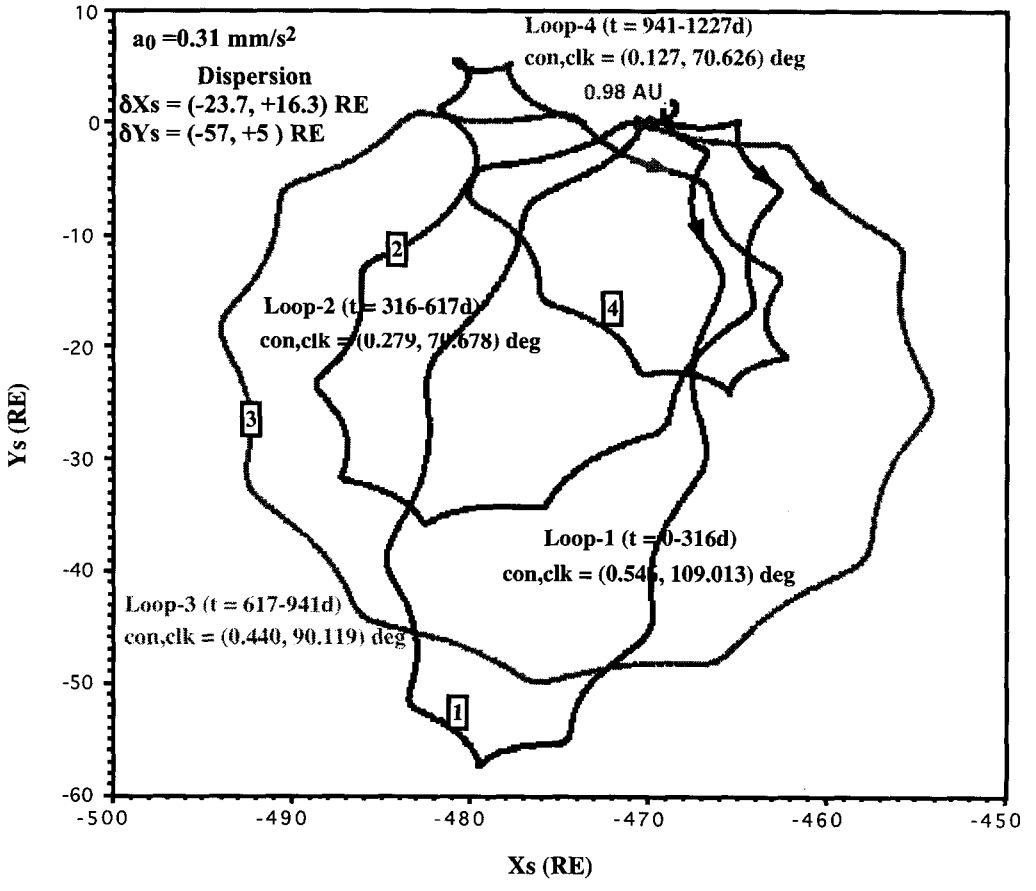


Figure 2: Sub-L1 Orbit Excursions Using Fixed Sail Orientation

Method 2-Optimal Steering: Like the previous case, this method also aims to confine the excursion from Sub-L1 but uses a continually varying sail cone & clock angles. In this case, the degree of control variables is sufficient to match the velocity (zero relative to Earth in a rotating frame) as well at the end of each loop. Figure 3a shows the first nine loops of orbits and the 11th loop, each with the identical sailcraft state at the beginning and end of a loop. The anticipation was that this procedure could be repeated indefinitely, because each loop has nearly identical initial and final condition for each loop and the Sun & Earth relative geometry. But this expectation was not realized after the Loop-9. Figure 3a shows the first 9 loops, indicating maximum excursion less than 3.1 RE. By dictating that the sailcraft return to the Sub-L1 point in about 30 days, the size of a loop is controlled to be small. Contrary to one's expectation, orbit loops are not overlapping on

top of one another but spread like a flower petal without special order. This I believe is caused by the varying solar range of Earth affecting the thrust magnitude and wobbles induced by the moon. Acquisition of a similar 10th loop was unsuccessful. A solution could be obtained only when the loop became a 165-day loop having sailcraft excursion extending to 63 RE.

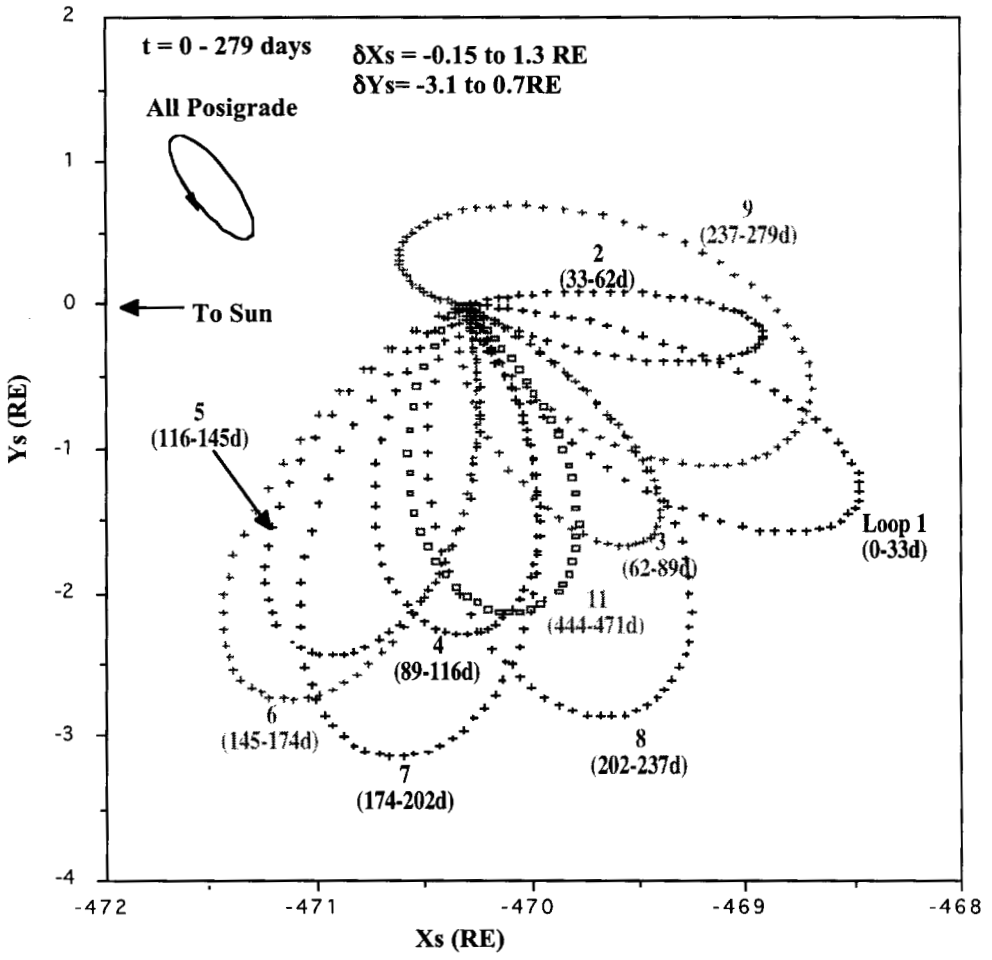


Figure 3a: 0.98-AU Sub-L1 Station Keeping Using Minimum-Time Steering (Loops 1-9 and 11)

This is illustrated in Figure 3b. The suspected reason for the situation is that a sailcraft acceleration level of 0.31 mm/s^2 is insufficient to place the station 0.02 AU in front of Earth and to keep pace with Earth motion when Earth is near its perihelion (beginning of 10th loop). Earth-Sun range varies from 0.983 to 1.017 AU. One might expect a 10th multi-loop figure to emerge but failed in that effort as well. This might be the nature of the minimum-time steering law, but answers to this will have to wait for further studies. Perhaps one needs to create other kind of steering laws, which are tailor made for station

keeping and tested. Once the 10th loop difficulty is overcome, 30-day Loop-11 can be resumed, as seen in Figure 3a.

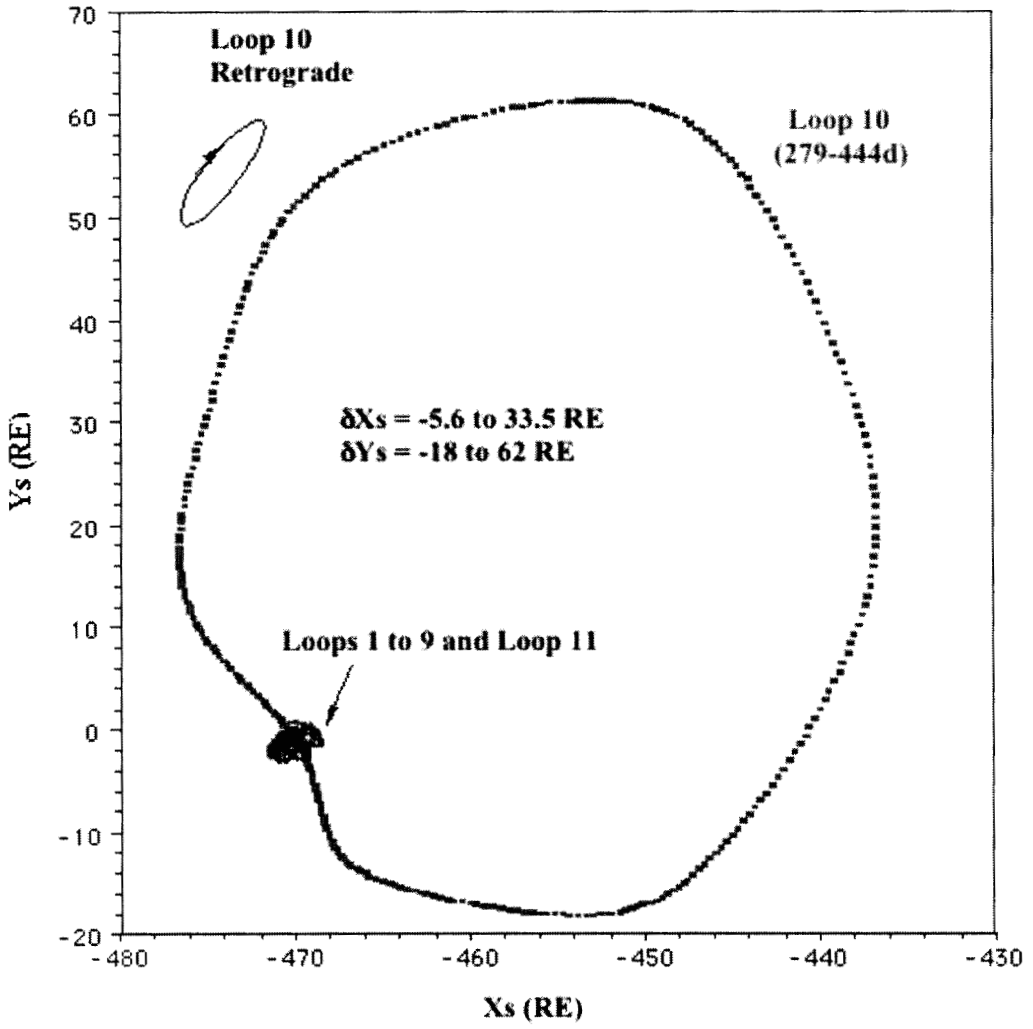


Figure 3b: 0.98-AU Sub-L1 Station Keeping Using Minimum-Time Steering (Loops 1-11)

The cone angle history corresponding to Figures 3a and 3b is given in Figure 4. Cone angles remain small most of the time but a spike-like cone angle change is observed at the beginning of each loop. The velocity requirement at end points, i.e. for sailcraft to co-circulate about Sun exactly with Earth is creating a stressful steering profile at the beginning of each loop.

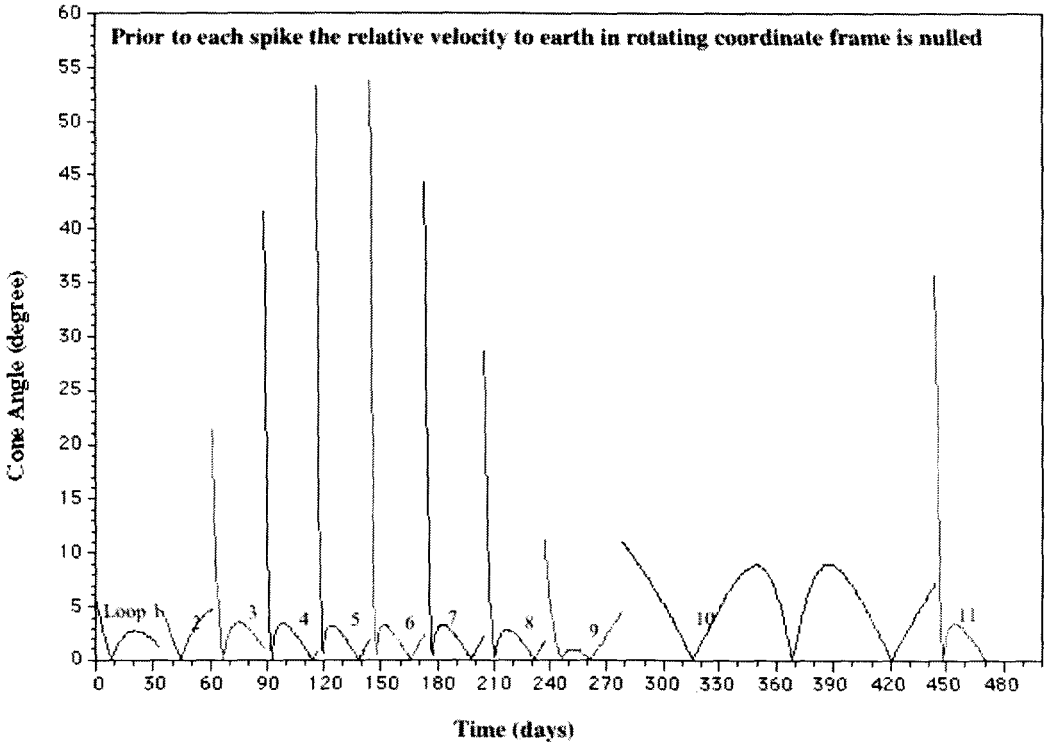


Figure 4: 0.98-AU Sub-L1 Station Keeping Cone Angle History

0.98-AU NASA-NOA GEOSTORM WARNING MISSION DESIGN

Mission Concept

In 1999, a geostorm mission concept was born out of the combined needs of the NASA and NOAA. For NASA it was to perform a solar sail technology validation mission (New Millennium ST-5 mission) and NOAA was expecting to improve the solar weather prediction capability[2]. As stated in the introduction, the concept contained a mission salvaging option dictating the mission to have three stages: 1) A chemical injection into a Earth-Sun L1-halo orbit from LEO or from a piggyback ride on a GTO (Geosynchrnous Transfer Orbit), 2) A sail driven transfer from L1-halo to Sub-L1 point, and 3) Maintaining the near Sub-L1 orbit for the duration of 1-3 years. Descriptions of these mission phases are provided in the following.

LEO or GTO to L1-Halo Orbit Transfer

This phase of mission starts with a transfer from a 200-km Earth parking orbit to a Halo orbit similar to the one used for GENESIS[4] (NASA Discovery 4 Mission). Martin Lo[4] provided an example LEO-Halo transfer orbit. The assumed departure from LEO is October 10, 2008 and the Halo orbit injection occurred on January 25, 2009. The total transfer time is 107.6 days. The breakdown of the ΔV required is summarized in Table 2. If a piggyback on GTO option were to be used, a very complex maneuver scenario is

anticipated. If the GTO were a perfect match for the unconstrained GTO-L1 transfer, the ΔV from GTO-L1 is simply equal to the ΔV difference between the LEO-L1 and the LEO-GTO (2.522 km/s). Thus, the ΔV for a GTO-L1 transfer is 0.686 km/s, as indicated in Table 3. However, this is extremely unlikely. The facets of available GTO parameter offsets from the perfect GTO are many; perigee altitude offset, wrong inclination, nodal line offset, apsidal line offset to name a few. Even if these could be corrected with some ΔV, it is likely that the timing will be off entailing a long waiting in earth orbit. Then a long-term exposure to the Van Allen radiation will become an issue, forcing perigee raise maneuvers creating more ΔV penalty. Without the knowledge of a particular piggyback GTO characteristics and the specific date/time, it is very difficult to estimate ΔV penalties reliably. ΔV penalties ranging from 200 to 450 m/s, shown in Table 3 is based on a brute force preliminary analysis. With Piggyback, on board ΔV is much bigger and the spacecraft will be larger. More over, the mission operations scenario will be complex and burdened with many uncertainties.

Table 2: LEO-L1 Transfer ΔV Summary

Event	ΔV (km/s)
	Deterministic
LEO Departure (2008/10/10)	3.208
DSM-1 (@78d	0.010
L1-Injection @107.6d	0.006
	Statistical
Injection Error (Assume Star/30BP Motor)	0.15
Station Keeping at L1	0.02
Misc.	0.01
Total ΔV/(S/C ΔV)	3.404/0.196

Table 3: GTO-L1 Transfer ΔV Summary

Event	ΔV (km/s)
	Deterministic
GTO to L1	0.702
	Statistical
GTO-L1 gravity loss	0.07
Station Keeping at L1	0.02
GTO-L1 penalties	0.2-0. 5
Total S/C ΔV	0.992-1.292

L1-Halo to Sub-L1 Transfer

After arriving at L1-halo and confirming that the sail deployment is successful, solar sailing will be initiated to go to Sub-L1 point. In an example to follow, the departure time is arbitrarily set 60 days after the L1-Halo orbit injection. As shown in Figure 1, a_0 required for a 0.98-AU Sub-L1 station is 0.31 mm/s^2. The design of the Halo to Sub-L1 orbit transfer is based on 1) a perfect sail model and 2) the minimum-time steering law. Current sail technology predicts uncertain performance when the sail is tilted more than 45 degrees away from Sun. So, two types of trajectories are generated, namely without and with the 45° cone angle constraint. The resulting orbits are shown in Figure 5 and the corresponding thrust profiles (cone & clock) in Figures 6a and 6b.

Figure 5 contains: 1) the ballistic orbit from LEO to L1-Halo orbit, 2) the Halo Orbit, 3) the orbit from Halo to Sub-L1 without cone angle constraint, 4) the orbit from Halo to Sub-L1 with 45 degree cone angle constraint, 5) the runaway path from Sub-L1 if cone angle were fixed at 0 degree, and 6) a 180-day closed loop about Sub-L1 representing a mode of station keeping. Note that the Sub-L1 point as shown is biased off

the Earth-Sun line (i.e. Ys= -40 RE) in order to satisfy certain communication's requirement.

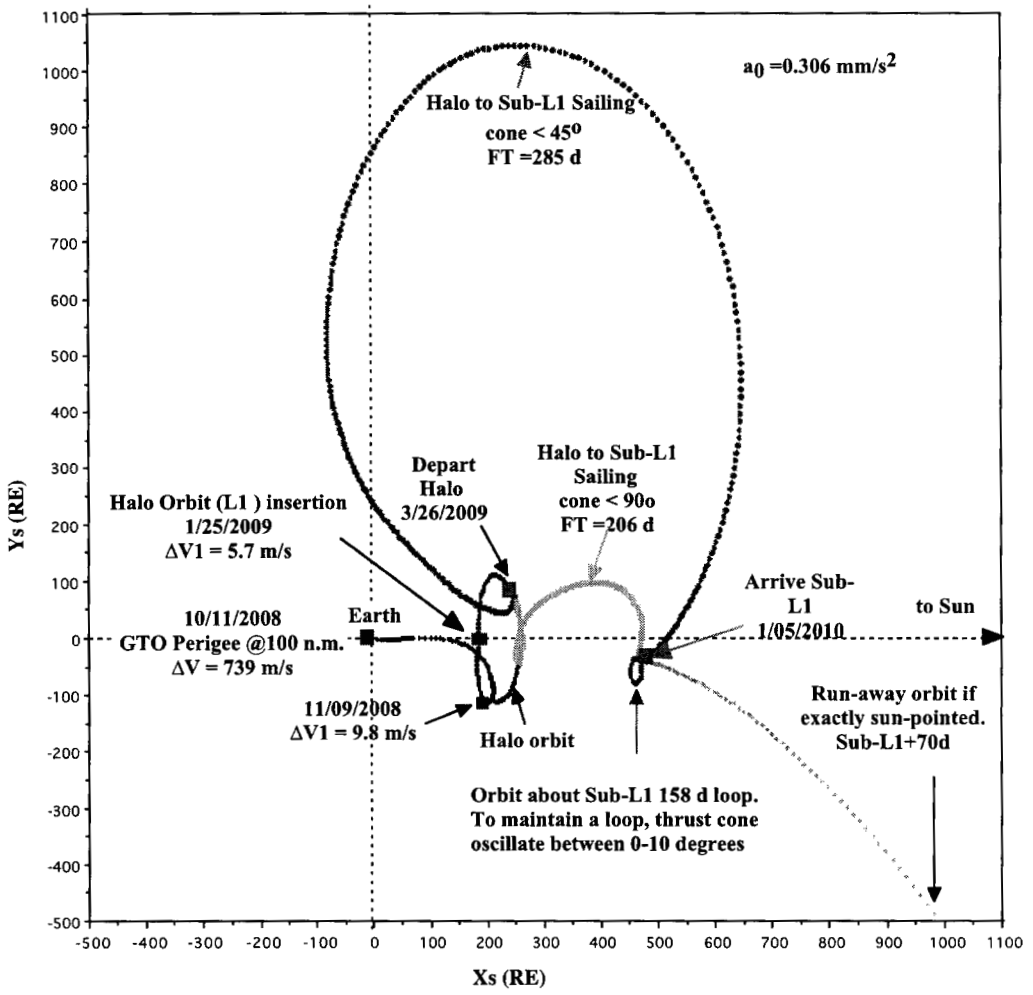
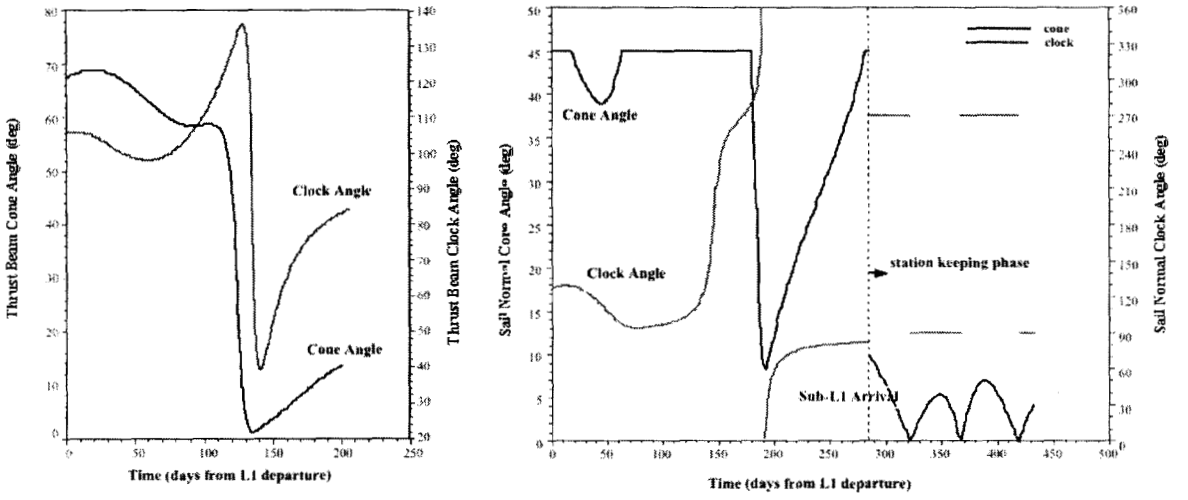


Figure 5: 0.98-AU Sub-L1 Geostorm Monitoring Mission Orbits

The difference in the sailing path between the unconstrained and constrained cone angle pointing is quite prominent for the L1-Halo to Sub-L1 transfer. Without cone angle constraint, the sail path is an efficient small loop. With the constraint, a lack of in-ward thrust capability drives the craft to tread into the unwanted region of space behind Earth. The net result is that it costs an extra 80 days in flight time compared to the unconstrained case. The sail cone angle can be as large as 70 degrees in the unconstrained case as seen in Figure 6a.



a: Unconstrined Cone Angle Sailing **b: Constrined Cone Angle Sailing**

Figure 6: 0.98-AU Halo-Sub L1 Transfer Sail Angle History

Station Keeping About Sub-L1

After arriving at Sub-L1, a fast runaway from Sub-L1 is seen unless the sail angle is adjusted to counteract various perturbations, including unpredictable erroneous sail force. However, the effects of un-modeled (stochastic) error sources on station keeping cannot be addressed in this deterministic optimization algorithm. For the purpose of a geostorm warning, a large station excursion up to 50 RE or more from the Sub-L1 is perhaps acceptable, then the fixed cone & clock angle of **Method-1** discussed earlier is simple and convenient and requires revisions at about 300-day intervals. The **small** 180-day loop shown in Figure 5 is generated using the continuous minimum-time steering law (**Method-2**) and represents a tightly confined station drift control. However, the anticipation is that every half a year, this tight confinement capability will be lost because of the eccentric Earth orbit and inherent defective nature of the sail force. This is because, unlike conventional expendable propulsion system, the sail lacks the freedom to vary the thrust magnitude (fixed by the solar range and sail surface properties) or to provide the thrust in any direction (radially outward always). It appears that the "on time" guidance capability expected of conventional thrusting may not be attainable with sail. Depending on the orbit geometry at the time of thrust revision, one may have to wait for a long time for the sailcraft to arrive at a favorable geometry to regain its control authority. The Loop-10 in Figure 3b is an example of this argument.

SUMMARY

This paper examined the feasibility of conducting a geostorm monitoring mission including sail orbit transfer and the methods of station keeping after arriving at Sub-L1. Assuming that the current sail technology level is represented by the sail loading range of

10-14 g/m2 and a sail size of 10,000 m^2, a small (<100 kg bus) monitoring station will be close to Earth at a range of 0.97 to 0.98 AU from the sun, requiring a N-body formulation including Sun, Earth and Moon. The results of this study indicate that, by setting the sail normal slightly biased away from the sun, a Sub-L1-Halo station can be maintained for a period of about 300 days without any interim adjustments (only if the sail is perfect). On the other hand, a tightly confined Sub-L1-Halo orbit is possible only for a period of about half a year but is difficult during the other half. Based on the station keeping analysis carried out in this paper it is anticipated that a conventional guidance strategy of "nudging back to nominal" is unlikely to bring satisfactory results.

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