

SIM Trajectory Design

Wyatt R. Johnson*

Jet Propulsion Laboratory, Pasadena, CA, 91109-8099

SIM (Space Interferometry Mission) is a mission scheduled to launch in 2010 and will be the first spacecraft to use interferometry to measure the positions of stars to within 1 micro-arcsecond – a degree of precision never before achieved. The flight hardware required to achieve this level of precision is very sensitive to its external environment, which places a number of challenging constraints on the trajectory design. This paper discusses the various trajectory options that were considered.

I. Introduction

THIS is the introduction section. Insert references to literature that talks about the various solar trajectory options. ETSO, ELSO, Oscillating Solar Orbit, Horseshoe Orbit, etc. Refereces to papers, like this one.¹

II. Trajectory Options

The requirements and constraints on SIM's trajectory are listed in Table 1.:

Table 1. SIM trajectory requirements and constraints.

Constraint	Value	Driver
Mission lifetime	10.5 years	science
Injected mass	6230 kg	flight system
Observable portion of sky	100% every 4 months	science
Minimum Earth-SIM range	0.2 AU after 2 years	science
Minimum Sun-SIM range	0.95 AU	thermal
Maximum Sun-SIM range	1.10 AU	power
Sun Exclusion Zone	± 60 deg	flight system
Post-launch delta-V capability	0 m/s	flight system
Launch Date [CBE]	28 Feb 2010	

Because of numerous issues (thermal sensitivity, Earth albedo, science planning complexity issues, and the long duration of individual science observations),² SIM can not be placed into Earth orbit. The alternative is to place SIM into a heliocentric orbit, similar to the Spitzer/SIRTF Space Telescope's orbit.³ Unlike Spitzer, SIM does not have any telecom geometry constraints (which was a driving constraint on the orbit which was eventually selected for Spitzer). An Earth Trailing Solar Orbit (ETSO) will cause SIM to drift from Earth at a rate of about 0.1 AU per year. Since SIM has a prime and extended mission durations of 5.5 and 10.5

*Senior Engineer, Mission Design and Navigation, 4800 Oak Grove Dr., Pasadena, CA, 91007, Member AIAA.

years, the telecom system will be stressed even more than Spitzer, which has an extended mission of only 5 years. Complicating the issue is that current science requirements result in a weekly data volume of 210 Gbits per week which must be supported throughout the mission duration. In the ongoing trajectory design process, several heliocentric orbits were considered. The following sections will discuss each of these, and their respective pro's and con's for use on SIM.

A. ETSO and ELSO (Earth-Trailing and Earth-Leading Solar Orbits)

The current baseline trajectory for SIM is to launch into an Earth-Trailing Solar Orbit with a C_3 of $0.6 \text{ km}^2/\text{s}^2$, chosen to minimize average Earth-SIM range over the 5.5 prime mission. For a spacecraft to trail behind Earth, it's orbit should be slightly eccentric, with a semi-major axis greater than 1 AU. As the spacecraft travels outside the orbit of Earth, the spacecraft will slow down (relative to the Sun), and lag a little more behind the Earth. As the spacecraft descends towards perihelion, it will speed up and catch up slightly with Earth. But because the osculating period of the spacecraft is greater than a year, the spacecraft will drift away from the Earth. A typical ETSO trajectory is illustrated in Fig. 1(a).

Because the trailing motion is induced by travelling outside the orbit of Earth, away from the Sun, the requirement on the minimum Sun-SIM distance of 0.95 AU is virtually always met for an ETSO. Though the thermal constraint is tighter than the power constraint (maximum Sun-SIM range of 1.10 AU), the minimum Sun-SIM range constraint is verified as not being violated.

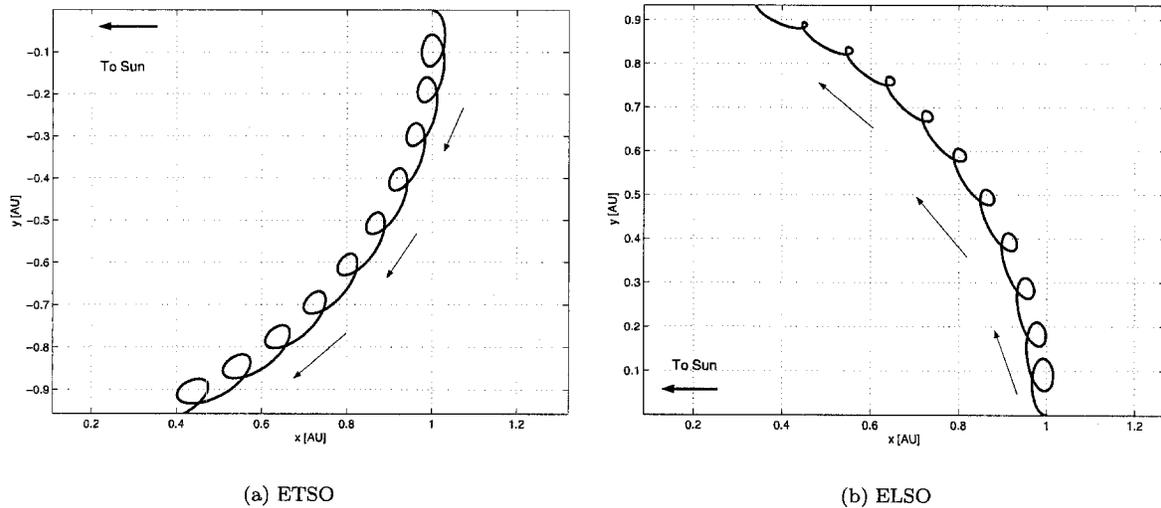


Figure 1. A representative ETSO (Earth Trailing Solar Orbit) and ELSO (Earth Leading Solar Orbit) launching Mar 1 2010, with a $C_3 = 0.6 \text{ km}^2/\text{s}^2$. The Sun is at the origin, and the Earth is at coordinates (1,0) in the rotating frame.

The ELSO option is generally similar to the ETSO, with a few key differences. The leading aspect of the trajectory requires the spacecraft's period to be less than a year, and thus, its semi-major axis to be under 1 AU. The perihelion of a spacecraft on an ELSO trajectory could more easily hit the 0.95 AU constraint than a similar ETSO. The launch asymptote is still chosen to minimize the Earth-SIM range, but since the perihelion constraint is usually active, the drift rate of an ELSO is somewhat higher than for an ETSO. A typical ELSO trajectory is shown in Fig. 1(b). Figure 2 illustrates the performance of the optimal ETSO and ELSO trajectory (in terms of minimizing the maximum Earth-SIM distance) over the 10.5 year mission. Although higher C_3 's (up to a certain point) allow for an improved Earth-SIM range at the end of mission,

the returns begin to level off (around a C_3 of $3.0 \text{ km}^2/\text{s}^2$). The current launch mass allows for an injected C_3 of up to $0.6 \text{ km}^2/\text{s}^2$.

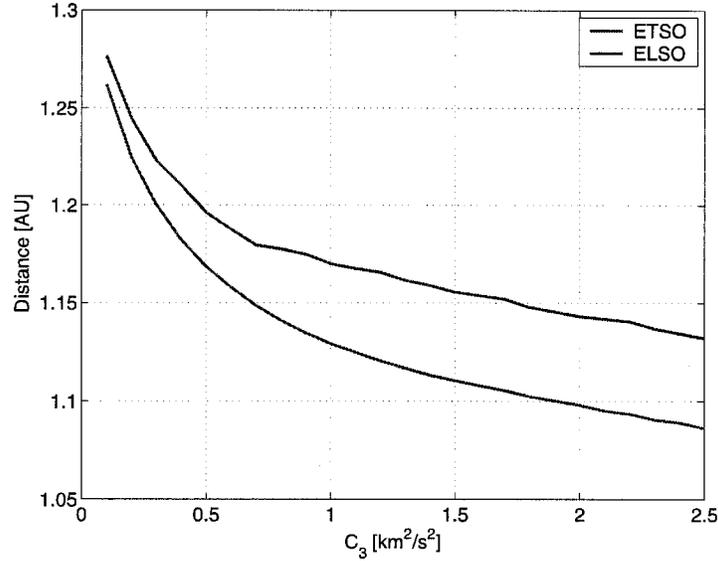


Figure 2. Maximum distance from Earth over 10.5 years.

If the conventional X-band link is used, the 70m DSN stations will become necessary to download the science data at the desired data rates towards the end of the mission. These 70m DSN stations will be heavily used to support other missions, especially Mars missions, which will occur every synodic period. Mars missions rely heavily on the DSN stations to provide OD (orbit determination) support during their cruise and approach phases. Figure 3 illustrates the resource contention SIM would have with a Mars-bound spacecraft during the 10.5 years of SIM's lifetime. During the first month or two after a Mars-bound spacecraft leaves Earth, the Mars spacecraft is leading the Earth. As the spacecraft's distance from the Sun increases, its heliocentric velocity decreases, and it eventually starts lagging the Earth, all the way to arrival at Mars. The initial geometry is favorable for a spacecraft on an ETSO trajectory, but may provide some contention for a spacecraft on an ELSO trajectory. However, the geometry for the remainder of the time-critical cruise and approach phases are much more favorable to a spacecraft on an ELSO trajectory. In a year, SIM will drift about 3.4 degrees away from Earth, while a Mars-bound spacecraft will typically make a ~ 180 degree transfer in 7-9 months. Since SIM will drift relatively slowly compared to the Mars-bound spacecraft, the angular profile shown in Fig. 3 is representative for any SIM launch date.

B. Oscillating Solar Orbit

One of the driving constraints on SIM is the inability to perform any post-launch ΔV , as SIM has no propulsion module. The selected trajectory must be stable (ruling out libration point trajectories, which require periodic correction maneuvers). Because SIM must be in a solar orbit, the orbit options are extremely limited. We can examine the entire space of orbits for a given C_3 by rotating the launch asymptote around in all possible directions (all RLA's, and DLA's less than 28.5 degrees, realizable from Kennedy Space Center). The ecliptic cone angles achievable will depend on the launch date. Figure 4 shows the performance of all outgoing asymptotes with a C_3 of $0.6 \text{ km}^2/\text{s}^2$. The launch space is divided into 2 regions, separated by the

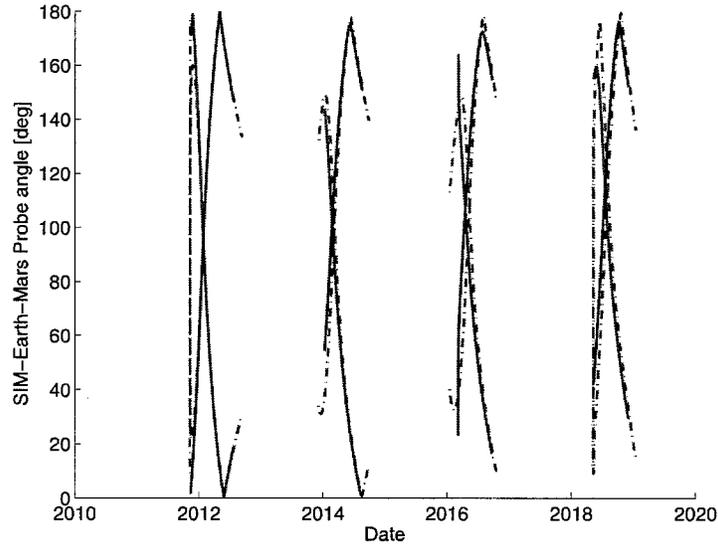


Figure 3. Angle between SIM, Earth, and a Mars-bound spacecraft. Blue indicates SIM is on an ETSO trajectory, while red indicates an ELSO trajectory. Solid lines indicate the Mars-bound spacecraft is on a Type-1 trajectory, while dashed lines indicate a Type-2 trajectory.

2 vertical bands. The region on the left is the space of all ELSO trajectories, while the region on the right is the space of all ETSO trajectories. Most of these ETSO's and ELSO's perform quite poorly, as indicated by the dark red color. However, as the RLA (and to some extent, the DLA) approaches one of the 2 bands, the maximum Earth-SIM distance goes down to about 1 AU (i.e., the best-performing ETSO or ELSO for this C_3). As the RLA moves even closer to the band, the maximum Earth-SIM distance quickly blows up to 2 AU. The bands themselves appear to be chaotic in nature, where even a small change in the direction of the outgoing asymptote would produce a large change in the actual trajectory. However, each band has an area with a concentration of blue (i.e., a potentially orderly space yielding good performance), around the center of each band ($DLA \approx 1.0$ deg).

A close-up view of the right-hand band is shown in Fig. 5. This region is approximately 1 deg by 1 deg in size, and should be achievable by the launch vehicle. At the time of this writing, the SIM ICM (Injection Covariance Matrix) is not yet available, but the numbers should be similar to Spitzer. The 3σ delivery error on Spitzer⁴ (for a PCS of 99.9%) was 0.0211 deg in DLA, 0.2283 deg in RLA, and 13.61 m/s in V_∞ . Several perturbed trajectories were examined (perturbing launch asymptote and solar radiation pressure) and this orbit remained intact. However, for a PCS of 99.7%, the 3σ error on RLA goes up to 1.1745 deg. While this size error still fits into the ideal region in Fig. 5, there is no margin remaining for additional errors.

There is also a tiny blue blip on the far right of Fig. 4, (RLA=355.8 deg, DLA=3.8 deg). This launch asymptote makes a close pass to the Moon, and can either cause the trajectory to remain in the Earth-Moon system, or eject from the Earth-Moon system, in a chaotic fashion.

A sample trajectory from the region of Fig. 5 is displayed in Figure 6(a). This trajectory belongs to the class known as "Oscillating Solar Orbit", previously found by Ocampo,¹ which in turn, belongs to the QS (quasi-satellite) class of orbits. Because this trajectory has no post-launch ΔV , and launches from Earth, the Oscillating Solar Orbit is not periodic. Given enough time, the trajectory will eject from the oscillatory pattern and into a horseshoe trajectory. This particular example of the oscillating solar orbit is launched into a ~ 6 month Earth-leading loop, and then completes 2 Earth-trailing loops, followed by 2 Earth-leading

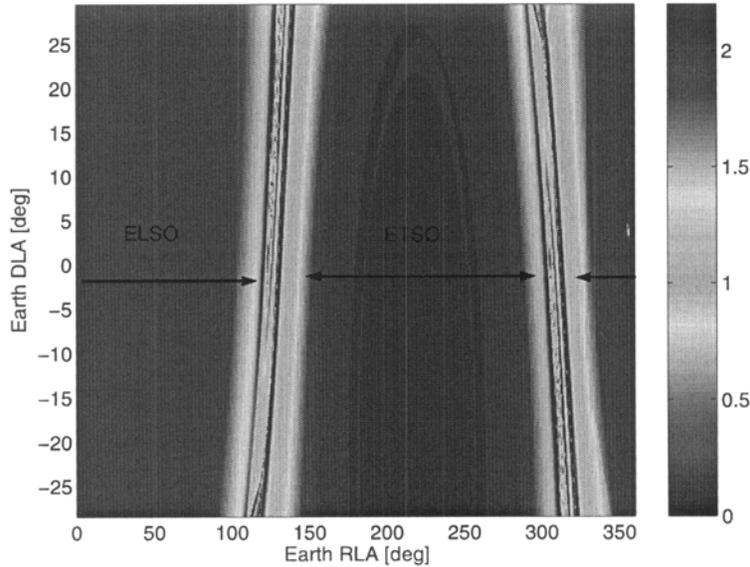


Figure 4. The color indicates the maximum range SIM would achieve on Feb 14, 2010 (a previous target launch date), over a 10.5 year duration, with a launch C_3 of $0.6 \text{ km}^2/\text{s}^2$. Red values indicate SIM reaches a maximum distance of $\sim 2 \text{ AU}$ (i.e., opposite side of Sun from Earth), while blue values indicate a favorable Earth-SIM distance.

loops. This pattern (2 leading loops, 2 trailing loops) continues until the trajectory makes a close approach to Earth, and the spacecraft is ejected into a horseshoe 15 years after launch. The oscillating solar orbit trajectory has a significant component out of the ecliptic, which will allow near-continuous communication with Earth. The Sun-Earth-Probe angle [see Fig. 6(c)] for this case never dips below 7.6 deg, but the Sun-Probe-Earth angle [Fig. 6(d)] has a global minimum of .9 degrees, spending a total of 10 days (out of 10.5 years) with the SPE angle less than 5 degrees.

For SIM, this trajectory is almost completely ideal — The trajectory is a solar orbit, the maximum Earth-SIM distance is small over the duration of the extended mission, perihelion is around 0.98 AU, and no propulsion module is needed. However, the oscillating solar orbit violates the 0.2 AU science requirement (minimum Earth-SIM distance after 2 years from launch).

The size of the loops is a function of the launch C_3 . If the C_3 is increased too much, the 0.95 AU solar constraint will be violated long before the 0.2 AU science requirement is met. Also, the oscillating solar orbit becomes more sensitive to the launch asymptote as the C_3 increases.

C. Horseshoe Orbit

Another interesting option for a SIM trajectory is the horseshoe orbit, which in the Sun-Earth rotating frame, appears to describe a horseshoe. When an object in a horseshoe orbit approaches the smaller of the primary bodies, the object gains or loses energy by the gravity assist, and alternately leads or lags the smaller primary. The obvious drawback to using a horseshoe for SIM is that because the orbit never intersects Earth, a deep-space maneuver is required. However, the advantages of the horseshoe may outweigh that single disadvantage (if the required horseshoe insertion maneuver is sufficiently small) — its a solar orbit that we can design the minimum Earth-SIM range to be 0.2 AU (or higher), and we can change the drift rate from Earth.

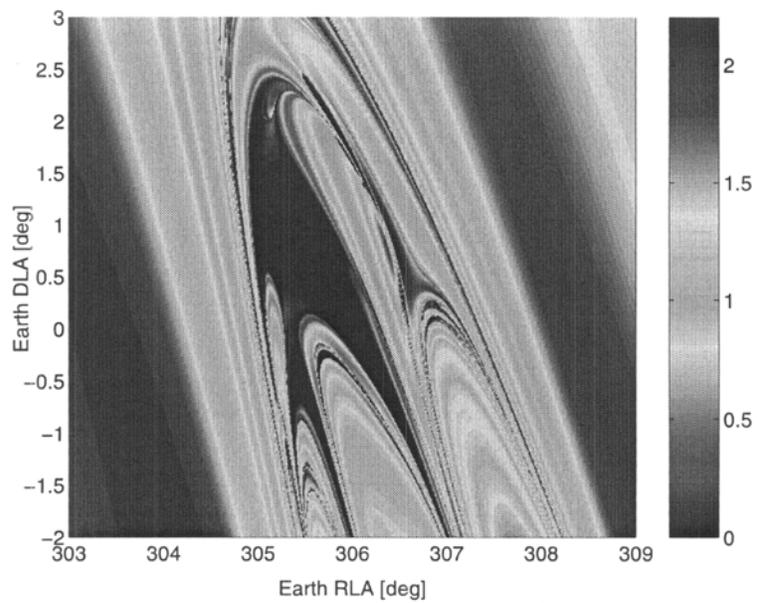
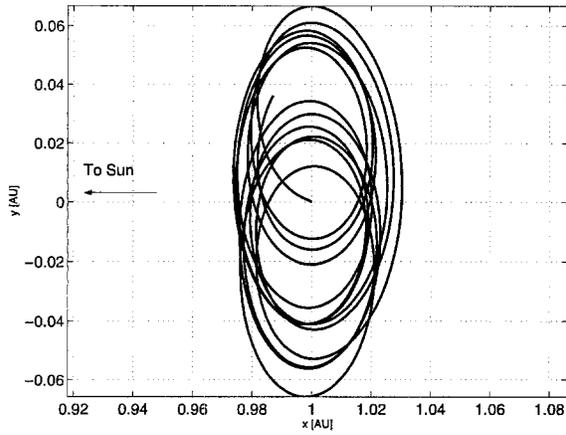
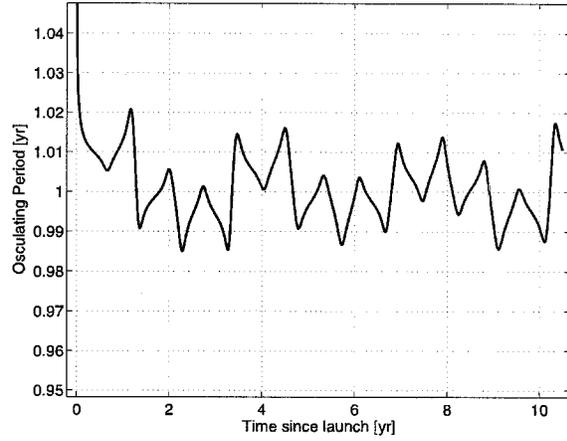


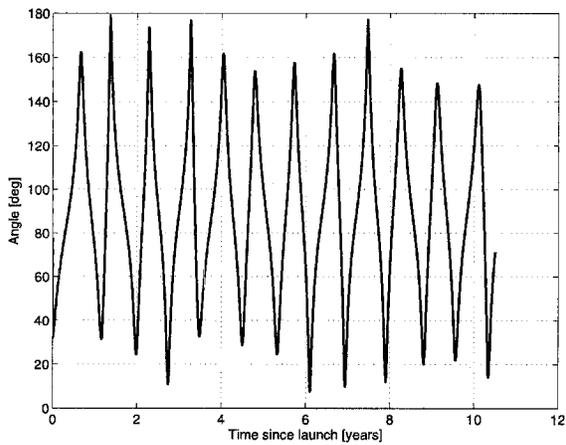
Figure 5. The color indicates the maximum range SIM would achieve on Feb 14, 2010 (a previous target launch date), over a 10.5 year duration, with a launch C_3 of $0.6 \text{ km}^2/\text{s}^2$. Red values indicate SIM reaches a maximum distance of $\sim 2 \text{ AU}$ (i.e., opposite side of Sun from Earth), while blue values indicate a favorable Earth-SIM distance.



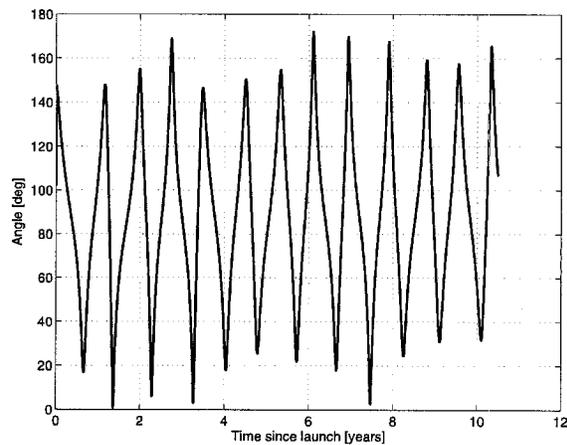
(a) Overview



(b) Period



(c) Sun-Earth-Probe angle



(d) Sun-Probe-Earth angle

Figure 6. An oscillating solar orbit.

Several horseshoe trajectories were optimized using a GA (Genetic Algorithm) analysis tool. The optimization parameters were the launch asymptote (direction and magnitude), the DSM (deep space maneuver) delta-V, and the time of the delta-V. The objective functions included the launch C_3 , the DSM magnitude, the time between launch and the DSM, and the number of days during a 10.5 year period that the spacecraft spends between 0.2 AU and 0.4 AU (or some other upper bound) away from Earth. The time delay of the DSM is important because a DSM of any appreciable magnitude would delay the IOC (in-orbit checkout) until after the DSM is complete. In the baseline ETSO trajectory, the IOC begins immediately after launch and lasts for 6 months, during which time, the science instruments are carefully calibrated following the stresses of launch. A DSM would invalidate any previous precise calibrations, and would effectively delay the start of the science phase. The propellant mass required (both launch as well as for the DSM) are important separately, as well as collectively. The total propellant needs will dictate the dry mass margin that the launch vehicle is capable of delivering, but the DSM magnitude will determine the size of the onboard propulsion module that would have to be added to SIM. Finally, the cost savings to the telecom system begin to diminish if the spacecraft ever exceeds 0.4 to 0.6 AU distance from Earth.

As these objectives are somewhat competing with each other, the GA was set to find the non-dominated front of “best solutions” (the space of solutions such that no other solution can be uniformly better than another.) For example, the time duration that the spacecraft spends between 0.2 and 0.4 AU is related with the size of the DSM. One of those objectives may improve at the expense of the other.

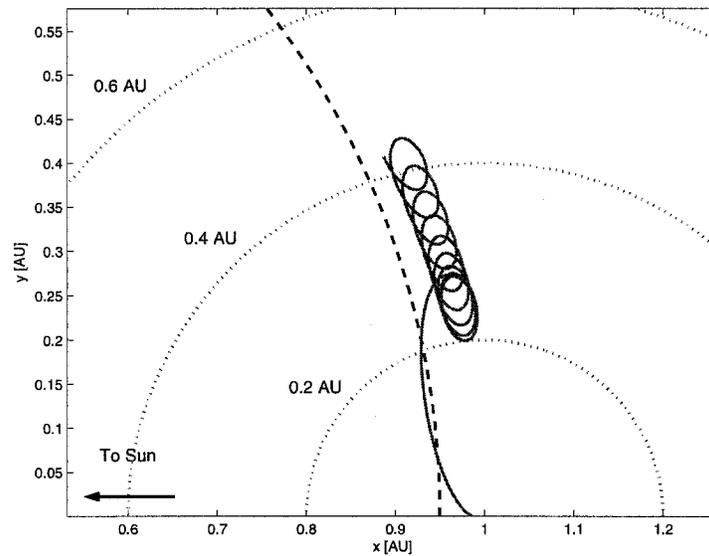


Figure 7. A horseshoe trajectory optimized for maximum time between 0.2 AU and 0.4 AU distance from Earth (the 0.4 AU distance was relaxed slightly to reduce the DSM magnitude). The black line indicates the 0.95 AU Sun-SIM constraint.

Figure 7 depicts an optimized horseshoe trajectory, shown in the Sun-Earth rotating frame. This trajectory was optimized to provide maximum time between 0.2 AU and 0.4 AU (not including time spent before the DSM). This trajectory launches into an ELSO on June 1, 2010 with a C_3 of $0.21 \text{ km}^2/\text{s}^2$. At L (launch) + 270 days (the upper constraint considered for DSM time relative to launch), a $451 \text{ m/s } \Delta V$ is performed, which transfers the spacecraft onto the inbound portion of a horseshoe trajectory. At L + 2.3 years, the spacecraft makes its closest approach to Earth at 0.2 AU, and begins the outbound portion of the horseshoe. The success of the DSM is critical, as the initial trajectory at launch is a poorly performing ELSO, with a

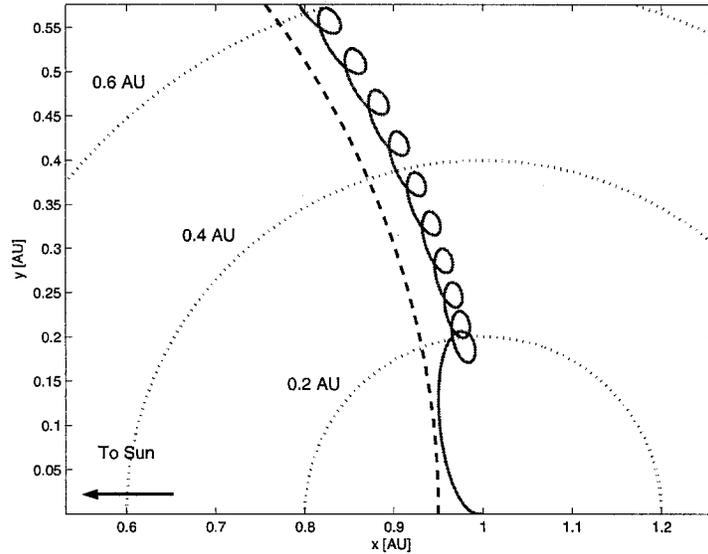


Figure 8. A horseshoe trajectory optimized for maximum time between the DSM and 0.6 AU distance from Earth.

drift rate of about 0.25 AU/year. By comparison, the average drift rate in this horseshoe trajectory is about 0.027 AU/year — an improvement by nearly an order of magnitude. We note that the trajectory does violate the 0.95 AU briefly after launch, however, the thermal sensitivity issues only become significant after the TPS degrades over the life of the mission. The requirement is to stay outside the 0.95 AU constraint after during the extended mission (after $L + 5.5$ years).

If we relax the maximum allowable Earth-SIM distance from 0.4 AU to 0.6 AU, we obtain the horseshoe trajectory shown in Figure 8. This trajectory launches Feb. 14, 2010 with a C_3 of $0.30 \text{ km}^2/\text{s}^2$. As before, the optimal trajectory hit the upper constraint on DSM time, at $L + 270$ days, but the trajectory only has a DSM magnitude of 273 m/s. The drift rate on this horseshoe is about 0.04 AU/year, which is still considerably slower than the ~ 0.1 AU/year drift rates on ETSO trajectories.

III. Conclusions

The science and flight system constraints force SIM to adopt a solar trajectory. Assuming no delta-V capability, the only three options are the ETSO, ELSO, or Oscillating Solar Orbit trajectories. If a DSM of $\sim 200\text{-}500$ m/s is possible (with a corresponding wait time of 8-9 months), then a horseshoe trajectory becomes a viable option. The Oscillating Solar Orbit provides the shortest overall Earth-SIM distance, but fails to meet one of the science requirements and has the smallest margin on launch injection errors. Of the remaining options, the horseshoe trajectory has the lowest drift rate, but at the expense of requiring an onboard propulsion module and several months wait before the start of the science phase. The ETSO trajectory has the next lowest drift rate, but will have the highest DSN contention with Mars-bound spacecraft. Finally, the ELSO has the fastest drift rate of these trajectories.

IV. Acknowledgments

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. I would like to thank the SIM Mission Design Manager Richard Machuzak for pushing to investigate other orbit options, even though the ETSO was the clear winner from the start. I would also like to thank Mark Garcia for his contributions on the SIRTf/Spitzer material.

References

¹Ocampo, C., "Solar Orbit Options for the Space Infrared Telescope Facility," Jet Propulsion Laboratory, JPL IOM 312/91.2-1684, Pasadena, CA.

²Machuzak, R., "Personal communication," Jet Propulsion Laboratory, California Institute of Technology.

³Garcia, M., "SIRTf Trajectory Design and Optimization," *AAS/AIAA Spaceflight Mechanics Meeting*, Santa Barbara, CA, Feb. 2001, pp. 1019-1031, AIAA 01-174.

⁴Garcia, M., "Personal communication," Jet Propulsion Laboratory, California Institute of Technology.