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THE TPF MISSIN AT L_2

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Abstract

The Terrestrial Planet Finder (TPF) is one of the center pieces of NASA's Origins Program. The goal of TPF is to identify terrestrial planets around stars nearby the Sun. For this purpose, a space-based interferometer with a baseline of approximately 100 m is required. To achieve such a large baseline, a distributed system of five spacecraft flying in formation is an efficient approach. Since the TPF instruments need a cold and stable environment, a halo orbit about L_2 is ideal. First, we describe formation flight near the Lagrange point is feasible for the TPF mission. Second, we propose a novel approach for human servicing of Lagrange point missions by placing a Lunar service station in an Lunar L_1 orbit. The TPF spacecraft can be transferred to a Lunar L_1 orbit in a few days and requires relatively little delta-V. This efficient transfer results from the system of low energy pathways connecting the entire Solar System generated by the Lagrange points. The halo orbits are the portals of this Interplanetary Superhighway. A Lunar Station at the L_1 portal, in addition to servicing missions from the Sun-Earth Lagrange points, may play an even more important role in the future development of space.

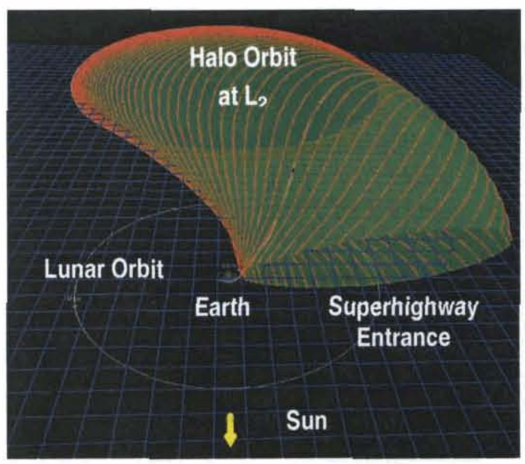

Figure 1. The TPF halo orbit and transfer trajectory is selected from a family of trajectories on the special surface consisting of free transfer trajectories emanating from the halo orbit about L_2. The gray orbit around the Earth is the lunar orbit. The yellow arrow points towards the Sun.

1.Introduction

1.1 The TPF Mission

The existence of life beyond Earth is a fundamental question for humanity. To answer this question is one of the key goals of NASA's Origins Program. The TPF Mission (Terrestrial Planet Finder [1]) is a center piece of the Origins Program to identify Earth-like planets around stars nearby the Solar System where there is potential for life. For this purpose, a space-based infrared interferometer with a baseline of approximately 100 m is required. To achieve such a large baseline, a distributed system of five spacecraft flying in formation is an efficient approach. The current concept has four 3.5 m diameter telescopes, each with its own spacecraft, and a central spacecraft that collects and combines the beams. Since the TPF instruments need a cold and stable environment, near Earth orbits are unsuitable. Satellites in Earth orbit are exposed to the radiation of the Earth and the Moon. Furthermore, the thermal cycling from the frequent encounter with Earth's shadow creates a thermally unstable environment which is unsuitable for infrared missions. Two potential orbits have been identified: a libration orbit near the L_2 Lagrange point and a SIRTF-like heliocentric orbit. In this paper, we focus on the first case: an orbit near L_2 (see Figure 1).

The formation flight problem near the Lagrange points is of great interest. The first constellation in ring formation in an L_1 quasihalo orbit was constructed by Barden and Howell [2] and Barden [3]. Scheeres [4] demonstrated control strategies which looked extremely promising. However, all of these constellations were designed in a loose formation where the shape of the formation is not strictly controlled. In the latter half of FY2000, the Lagrange Committee was formed to study the feasibility of formation flight near L_2 for the TPF mission. Several simulations were performed indicating for the first time that formation flight near L_2 is possible for a TPF-like mission. In this paper, we provide the first simulation of the actual TPF mission orbits about L_2. The main result is that formation flight near L_2 is dynamically possible for the TPF Mission. More specifically, transfer, deployment, and linear control around a nonlinear baseline libration orbit near L_2 is adequate for the TPF Mission.

1.2 Advantages of a Mission Near L_2

There are several advantages to a libration orbit near L_2. Such orbits are easy and inexpensive to get to from Earth. Moreover, for missions with heat sensitive instruments (e.g. IR detectors), libration orbits provide a constant geometry for observation with half of the entire celestial sphere available at all times. The spacecraft geometry is nearly constant with the Sun, Earth, Moon always behind the spacecraft thereby providing a stable observation environment, making observation planning much simpler. Since libration orbits will always remain close to the Earth at roughly 1.5 million km with a near-constant communications geometry, the communications system design is simpler and cheaper. The transfer from the Earth to a libration point orbit is cheap and easy, this has two advantages. First, libration orbits require less energy to achieve, hence slightly more mass may be delivered there than to heliocentric orbits. Second, in the event of a failed spacecraft, a replacement spacecraft can be quickly and easily sent to restore the constellation. For a SIRTF-like heliocentric orbit, this could be very costly and may be prohibitive in some instances. Furthermore, libration orbits are excellent staging locations for human presence in space. In sum, it is feasible for human servicing of missions in libration orbits, but extremely difficult and costly to do so in heliocentric orbits.

1.3 Overview of the Simulations

We model this problem with the Restricted Three Body Problem (RTBP). Solutions within this model are easily moved to the full N-body model with JPL planetary ephemerides. Previous work (see [5]) indicates that the results and conclusion of the simulations are preserved under this model transfer.

In order to study such a complex problem, an interactive simulation environment with constant visual feedback is extremely powerful and convenient. Some of the issues, such as the changing scale of the problem, provide challenges to both the numerical as well as the graphical computations. For instance, the baseline halo orbit has y-amplitudes on the order of 700,000 km. Where as the diameter of the formation is a mere 100 m. Another example is the computation and visualization of the manifolds. Interpolation of points on the manifold for trajectory computations require highly accurate numerics; whereas the interactive visualization requires fast computations of the points on the manifold to support real-time interactions. The successful management of these conflicting requirements is very important to the these simulations.

From the dynamical point of view, the TPF Mission can be broken into four scenarios:

Launch and Transfer to L_2 Halo Orbit,
Deployment into Initial Formation,
Pattern Maintenance,
Reconfiguration into New Formation.

In this paper, we describe the simulations performed for each of the scenarios. We describe the control algorithms and estimate the ΔV required for each of the scenarios. The formation pattern chosen for this study is that of an N-gon as described in the TPF book [1].

2. Orbital Structures Near L_2

For our simulations, all trajectories are integrated with the influence of the planets and the moon using the JPL ephemeris models. However, in order to better understand the possible motions about L_2, it suffices to consider the motions of the RTBP. Experience shows that solutions from the RTPB are readily moved into the full ephemeris model while preserving their salient features. We provide a brief description of the RTBP next. An excellent exposition of the problem is provided by Szebehely [6].

The RTBP describes the motion of a massless particle (spacecraft) in the gravitational field produced by two primaries (e.g. Sun and Earth). In a synodical reference system, the equations of motion can be written as (see [6]),

$$x''-2y'=\Omega_x,$$
$$y''+2x'=\Omega_y,$$
$$z''=\Omega_z,$$

where

$$\Omega(x,y,z)=\frac{1}{2}\left((1-\mu)\ r_1^2+\mu\ r_2^2\right)+\frac{1-\mu}{r_1}+\frac{\mu}{r_2}$$

The RTBP has five libration points, two of them, L_4 and L_5 form an equilateral triangle with the primaries, the other three are collinear with y=z=0. If x_{Lj} denotes the value of the x coordinates of L_j, j=1,2,3, we will assume that the positions of these points and the primaries are such that

$$x_{L2} < x_{m2} = \mu - 1 < x_{L1} < x_{m1} = \mu < x_{L3}.$$

For small values of μ, both $\mu - 1 - x_{L2}$ and $\mu - 1 - x_{L1}$ are $3^{-1/3}\ \mu^{1/3} + O(\mu^{2/3})$ and $x_{L3} = 1 + O(\mu)$.

We now examine the phase portrait around the collinear equilibrium point L_2 using what is called the reduction to the central manifold (see [7] and [8] for more details). Figure 2 below depicts a typical Poincaré section of an energy surface near L_2. This is generated by marking where an orbit near L_2 pierces the XY-plane with Z'>0. The symmetry of the plot is a consequence of one of the natural symmetries of the problem. There are three fixed points corresponding to three periodic orbits. The central fixed point corresponds to the vertical Lyapunov orbit. The two fixed points on the side correspond to the two halo orbits on this energy surface. We note that around the halo orbit, are various rings generated by quasiperiodic orbits around the halo orbit. Quasiperiodic orbits live on tori in the energy surface which when intersected with a plane, produce the rings that we observe around a halo orbit. Similarly, there are quasiperiodic orbits around the vertical Lyapunov orbit.

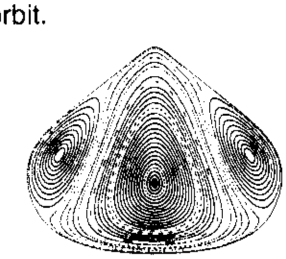

Figure 2. Poincaré map on the center manifold in the vicinity of L_2.

This means that around the halo orbit, there are families of quasiperiodic orbits of the same energy from which we can construct trajectories for the formation. However, the problem is that the energy surface also has unstable components. Hence, these quasiperiodic orbits are inherently unstable, just like the halo orbits, and must be maintained. But, also like halo orbits, the maintenance required is inexpensive and infrequent. With this portrait of the phase space region around the halo orbit, we describe next formation flight near L_2.

3. TPF Mission Simulation Scenarios

3.1 Two Orbital Strategies for TPF

Two basic orbital design strategies for TPF were considered: the Nominal Orbit Strategy, and the Baseline Orbit Strategy. In the Nominal Orbit Strategy, each spacecraft follows its own predefined orbit, called the Nominal Orbit. When the spacecraft deviates significantly from the nominal orbit, control via thruster burns are used to retarget the spacecraft back to the nominal trajectory. In the Baseline Orbit Strategy, a Baseline Orbit, such as a halo orbit, is first computed. The formation trajectories are defined relative to the Baseline Orbit. All controls are targeted to place the spacecraft back onto the relative orbits. The Baseline Orbit approach is the sensible strategy to adopt, since the TPF formation changes several times daily. Hence rigid nominal orbits for the formation cannot even be defined rigorously. Note that a Baseline Orbit may have no spacecraft on it.

3.2 TPF Mission Phases

TPF Launch and Transfer Phase

For this simulation, we assume the spacecraft starts in a typical 200 km altitude parking orbit near Earth at 28.5 deg inclination and a halo orbit is used as the Baseline Orbit. At the appropriate time, the spacecraft performs a major maneuver of about 3200 m/s. This injects the spacecraft onto the stable manifold of the halo orbit to begin the Transfer Phase. The transfer trajectory is designed by using an orbit of the stable manifold with a suitable close approach to the Earth.

TPF Deployment Phase

It is assumed that all the spacecraft of the formation reach the Baseline Orbit in a single spacecraft (the Mothership). This begins the Deployment Phase. The five satellites are maneuvered to reach their initial positions on the different points of the 20-gon (100m diameter, see Figure 3 and 4.) at the same time. The Deployment Phase can last several hours. In the simulations to be described in the following sections the deployment time varied between 1 and 10 hours.

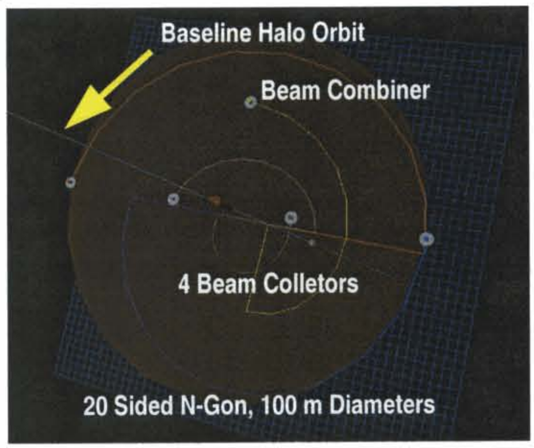

Figure 3. TPF configuration along baseline halo orbit.

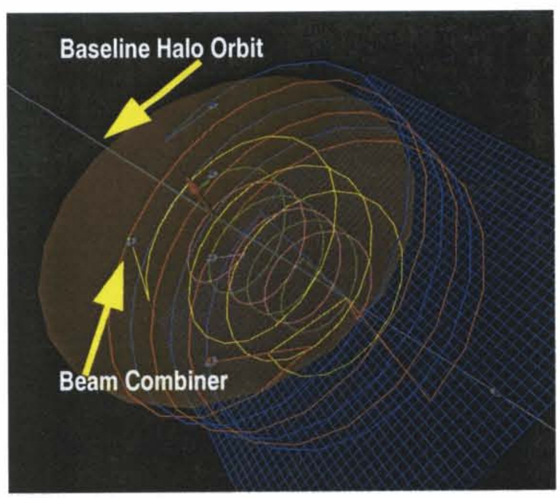

Figure 4. TPF repoints after 3 revolutions pointed at a fixed star.

The TPF Formation spiraling around the Baseline Halo Orbit (diagonal trajectory). The semi-transparent orange 20-gon is the 100 m diameter of the simulated aperture of the interferometer. The red arrow normal to the 20-gon at its center is the direction of the star system currently being observed. The spacecraft and their orbital trails are color coded. The combiner spacecraft and its trail are yellow. In Figure 3, the formation is just starting an observation. In Figure 4, the formation has made an observation for several revolutions and is in the process of reconfiguring for a new observation. The mothership is barely visible at the lower right hand corner on the halo orbit.

Since the X-amplitude of the halo orbit is around 700,000 km, a 100 m formation around the halo orbit cannot be seen when the halo orbit is viewed as a whole. Figure 5 provides an exaggerated view by blowing up the diameter of the formation from 100 m to 100,000 km. At this range, the nonlinear forces do become significant. Nevertheless, the LTool differential corrector used to compute both cases had no difficulty holding onto the formation. Figure 6 is a closeup view of the formation.

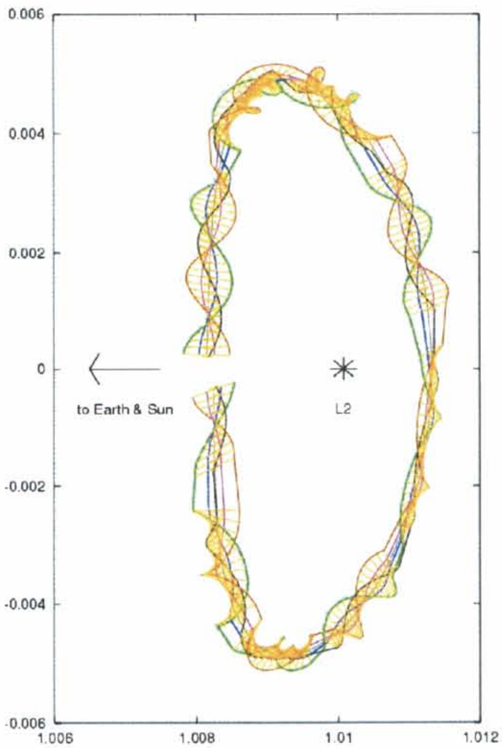

Figure 5. TPF formation exaggerated to a 100,000 km diameter around a halo orbit.

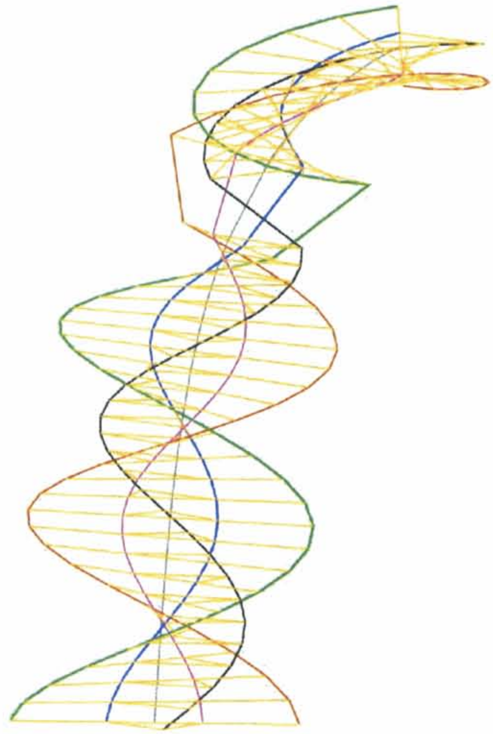
Figure 6. Close up view of the orbits of the exaggerated formation along the halo orbit at the center.

Pattern Maintenance Phase

Once the initial configuration has been established, the spacecraft will maneuver to follow the edge of the 20-gon to provide a suitable spin rate for the formation. The nominal spin rate used for this simulation is 360 deg every 8 hours. The period where the pattern is maintained is called the Pattern Maintenance Phase.

Reconfiguration Phase

Once sufficient data has been acquired for one star system, the formation will be pointed at another star for observation. Repointings occur during the Reconfiguration Phase (see Figure 4). The Reconfiguration Phase is similar to the Deployment Phase except the spacecraft do not depart from the same location (i.e. the Mothership).

4. Formation Flight Near L_2

The basic operational concept for the TPF mission is to spin the satellites in an inertial plane with the spin-vector pointed towards a selected star in the sky. For this purpose, we have taken the configuration of five spacecraft specified in the TPF book (see [1]) as represented in Figure 3. As explained earlier, to accomplish the mission, a Baseline Orbit approach seems best. We select an L_2 halo orbit as a Baseline Orbit. The satellites will be moving in nearby orbits, although none of them will be following the Baseline Orbit.

Following the basic TPF concept, we select a plane which translates in space according to the base orbit, but always pointing towards a fixed inertial position in the sky. Inside the plane, each one of the spacecraft follows the edges of a 20-sided N-gon. Essentially, three N-gons are used to build the formation. The outermost one, of diameter D, contains two spacecraft on phases 0 and 180 degrees respectively. The innermost one, of diameter D/3, is in phase with the outermost one and contains two more satellites located respectively on its phases 0 and 180. We have, in this way, the first four satellites aligned and evenly spaced. The remaining satellite, the collector, is located on phase 0 of a intermediate N-gon of diameter D/sqrt(3) which in turn has a phase of 270 degrees with respect to the other S/C. This configuration gives us the required geometry for TPF, with D equal to 100m (see Fig. 4).

During observational periods, the described formation has spin on the selected plane at the rate of R revolutions per day. A value of R = 3 is desired for the TFP mission. Since we are dealing with an unnatural motion, pattern maintenance maneuvers must be performed often to maintain this formation. According to the requirements of the mission, these maneuvers have to be done impulsively for each satellite when it reaches each one of the vertices of its corresponding N-gon in order to target the next vertex in P/N time, were P=1/R is the spin period of TPF in days.

Using the full JPL ephemeris, we have implemented this targeting procedure to obtain the estimates of the impulsive maneuvers, assuming that they are performed without error. The results show that they are practically independent of the baseline orbit selected. We will use a halo baseline orbit of about 100,000 km of Z-amplitude just to get an idea of the costs. The cost of the pattern maintenance in terms of ΔV/Day behaves linearly in D and quadratically in R. A suitable rule of thumb for a satellite in a 20-gon of diameter D meters and spinning at the rate of R revolutions per day, is the following:
Formation maintenance cost per satellite in cm/s per Day = 0.0023 *D *R *R.

So, for the TFP formation of diameter D, this is the cost for each of the outermost satellites, for each of the innermost ones, the cost is 1/3 of this value, and for the collector, the cost is 1/ sqrt(3) of the mentioned value. Also, an important point to note is that the magnitude of each one of the pattern maintenance maneuvers is independent of the vertex (phase) of the N-gon where the satellite is located.

Another important issue for the TPF mission is the estimate of the cost of the deployment of the formation, which in turn will give us preliminary estimates for the cost of reformation, this is the cost of changing the inertial pointing direction of the constellation.

Following again the Baseline Orbit approach, we assume that the satellites have been transferred to the baseline halo orbit and have to be deployed from a mothership. Once an initial 20-gon configuration has been selected for the formation, the basic approach consists again in targeting the final destination of each satellite with a desired transfer time, assuming that the departure is done from the base orbit. In the simulations we must assume that all the satellites reach their final destination (the corresponding first vertex of their nominal 20-gon) at the same time. At this time, the first pattern maintenance maneuver should be performed to maintain the formation. Otherwise, the satellites should be "stopped" at the vertex and wait for the first pattern maintenance maneuver; this increases the technical complexity, risk and cost of the mission. We note that for this purpose the satellites need not depart immediately from the mothership.
In the simulations we also assumed that the deployment is performed using two

impulsive maneuvers. The first one is for the departure of the satellite from the mothership in the base orbit and the second one is when the satellite reaches its destination in the N-gon. Because of the fact that just when reaching the first vertex of the N-gon we perform the maneuver to target the next one, the second part of the deployment maneuver is not well defined, in the sense that we can only compute the vectorial sum of two maneuvers that are performed together: the N-gon "insertion" plus the first pattern maintenance maneuver. Nevertheless, here we will present estimations of the results associated with the deployment only, correcting for the fact that all pattern maintenance maneuvers have the same magnitude except for the first one which, when computed, contains also "part" of the deployment procedure.

Let us assume that we want to transfer a satellite from the baseline orbit to the initial vertex of an N-gon of diameter D meters which spins at a rate of R revolutions per day. The computations show that the ΔV cost behaves approximately linearly in D, is asymptotic in R and in the deployment time and can be considered independent of the orientation of the N-gon with respect to the baseline orbit, or equivalently with respect to the inertial pointing direction. In the next table we show rules for some typical cases:

Deployment Time (Hours)	R=1 (cm/s)	R=3 (cm/s)
1	5.5e-2 * D	5.6e-2 * D
3	1.9e-2 * D	2.7e-2 * D
5	1.3e-2 * D	2.2e-2 * D
10	0.9e-2 * D	1.8e-2 * D
100	0.5e-2 * D	1.5e-2 * D

Table 1. Rules for deployment cost (independent of N-gon orientation, D=Diameter in meters)

Transfer times between 5 and 10 hours seem appropriate in terms of both cost and practical implications. Of course 100Hr deployment time is too long for practical applications and it has been included only for illustration of the asymptotic behavior.

As previously stated, the process of the reconfiguration of the constellation can be approached in a similar way to the deployment, except for the fact that the satellites depart from the last vertex of the N-gon instead of from the baseline orbit. Since the deployment cost is independent of the orientation of the N-gon, when the change of the pointing direction is small, the above table can be used as a rough estimate of the cost changing D for twice the distance between the departure and final vertices, measured in a reference frame moving with the baseline orbit. Nevertheless better estimates for the reconfiguration cost would have to be done when the stars to be examined by TFP are identified. Of course, a correct choice of the order for observation is crucial in the overall mission cost.

In the next table we present an estimation of the ΔV cost associated with satellites located in an N-gon of 50 and 100 m around an L_2 baseline halo orbit spining at the rate of 3 revolutions per day for a 10 year mission. Halo insertion cost due to transfer from the Earth and station keeping including avoidance of the exclusion zone that could be required in case of using an L_2 Lissajous orbit are also included. The usual station keeping can be assumed to be absorbed in the frequent pattern maintenance maneuvers. Maneuvers are also considered performed without error, so control correction maneuvers are not included.

Maneuvers per S/C (m/s)	50 m Diameter Case	100 m Diameter Case
Halo Insertion	5	5
10 Hours Initial Deployment	0.009	0.018
Formation Maintenance	0.1/Day	0.2/Day
Z-Axis Station Keeping	3/Yr	3/yr
Reconfiguration (estimate)	0.05/Day	0.1/Day
10 Year ΔV Budget (m/s)	585	1135

Table 2. TPF 10 Year Simulation ΔV Budget in 20-Gon spinning at 3 Rev/Day

5. Issues and Approaches of TPF Simulations

The TPF configuration can be classified as a small diameter formation where the transfer is done by means of a mothership inserted into a libration point orbit and followed by the deployment of the satellites. Although the simulations predict no problem in terms of ΔV for the maneuvers to be done during the deployment, a key point which must be addressed in the future is the optimal time span and sequence of the deployment that avoids the risk of collision, especially when the satellites depart from the mothership.

As we have done in the simulations, the optimal strategy should include the synchronization of the arrival time to each corresponding initial vertex of the N-gon after deployment. Simulations reveal that transfer time doesn't seriously affect the ΔV consumption when the transfer time is chosen in an interval between 3 and 10 hours, so there is a considerable margin of time to design a sequential deployment in such a way that the final synchronization may be achieved while avoiding the collision problem.

The same approach is valid for the reformation problem, although in this case the risk of collision happens during the excursions of the satellites from its initial position to its final destinations, especially if swapping between the relative positions of the satellites has to be done to keep some homogeneity in the fuel consumption in all the spacecraft. This must be planned accurately when the possible star targets for TPF have been identified.

In terms of pattern maintenance maneuvers and reformation approach, TPF will need autonomous navigation. Maneuvers have to be done too often to be planned from the Earth. To keep the formation controlled, a suitable approach is for one of the satellites, for instance the combiner, to be in charge of measuring the relative positions between the other ones and to command appropriate maneuvers in an automatic way. This strategy decouples the station keeping problem. One leg would be the station keeping of the combiner, which could be even tracked from Earth leaving autonomous navigation only locally in the formation, and the other one would be the autonomous station keeping of the formation with respect to the combiner. From the experience of our simulations, it seems that due to the large numbers of maneuvers required, the station keeping could be absorbed by changing slightly the pattern maintenance maneuvers in an automatic way once the combiner has performed a station keeping maneuver planned from Earth, in case that autonomous navigation for the combiner were not implemented. In any case, further simulations including these issues, have to be done in order to estimate the suitable time spans between station keeping maneuvers of the combiner that doesn't imply the change or the addition of new thrusters, and moreover, the station keeping be absorbed by the pattern maintenance maneuvers.

Another important issue for the TPF concept is the size of the maneuvers to be done. Most of them are about 1 mm/s. Are there high precision small thrusters at this level? We must also take into account that maneuvers will be performed with an error. Even when using high precision thrusters, corrections will have to be applied in order to force the spacecraft to follow their corresponding edge in the N-gon. Again, if we want to have good observational periods, this requires almost instantaneous reaction in the sense of the on-board autonomous navigation previously stated. Moreover, correction maneuvers will be on the order of a fraction of the nominal ones, emphasizing again the need of high precision small thrusters.

6. TPF Formation in Heliocentric Orbit

We briefly describe the performance for the TPF formation control in the heliocentric orbit similar to the SIRTF orbit (Figure 7). Surprisingly, there is virtually no difference in the maneuvers needed to control the TPF formation in either environment (difference is 10^{-3} m/s per year). Although in the halo orbit environment, station keeping, however small, is still required. In hind sight, this is not so surprising since for both environments, the gravity is very weak. Hence linear controls should work well.

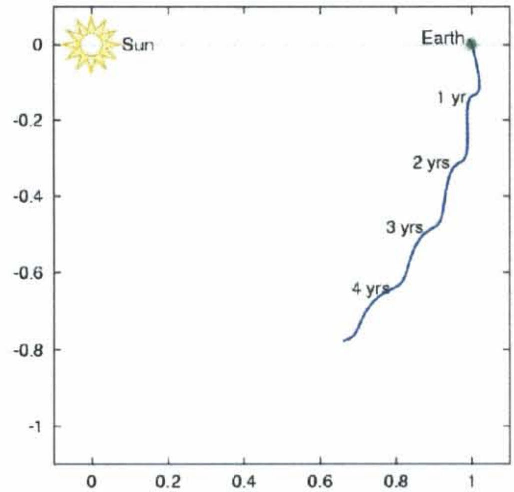

Figure 7. TPF heliocentric orbit similar to the SIRTF orbit.

The more serious issues between the two approaches are the telecommunications, risk, and spacecraft mass. For the halo orbit, the spacecraft will always be within 1.5 million km of the Earth making the communications with Earth relatively straight forward. Whereas with the heliocentric orbit, within 5 years, the spacecraft can drift more than 1 AU away from the Earth. This requires a communications system which is much more substantial.

As the mission progresses, should any one of the spacecraft malfunctions, the further the S/C is away from the Earth, the more difficult it will be to replace the defective spacecraft due to the ΔV cost. Human servicing the defective spacecraft is virtually impossible. For a distributed system like the TPF flock, this greatly increases the risk for the mission.

Finally, the mass savings from the halo orbit is negligible compared with the heliocentric orbit.

7. Human Servicing

Our Solar System is interconnected by a vast system of tunnels winding around the Sun generated by the Lagrange Points of all the planets and their moons. These passageways are identified by portals around L_1 and L_2, the halo orbits. By passing through a halo orbit portal, one enters this ancient and colossal labyrinth of the Sun. This natural Interplanetary Superhighway (IPS, see Figure 8) provides ultra-low energy transport throughout the Earth's Neighborhood, the region between Earth's L_1 and L_2. This is enabled by a coincidence: the current energy levels of the Earth L_1 and L_2 Lagrange points differ from that of the Earth-Moon by only about 50 m/s (as measured by ΔV). The significance of this happy coincidence to the development of space cannot be overstated. For example, this implies that lunar L_1 halo orbits are connected to halo orbits around Earth's L_1 or L_2 via low energy pathways. Many of NASA's future space observatories located around the Earth's L_1 or L_2 may be built in a lunar L_1 orbit and conveyed to the final destination via IPS with minimal propulsion requirements (Figure 9). Similarly, when the spacecraft or instruments require servicing, they may be returned from Earth libration orbits to the Lunar L_1 orbit where human servicing may be performed. Since the lunar L_1 orbit may be reached from Earth in less than a week, the infrastructure and complexity of long-term space travel is greatly mitigated. The same orbit could reach any point on the surface of the Moon within hours, thus this portal is also a perfect location for the return of human presence on the Moon. The lunar L_1 orbit is also an excellent point of departure for interplanetary flight where several lunar and Earth encounters may be added to further reduce the launch cost and open up the launch period. The lunar L_1 is a versatile hub for a space transportation system of the future. See Lo and Ross [10].

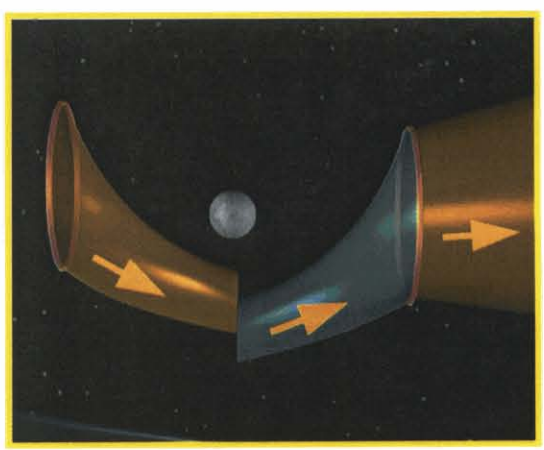

Figure 8. The Interplanetary Superhighway in the Sun-Earth-Moon environment.

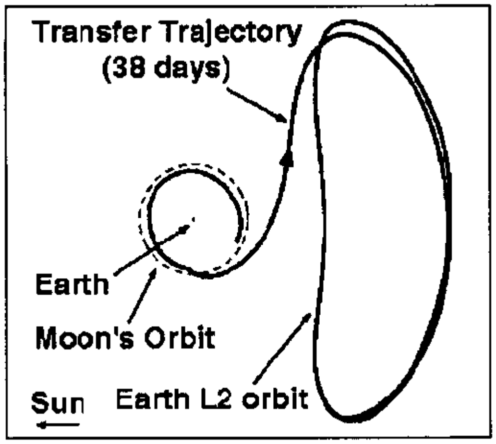

Figure 9. The transfer from Lunar L_1 halo orbit to Earth L_2 orbit in Sun-Earth rotating frame.

The Lunar L_1 halo orbit appears as a circular orbit within the Lunar orbit in Figure 9 since the Sun-Earth rotating frame is used. The point design trajectory connecting the Lunar L_1 orbit with an orbit around the Earth L_2 requires 14 m/s and approximately 38 days for the transfer between the regions around the two libration points. For rendezvous missions, the ΔV cost will increase and phasing becomes a serious issue currently under study.

8. Conclusions

Formation Flight Near L2

The results of the simulations carried out in this paper reveal that formation flight is dynamically possible near L_1/L_2. Moreover, the baseline orbit dynamics, station keeping and transfer procedures are well known and have been implemented successfully for single libration point spacecraft since 1978. For the case of TPF, L_2 is a suitable location, especially for its geometry with respect to Earth and Sun and the ΔV expenditure is affordable for a mission of such a considerable time span. However, formation flight requires new needs such as autonomous on-board navigation for station keeping, deployment of the formation, precise pattern maintenance maneuvers, reconfiguration strategies, and the control of precise formations in the libration point environment. Some of these points have been idealized or excluded from our simulations. These important issues must be addressed in future work.

Human Servicing Near EL1

The possibility of human servicing of libration missions greatly reduces the risk of complex missions such as TPF. Once extended human presence is established at a Lunar L_1 gateway station, other options present themselves. The building and assembling of instruments and telescopes at the L_1 facility is a possibility. Telescope designs requiring thin-film technology may benefit greatly from such a facility in space.

Acknowledgments

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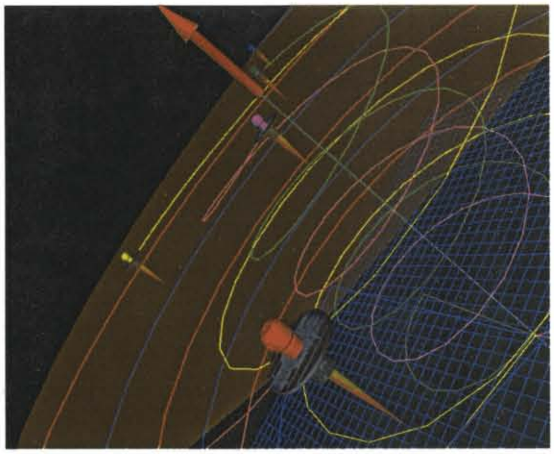

The TPF mission design strategies presented in the previous sections form a complex problem for which an interactive simulation environment with constant visual feedback is extremely useful.