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Searching for life with the Terrestrial Planet Finder: Lagrange point options for a formation flying interferometer

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Abstract

Whether life exists beyond Earth is a fundamental question. To answer this and related questions requires access to space, making the search for life within our solar system and beyond a quest that only the National Aeronautics and Space Administration (NASA), along with its international partners, can answer. The Terrestrial Planet Finder (TPF) is one of the key missions in NASA's Astronomical Search for Origins. In this paper, we describe the mission design for TPF assuming a distributed spacecraft concept using formation flight around both a halo orbit about the Sun–Earth L_2 as well as a heliocentric orbit. Although the mission architecture is still under study, the next two years will include study of four design concepts and a down select to two concepts around 2005. TPF is anticipating a Phase A start around 2007 and a launch sometime around 2015.

Keywords: Astronomical search for origins; Searching for life; Terrestrial Planet Finder; TPF; Halo orbit; L_2; Heliocentric orbit

1. The search for life beyond the solar system

For over 2300 years Greek philosophers, medieval scholars, science fiction authors, and modern scientists have argued passionately about whether or not life exists beyond the Earth. Do other living creatures or intelligent beings inhabit other worlds? Does the Universe teem with life inhabiting every possible cosmological niche, or is life a rare occurrence? For most of human history we were not aware of the full complement of objects in our own solar system, the physical conditions on the planets, the range of environments that life might inhabit, or the existence of planets in other solar systems. But modern technology has led to a rapid expansion of our knowledge in all of these areas in the past decade:

- Astronomers have extended the census of bodies on our own solar system to include dozens of nearly moon-sized objects in the Kuiper Belt, including the discovery, just this year, of a body half the size of Pluto orbiting far from our Sun.
- Planetary geologists have found evidence from space probes for water on Mars and under the ice on Jupiter's moon Europa.
- Biologists have found that life can thrive near undersea volcanic vents, in acidic streams, within rocks through the Antarctic winter, and in deep underground rock formations.
- In 1996, astronomers found the first Jupiter-sized planets orbiting nearby stars like our sun; more than 100 such planets are now known and the number is growing.

These discoveries reflect a remarkable confluence of human curiosity with science and technology as we address age-old questions with 21st century tools. Many of these questions demand access to space for their

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answers, making the search for life within our solar system and beyond a quest that only NASA, along with its international partners, can answer.

The NASA vision statement calls on the agency *"To Explore The Universe And Search For Life."* Within NASA's Office of Space Science, the search for life encompasses Solar System Exploration to look for prebiotic or habitable environments and life (fossil or extant) on a variety of solar system bodies, including Mars, certain "hospitable" moons of the outer planets, and comets, as well as the Astronomical Search for Origins to look for habitable planets and life on planets orbiting other stars. The field of Astrobiology, a multidisciplinary effort to understand the formation and evolution of life, provides an intellectual framework running through the entire program. This paper focuses on the search for habitable planets, and life, beyond the solar system.

Our own solar system contains only a few possible abodes for life. How much further must we search if we find no other life close to home? Looking far beyond the solar system, NASA seeks to understand the origins of life on a cosmic scale. Are we alone in the Universe? If so, why did life arise only on a single planet, the Earth? What was special about our home that nurtured life and made it possible only here? On the other hand, if we find life elsewhere, we will learn about the universal properties of life, with dozens – or even many hundreds – of examples. Perhaps, in our quest, we will learn if other intelligence is also present on planets around neighboring stars.

Only NASA, along with its international partners, can achieve these goals, as searching for habitable, terrestrial planets requires astronomical capabilities not possible from the surface of Earth, or even from low Earth orbit. A variety of missions will build up, over a decade, the scientific knowledge and technological prowess needed to look for life on distant planets. Within the next few years the Space Infrared Telescope Facility (SIRTF) and the Stratospheric Observatory for Infrared Astronomy (SOFIA) will observe the disks of gas and solid particles orbiting nearby stars that may be signposts of the presence of planets. A decade from now, the James Webb Space Telescope (JWST) will study the structure and composition of these disks in great detail, looking for material trapped in resonances due to orbiting planets and searching for spectral signatures of pre-biotic organic molecules. Yet, as important as these three major missions are, none will have the capability to study Earth-like worlds, if they exist. That task will require different capabilities and still more demanding technologies.

The first mission specifically intended to find Earth-like planets will be the competitively selected Discovery mission, *Kepler*, which will be launched in the last half of this decade. *Kepler* will monitor 100,000 distant stars (as far as a thousand light years away) looking for the small, hours-long diminution in a star's brightness due to the passage of planet in front of it. From the statistics of these planetary transits, *Kepler* will assess the incidence of terrestrial planets orbiting stars like our sun. In roughly the same time frame, the Space Interferometry Mission (SIM) will target our closest stellar neighbors, those stars located within 100 light years, measuring their positions very precisely to look for the telltale motion of an orbiting planet gravitationally tugging its parent star back and forth. SIM will reveal the underlying architecture of solar systems and determine whether our system with its arrangement of cold, distant gas-giant planets and warm, inner, rocky planets is a common or rare occurrence. SIM will be able to identify planets as small as three Earth-masses around the nearest stars.

Seeking direct signs of life – not just evidence for planets of the right size and location – will be the challenge for the Terrestrial Planet Finder (TPF), planned for launch in the middle of the next decade. TPF will separate the faint light of a terrestrial planet in the habitable zone from the glare of its parent star, seeking the first direct evidence for habitable worlds with moderate temperatures and abundant water. By building on the technology of SIM and JWST to reject starlight and to break the planet's light into its component colors, TPF will even be able to search for extant life using "biomarkers", spectral tracers of life's alteration of the chemistry of a planet's atmosphere.

How to implement the challenging goals of TPF is currently being investigated by NASA, utilizing scientists and technologists at NASA Centers, universities, and industry. Two architectures are presently being studied in the context of an aggressive program of technology and mission design: infrared interferometry and visible light coronagraphy. Within each architecture class, two missions of different scope are being investigated: one capable of reaching at least 150–250 stars and another capable of studying only 25–50 stars. The interferometers would use either a structurally connected set of telescopes for the modest scale mission or a formation flying set of telescopes for the full scale mission. The coronagraphs use either 4 or 8–10 m telescopes to accomplish the mission goals. The next two years will lead to four design concepts leading to a down select to two concepts around 2005. TPF is anticipating a Phase A start around 2007 and a launch sometime around 2015.

2. The TPF mission at the Sun–Earth L_2 and in heliocentric orbit

One approach to identify Earth-like planets around stars nearby the Solar System where there is potential for life is to use a space-based infrared interferometer

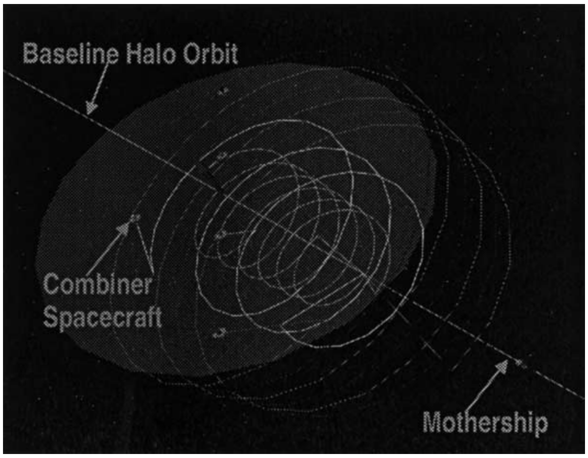

Fig. 1. TPF Interferometer Formation just after Deployment from the Mothership, spiraling around the Baseline Halo Orbit in a 100 m diameter 20-sided polygon (orange). The red arrow points at the star being observed.

with a baseline of approximately 100 m. To achieve such a large baseline, a distributed system of five spacecraft flying in formation is an efficient approach. The current concept as described in the TPF book (Beichman et al., 1999) has four 3.5 m diameter telescopes, each with its own spacecraft, and a central spacecraft that collects and combines the beams (see Fig. 1). 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 or for missions requiring a highly stable thermo-mechanical environment. Two potential orbits are considered in this paper: a libration orbit near the L_2 Lagrange point and a SIRTF-like heliocentric orbit. For a more detailed description of the TPF mission in orbit near L_2, see Gómez et al. (2001b). See Szebehely (1967) for background on Lagrange points.

The formation flight problem near the Lagrange points is of great interest. The first constellation in ring formation in an L_1 quasihalo orbit using the natural dynamics was constructed by Barden and Howell (1999), and Barden (2000). Scheeres (2000) demonstrated control strategies which look 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 Libration Orbital Dynamics Study Group 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. More specifically, transfer, deployment, and linear control around a nonlinear baseline libration orbit near L_2 is feasible for the TPF Mission (Gómez et al., 2001b) both dynamically and for the fuel required to maintain the formation.

2.1. Advantages of a mission near L_2

The use of libration orbits for space missions have a long history starting with the ISEE3 mission in 1978 (Farquhar, 2001). There are several advantages to a libration orbit around L_2. The Microwave Anisotropy Probe (MAP) mission recently launched into a Lissajous orbit around L_2 (see Cuevas et al., 2002). Such orbits are easy and inexpensive to reach from Earth. Moreover, for missions with heat sensitive instruments, orbits around L_2 provide a constant cold environment for observation with half of the entire celestial sphere available at all times. The observation geometry is nearly constant with the Sun, Earth, Moon always behind the spacecraft. This provides a stable observation environment, making observation planning much simpler. Since libration orbits will always remain close to the Earth at a distance of roughly 1.5 million km with a near-constant communications geometry, the communications system design is simpler and cheaper. The L_2 environment is also highly favorable for non-cryogenic missions requiring great thermal stability, such as the highly precise, visible light telescope coronagraph also being considered for TPF. In the rest of this article, however, we consider only the interferometer version of TPF.

The transfer from the Earth to a libration orbit is "cheap and easy". This has three 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 would be very costly and may be prohibitive in some instances. Third, libration orbits are extremely flexible and forgiving. Multiple options exists to accommodate changing requirements and new constraints. 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. For more information see the Proceedings for Libration Orbits and Applications Conference (Gómez et al., 2003) and visit the conference website, http://www.ieec.fcr.es/libpoint/main.html.

2.2. Overview of the simulations

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; these are energy surfaces on which the trajectories lie. 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 important to these simulations.

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

- Launch and Transfer to the Science Orbit
- Deployment into Initial Formation
- Pattern Maintenance
- Reconfiguration into New Formation

Gómez et al. (2001b) described the simulations performed for each of the scenarios for the TPF Mission in halo orbit. The formation pattern chosen for this study is that of a 20-sided polygon (20-gon) as described in the TPF book (Beichman et al., 1999). For our simulations, all trajectories are integrated using JPL's LTool (Libration Mission Design Tool) with a Solar System model provided by the JPL ephemeris, DE405.

2.3. 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 Orbit. 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 may change several times daily. Hence rigid nominal orbits for the formation cannot even be defined rigorously. Note that the Baseline Orbit itself may have no spacecraft on it (see Fig. 1).

3. TPF mission phases

3.1. 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° inclination and a halo orbit is used as the Baseline Orbit. At the appropriate time, the spacecraft performs a major maneuver to achieve a C_3 of −0.69 $(km/s)^2$ for the halo orbit, and a C_3 of 0.4 $(km/s)^2$ for the heliocentric orbit. This injects the spacecraft onto the transfer trajectory to begin the Transfer Phase. The transfer trajectory for the halo orbit case is designed by using an orbit of the stable manifold with a suitable close approach to the Earth. This method was first introduced by Simo's group (see the excellent four volume monographs by Gómez et al. (2001a)). It has been successfully used by the Genesis mission (see Howell et al., 1997) and the MAP mission (see Cuevas et al., 2002). For more information on other applications of this method, see Gómez et al. (2003).

3.2. 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 spacecraft (S/C) are maneuvered to reach their initial positions at the same time, although they can be individually deployed as well. Refer back to Fig. 1 which shows the four collector S/C are equally spaced along the 100 m diameter of a 20-sided polygon. The beam combiner S/C is in the plane of the

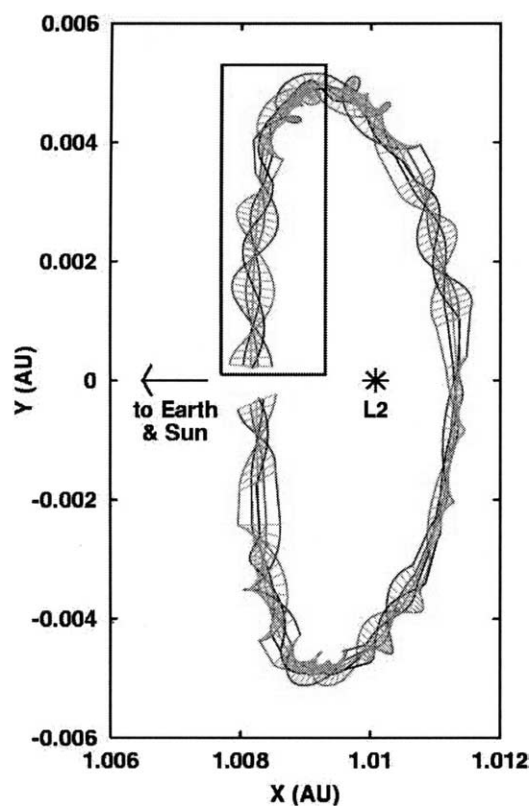

Fig. 2. TPF formation exaggerated to a 100,000 km diameter around the Baseline Halo Orbit. The horizontal yellow lines indicate the relative positions of the Baseline Halo Orbit (gray curve), the Combiner Spacecraft (black curve) and the four Collector Spacecraft (multicolor) at a particular time step.

polygon, offset from the center. The Deployment Phase can last several hours or longer. In the simulations described here the deployment time varied between 1 and 10 h.

Since the Y-amplitude (similar to semimajor axis) 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. In Fig. 2, the diameter of the formation is blown up from 100 m to 100,000 km. At this range, the nonlinear forces do become significant; nevertheless, the LTool differential corrector used had no difficulty holding onto the formation in either case. Fig. 3 enlarges the small rectangle region in Fig. 2 for a close-up view of the formation.

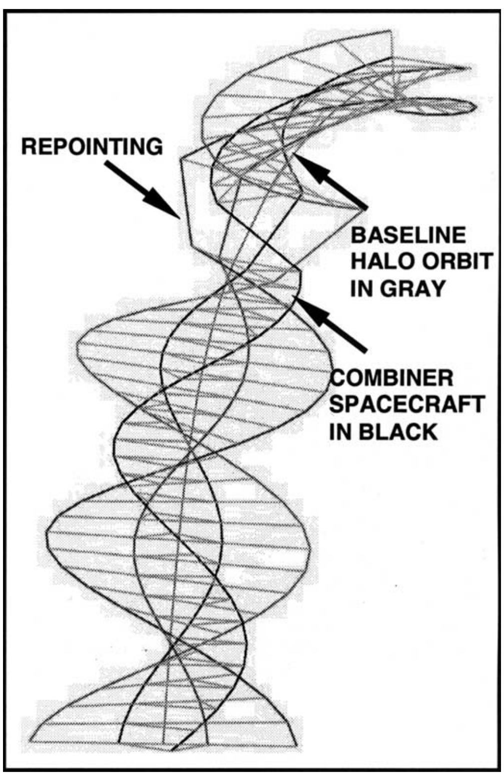

Fig. 3. Blowup of the small rectangle region in Fig. 2 for a close-up view of the formation. The colors of the curves are associated to different Spacecraft specified in the caption for Fig. 2. Note the repointing of the formation is shown by the linear portion of the curves.

3.3. Pattern maintenance phase

Once the initial configuration has been established, the spacecraft will maneuver to follow the edges of a 20-gon (approximating a circle) to provide a suitable rotation rate for the entire formation. The two S/C at the end of the 100 m diameter will follow the edges of a 20-gon with a diameter of 100 m. The two S/C in the interior of the 100 m 20-gon, will follow the edges of a 20-gon of 33.3 m diameter, etc. The nominal rotation rate for the entire system used for this simulation is 360° every 8 h. The period where the pattern is maintained is called the Pattern Maintenance Phase. But, for visualization purposes, each rotation period is increased from 8 h to 15 days. LTool was able to handle both situations.

3.4. Reconfiguration phase

Once sufficient data has been acquired for one star, the formation will be pointed at another star for observation. Repointings occur during the Reconfiguration Phase. This is indicated in Figs. 2 and 3 by the rectilinear portions of the formation orbits. The Reconfiguration Phase is similar to the Deployment Phase except the spacecraft do not depart from the same location (i.e. the Mothership).

4. TPF formation flight near L_2

The basic operational concept for the TPF mission is to rotate the satellite formation 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 Beichman et al., 1999). As explained earlier, to accomplish the mission, a Baseline Orbit approach seems best. In this section, we select an L_2 halo orbit as a Baseline Orbit. The satellites will be moving in nearby orbits, no spacecraft will be actually moving on the Baseline Halo Orbit.

In Table 1 below, we present an estimation of the ΔV cost associated with satellites located in a 20-gon of 50

Table 1
TPF 10 year simulation in Halo orbit ΔV budget spacecraft moving in 20-sided polygon, making three revolutions around polygon/day

	Maneuver cost per spacecraft	
	Diameter case (50 m)	Diameter case (100 m)
Large amplitude Halo insertion (m/s)	5.000	5.000
10 h initial deployment (m/s)	0.009	0.018
Formation maintenance (m/s/Day)	0.100	0.200
Z-axis station keeping (m/s/yr)	3.000	3.000
Reconfiguration (estimate) (m/s/Day)	0.050	0.100
10 Year ΔV budget (m/s)	583	1130

and 100 m around an L_2 Baseline Halo Orbit rotating at the rate of three revolutions per day for a 10 year mission. Halo insertion cost due to transfer from the Earth and station keeping cost, including avoidance of the exclusion zone that could be required in case of using an L_2 Lissajous orbit, are also included. Maneuvers are assumed to be performed without error, so correction control maneuvers are not included. The usual station keeping can be assumed to be absorbed in the frequent pattern maintenance maneuvers. This is because for typical halo missions, about 4–6 station keeping maneuvers are required per year with a total ΔV of less than 5 m/s. Thus, the deterministic formation maintenance maneuvers grossly overwhelm the station keeping maneuvers.

5. TPF formation flight in heliocentric orbit

We now describe the performance for the TPF formation control in a heliocentric orbit similar to the SIRTF orbit (Fig. 4). 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). In hind sight, this is less surprising due to the weak gravity fields of both environments. Hence linear controls should work well for short time intervals even for halo orbits. In the halo orbit environment, station keeping maneuvers, however small and infrequent, are still required. The frequency of the station keeping maneuvers will probably be greater than just 6 maneuvers per year because of the large numbers of daily formation maintenance maneuvers disturbing the orbit. But they can be easily combined with the huge numbers of repointing maneuvers. Exactly how frequently it is needed has not been determined. However, its total ΔV cost will likely remain very small as it is easily absorbed in the formation maintenance maneuvers. See Gómez et al. (1998) and Gómez et al. (2001a) for details on halo orbit station keeping.

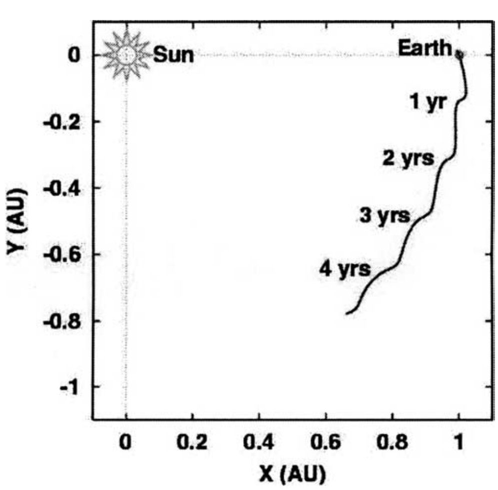

Fig. 4. TPF heliocentric orbit similar to the SIRTF Earth Trailing Orbit.

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, the spacecraft can drift more than 1 AU away from the Earth in 5 years. This requires a communications system which is much more substantial, heavy, and costly.

As the mission progresses, should any one of the spacecraft malfunction, 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. This is because the replacement spacecraft must go faster to rendezvous with the existing formation. Once it reaches the formation, the replacement spacecraft must slow down to match the formation speed. Human servicing of the defective spacecraft is virtually impossible in this scenario. For a distributed system like the TPF formation, this greatly increases the risk for the mission.

Finally, one of the most compelling reasons for preferring a halo orbit mission for TPF is its extreme flexibility and adaptability to changing mission requirements and constraints. For example, if mass becomes an issue, by using small amplitude Lissajous orbits via a lunar swingby, the C_3 can be lowered from -0.69 to -2.6. This was used by the MAP mission (see Cuevas et al., 2002). If antenna pointing issues arise, libration orbits may be chosen to accommodate a beam width ranging from 4° to 28°. Or if thrusters cannot be mounted on one side of the spacecraft due to contamination issues as for Genesis (see Bell et al., 1999; Lo et al., 2001), the libration orbit can be biased to avoid maneuvers in the direction where thrust is not readily available from the propulsion system. In some extreme instances, this is possible even in the development phase. Hence, from the project standpoint, a libration mission provides tremendous advantages. But the flexibility and adaptability of libration missions is its second most salient feature. Its most salient feature is the stable and constant environment and observation geometry that libration orbits at L_2 provide for the science observation.

6. Human servicing of L_2 missions

Our Solar System is interconnected by a vast system of dynamical 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 Figs. 5 and 6) provides ultra-low energy transport throughout the Earth's Neighborhood, the region between the Sun–Earth L_1 and L_2. This is enabled by a coincidence: the current energy levels of the Sun–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 Earth–Moon L_1 halo orbits are connected to halo orbits around the Sun–Earth L_1 or L_2 via low energy pathways, one is indicated in Fig. 6. But it appears as a near-circular arc (solid curve) within the Lunar orbit (dotted circle) in Fig. 6 since the Sun–Earth rotating frame is used. So the Moon and the Lunar L_1 are all rotating around the Earth in this frame and the typical halo orbit pattern is lost. The point design trajectory connecting the Earth–Moon L_1 orbit with an orbit around the Sun–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 as phasing becomes a serious issue currently under study.

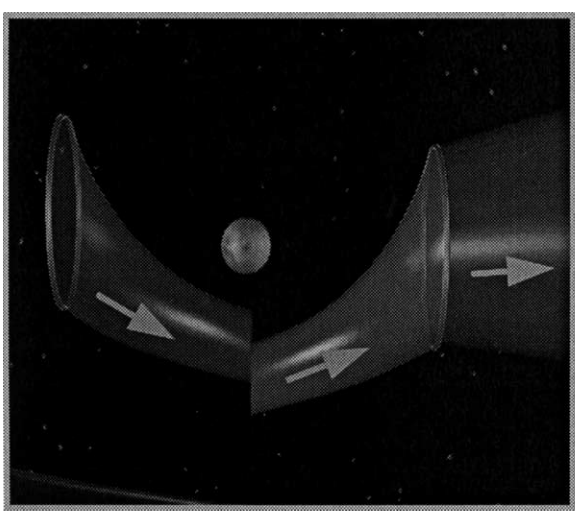

Fig. 5. The Interplanetary Superhighway in the Earth–Moon environment in Earth–Moon rotating frame.

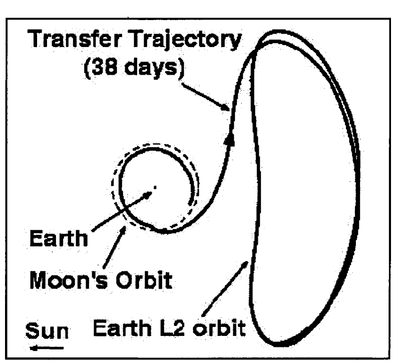

Fig. 6. The transfer from Earth–Moon L_1 halo orbit (the near circular solid arc inside the lunar orbit) to a Sun–Earth L_2 halo orbit in Sun–Earth rotating frame.

Many of NASA's future space observatories located around the Sun–Earth L_1 or L_2 may be built in an Earth–Moon L_1 orbit and conveyed to the final destination via IPS with minimal propulsion requirements (Figs. 5 and 6). Similarly, when the spacecraft or instruments require servicing, they may be returned from Earth libration orbits to the Earth–Moon L_1 orbit where human servicing may be performed. Since the Earth–Moon 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 a few days, thus this portal is a perfect location for the return of human presence on the Moon. The Earth–Moon 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 Earth–Moon L_1 is a versatile hub for a space transportation system of the future. For more information, see Lo and Ross (2001).

7. Conclusions

7.1. Formation flight near L_2 is feasible for TPF from the trajectory point of view

The results of the simulations described in this paper reveal that formation flight is dynamically possible near L_1/L_2. Moreover, the baseline orbit dynamics 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 an ideal location, especially for its geometry with respect to Earth and Sun. The ΔV expenditure is shown to be affordable for a mission of such a considerable time span. However, formation flight may require more autonomy on-board for deployment of the formation, precise pattern maintenance maneuvers, reconfiguration, navigation, station keeping, and the control of precise formations in the libration point environment. Some of these points have been idealized or excluded from our simulations. Many remaining issues must be addressed in future work.

7.2. Halo orbits provide many advantages for TPF

Halo orbits provide many advantages for TPF. The most outstanding is the stable and constant environment and geometry for TPF observations. The flexibility and adaptability of halo orbits are another key advantage over other approaches. Although more careful studies and comparisons are required since the architecture of the mission is still under development, the halo orbit at

L_2 provides an elegant solution to the requirements of the TPF mission.

Acknowledgements

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