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Getting to L1 the Hard Way: Triana's Launch Options

Martin B. Houghton

NASA's Goddard Space Flight Center, Greenbelt, Maryland 20771, USA
houghton@gssc.nasa.gov • Voice: (301) 286-0694 • Fax: (301) 286-1719

Abstract. Over the past four years, NASA's Goddard Space Flight Center has built and tested the Triana observatory, which will be the first Earth observing science satellite to take advantage of the unique perspective offered by a Lissajous orbit about the first Earth-Sun Lagrange Point (L1). Triana was originally meant to fly on the U.S. Space Transportation System (a.k.a. the Space Shuttle), but complications with the shuttle manifest have forced Triana into a "wait and see" attitude. The observatory is currently being stored at NASA's Goddard Space Flight Center, where it waits for an appropriate launch opportunity to materialize. To that end, several possible alternatives have been considered, including variations on the nominal shuttle deployment scenario, a high inclination Delta-type launch from Vandenberg Air Force Base, a Tsyklon class vehicle launched from Baikonur, Kazakhstan, and a ride on a French Ariane vehicle out of French Guiana into a somewhat arbitrary geostationary transfer orbit (GTO). This paper chronicles and outlines the pros and cons of how each of these opportunities could be used to send Triana on its way to L1.

Introduction

The Triana observatory, built by NASA's Goddard Space Flight Center and shown in Figure 1, will be the first Earth science mission to take advantage of the unique perspective offered by a Lissajous orbit about the first Earth-Sun Lagrange Point (L1). From this vantage point, Triana will, for the first time ever, send back images of a nearly fully lit Earth disk (see Figure 2), in 10 different wavelengths (UV, visible, and near IR), 24 hours a day.

In addition to its Earth viewing instruments, Triana has a suite of solar wind (i.e. space weather) instruments. Collectively, the data from Triana will be used to drive investigations in various research areas and to set the foundation for various education and outreach programs [1].

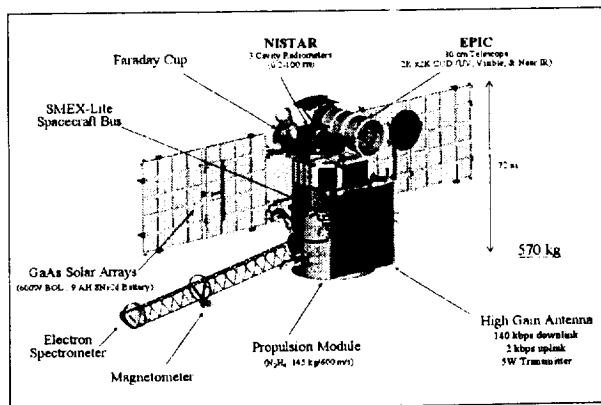


Figure 1: "Artist's rendering" of fully deployed Triana observatory

Baseline Trajectory & Orbit

Triana was originally meant to fly on the U.S. Space Shuttle. Its baseline trajectory is a direct transfer to a 15 x 4 deg (sun-earth-observatory angle) Lissajous orbit about L1. This trajectory flows directly from a circular low Earth orbit (nominally a Space Shuttle orbit) and has an outgoing asymptote that is essentially right along the Earth-sun line (Figure 3). It was chosen to simplify the

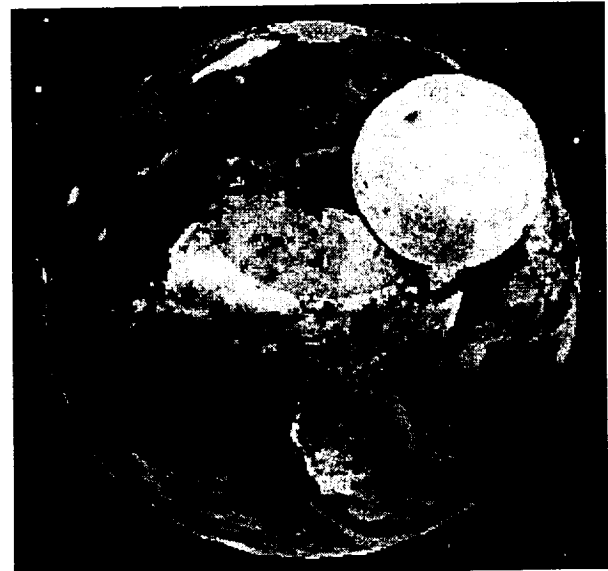


Figure 2: Image representative of those to be taken by Triana at L1 mission design and to minimize manifesting constraints (i.e. no lunar timing issues) with the Space Shuttle.

Triana's baseline mission orbit at L1 (a Lissajous) was designed so that the sun-earth-observatory angle never exceeds 15°, or goes below 4°. This was done to maximize the value of the science data and to avoid any communications issues, respectively. It was designed to accommodate a 2 year minimum mission with a 5 year goal (Figure 4).

Triana as a Shuttle Payload

Triana was originally meant to be flown on the U.S. Space Shuttle. As such, NASA's Goddard Space Flight Center built and tested the Gyroscopic Upper Stage (GUS) to deliver the final thrust needed to get Triana from the Shuttle's low earth orbit (LEO) to an L1 transfer trajectory and to interface Triana with the Italian Research Interim Stage (IRIS) airborne support equipment [2]. The arrangement is illustrated in Figures 5 & 6.

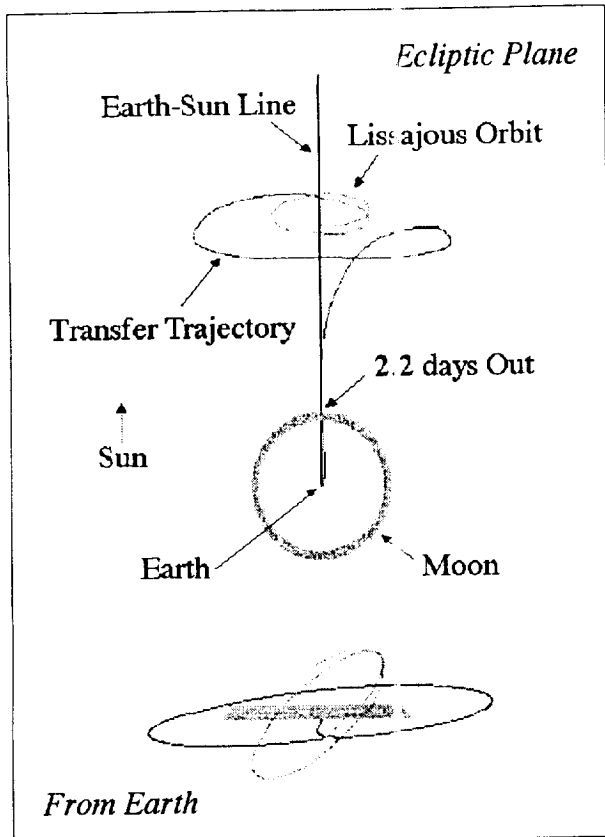


Figure 3: Views of Triana's baseline direct trajectory to L1 orbit

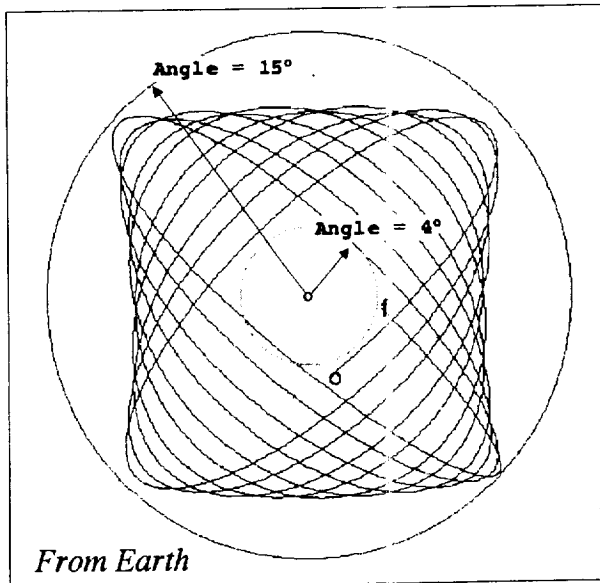


Figure 4: Triana's baseline 15 x 4 deg mission orbit (2-5 year life)

The procedure for actually flying Triana on the Space Shuttle is long and arduous, but begins with the Shuttle Program Office specifying an inclination and altitude for a given manifested mission and the Guidance, Navigation, and Control Center (GNCC) at Goddard generating first-cut LEO state vectors that match the specified conditions and are appropriate for use in getting to L1. Goddard uses a software tool called Generator, which was developed by

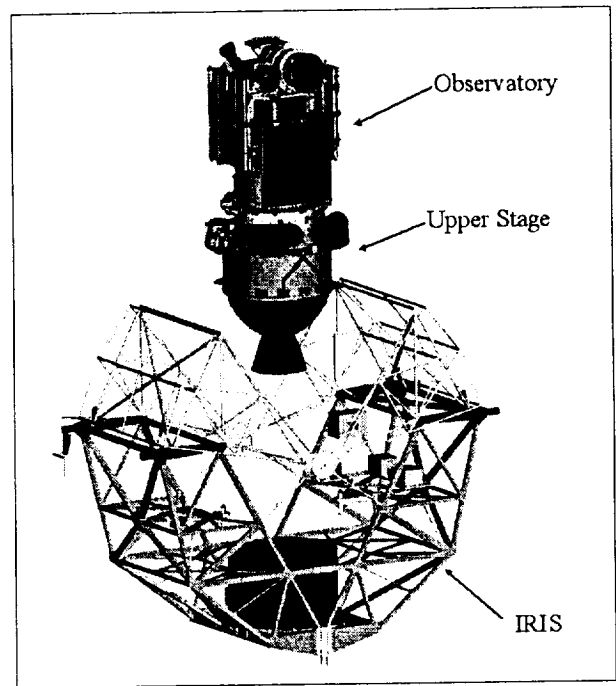


Figure 5: Triana atop its upper stage in proximity to its IRIS "cradle"

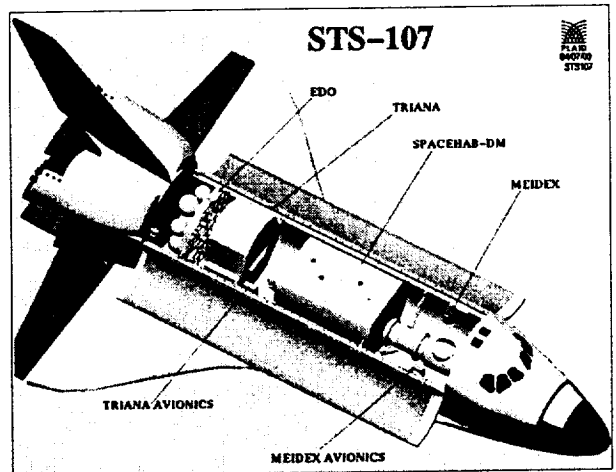


Figure 6: Triana's originally manifested STS-107 accommodations

Purdue University in West Lafayette, Indiana. Generator uses Dynamical Systems Theory (DST) to work "backwards" (using an ephemeris model) from a given Lissajous orbit to a specific LEO state. It uses invariant manifolds (Figure 7) to get initial trajectories which it then passes through a differential corrector to match the LEO conditions. The final solutions are verified by way of "proven" software at Goddard, such as the PC-based Swingby program (which uses high-fidelity force models), and sets of Transfer Trajectory Insertion (TTI) points (and associated ΔV 's) are then produced for use by the Shuttle Program in planning the given Shuttle mission (Table 1) [3].

The Shuttle Program Office works with a given set of TTI points to determine a mission timeline in which they are able to deliver Triana to a specified TTI point at the specified time to within a specified tolerance. In terms of cross-track and along-track errors, the agreed upon toler-

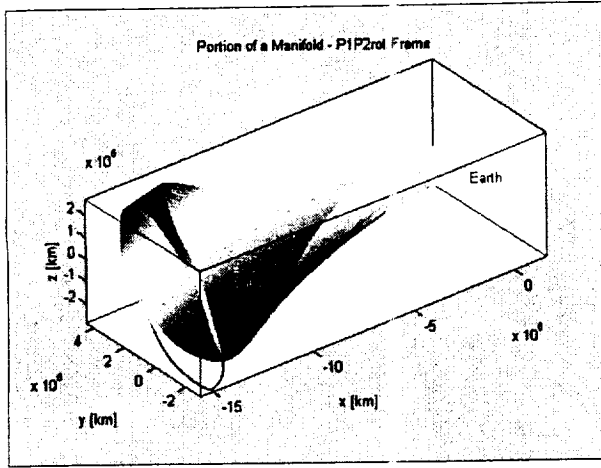


Figure 7: Sample manifold used in Triana's trajectory design process

ances boil down to 3.8° in right ascension and 1 minute in release (along-track) timing. Typical Shuttle orbits regress at rates as high as 0.47° per orbit, so the right ascension constraint gives the Shuttle Program a 16 orbit window to work with – 8 on either side of the TTI point (Figure 8).

Once Triana is released from the Shuttle and the Shuttle is given enough time to maneuver to a "safe distance", the GUS is ignited. The GUS provides a fixed ΔV that is set, by way of ballast weights, prior to launch, in order to match the required ΔV , as computed from the TTI table for the given mission scenario (altitude and inclination). Figure 9 shows how little the actual value changes with TTI date. The GUS is set to match the average value for a given launch period. Triana's hydrazine system is later used to make-up for any release and GUS ΔV errors.

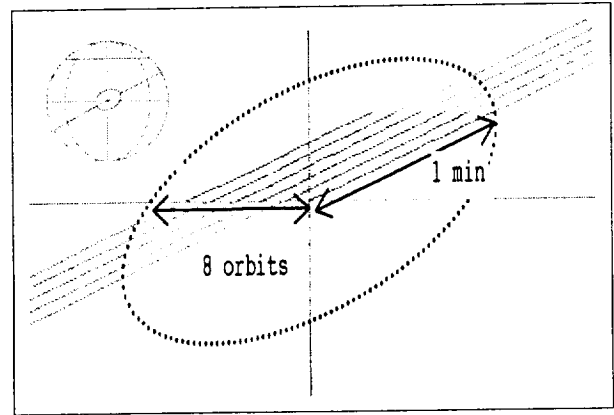


Figure 8: Triana's release window from Shuttle mission perspective

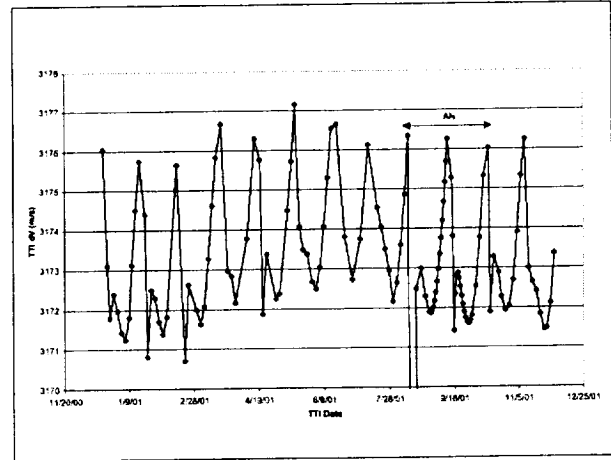


Figure 9: Representative TTI ΔV variation over the course of 1 year

TTI Date & Time (UTC)	Pre-TTI Position Vector (ECI MJ2000) (km)			Pre-TTI Velocity Vector (km/s)			Post-TTI Velocity Vector (ECI MJ2000)		
	X-Pos (pre)	Y-Pos (pre)	Z-Pos (pre)	X-Vel (pre)	Y-Vel (pre)	Z-Vel (pre)	X-Vel (post)	Y-Vel (post)	Z-Vel (post)
03/12/2002 04:54:55.246	-64.96.295660	-1.031.834389	1017.328778	0.545300198	-6.882538272	-3.498582205	0.768524656	-9.699978797	-4.930764184
03/13/2002 07:29:08.686	-65.33.324861	-1.111.128821	607.607440	0.823688739	-6.788818011	-3.624969011	1.161076325	-9.569556432	-5.109776909
03/14/2002 11:58:51.406	-65.09.307254	-1.311.011839	454.330635	1.102960140	-6.732747449	-3.655202927	1.554967693	-9.491915786	-5.153153097
03/15/2002 13:43:58.606	-64.83.153613	-1.451.700794	373.483822	1.295358237	-6.691632520	-3.667561448	1.826309911	-9.434451754	-5.170850526
03/16/2002 14:19:15.406	-64.57.246812	-1.581.433335	313.368529	1.453538958	-6.654868669	-3.675165133	2.049367116	-9.382777809	-5.181658658
03/17/2002 14:43:35.566	-64.31.384405	-1.691.035083	262.749165	1.593303689	-6.619817798	-3.680525835	2.246415876	-9.333351763	-5.189212655
03/18/2002 14:38:07.246	-64.05.365815	-1.751.941048	217.673800	1.721233509	-6.585488814	-3.684501314	2.426759620	-9.284851969	-5.194762340
03/19/2002 14:29:37.486	-63.79.117024	-1.851.370362	176.299456	1.840557349	-6.551457919	-3.687490786	2.594951562	-9.236721675	-5.198892597
03/20/2002 14:20:15.886	-63.52.544855	-1.961.857707	137.518166	1.953424733	-6.517431534	-3.689721093	2.754027949	-9.188574452	-5.201938340
03/21/2002 14:11:54.766	-63.25.505068	-2.061.667391	100.489825	2.061569344	-6.483115177	-3.691335137	2.906439171	-9.140017506	-5.204113586
03/22/2002 14:07:35.566	-62.97.772497	-2.151.998693	64.463595	2.166611243	-6.448146761	-3.692422921	3.054476240	-9.090560728	-5.205556890
03/23/2002 14:00:23.566	-62.68.927544	-2.231.342517	28.582285	2.270522812	-6.411941921	-3.693033680	3.200928512	-9.039401677	-5.206350159
03/24/2002 13:53:02.926	-62.38.485220	-2.311.072543	-7.931316	2.375112945	-6.373859016	-3.693171205	3.348355520	-8.985655214	-5.206510374

TTI Date & Time (UTC)	Pre-TTI State Vector (ADBAR/ MJ2000)			A (deg)	R (km)	V (km/s)	TTI Thrust Unit Vector (ECI MJ2000)		
	RA (deg)	Dec (deg)	B (deg)				X (unit)	Y (unit)	Z (unit)
03/12/2002 04:54:55.246	189.02514096	8.79185282	90.0000	117.21865841	6655.937	7.739945918	0.070452714	-0.889223044	-0.452016363
03/13/2002 07:29:08.686	189.70312839	5.23771139	90.0000	118.05433633	6655.937	7.739955649	0.106420344	-0.877113296	-0.468344933
03/14/2002 11:58:51.406	191.40427361	3.91402220	90.0000	118.25230998	6655.937	7.739955925	0.142502122	-0.869868965	-0.472251129
03/15/2002 13:43:58.606	192.68872125	3.21672100	90.0000	118.33302626	6655.937	7.739955150	0.167359915	-0.864557015	-0.473847894
03/16/2002 14:19:15.406	193.77808485	2.69854325	90.0000	118.38262822	6655.937	7.739954216	0.187796842	-0.859807240	-0.474830345
03/17/2002 14:43:35.566	194.75660548	2.26239085	90.0000	118.41757169	6655.937	7.739953149	0.205854436	-0.855278794	-0.475523012
03/18/2002 14:38:07.246	195.66247199	1.87411844	90.0000	118.44347175	6655.937	7.739952045	0.222382968	-0.850843620	-0.476036711
03/19/2002 14:29:37.486	196.51477783	1.51780227	90.0000	118.46294053	6655.937	7.739950938	0.237799614	-0.846446957	-0.476423018
03/20/2002 14:20:15.886	197.32680159	1.18387106	90.0000	118.47746143	6655.937	7.739949854	0.252382092	-0.842050873	-0.476711240
03/21/2002 14:11:54.766	198.10960415	0.86507153	90.0000	118.48796871	6655.937	7.739948685	0.266354394	-0.837617333	-0.476919846
03/22/2002 14:07:35.566	198.87384987	0.55492557	90.0000	118.49505001	6655.937	7.739947542	0.279925830	-0.833099543	-0.477060458
03/23/2002 14:00:23.566	199.63306922	0.24604340	90.0000	118.49902699	6655.937	7.739946434	0.293351231	-0.828422002	-0.477139437
03/24/2002 13:53:02.926	200.40000554	-0.06827454	90.0000	118.49992508	6655.937	7.739945337	0.306864305	-0.823501813	-0.477157272

Table 1: Sample set of Transfer Trajectory Insertion (TTI) points and velocity information for use in planning Triana's egression from the Shuttle

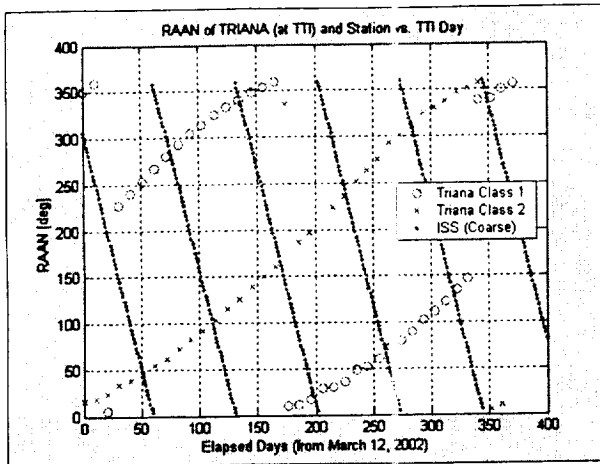


Figure 10: RAAN plot showing 12 opportunities on joint mission [3]

Optional Shuttle Scenarios

Several alternate Shuttle mission scenarios have been considered in an attempt to make Triana as compatible as possible with the Shuttle manifest. Triana was originally meant to fly on STS-107, at 150 nautical miles with an inclination of 39°, but that opportunity evaporated due to circumstances outside the control of Goddard, or anyone involved in the Triana project. Triana has re-baselined for a generic research flight at 150 nautical miles with an inclination of 28.5°. This is considered to be the most likely (Shuttle) scenario. The inclination change causes no real problems. Generator is able to find solutions over a very wide range of inclinations, as evidenced below, without changing the shape of the final Lissajous.

The feasibility of taking Triana along on a retrieval (e.g. UARS) or a rendezvous (e.g. Space Station) mission has been explored. These scenarios pose a problem only in that the right ascension of the ascending node (RAAN) of an object in low earth orbit regresses at a rate of several degrees per day (5 for Space Station, for example), due to the Earth's oblateness, and the RA of Triana's TTI point precesses at roughly 1°/day, due to the Earth's motion about the sun. This creates a situation in which the two coincide (a requirement, if the Shuttle is going to do both on the same flight) only 6 times per year. This number can be doubled by recognizing the fact that there exists one set of TTI points for use near a LEO ascending node and one set for use near a LEO descending node. Combining these sets gives 12 opportunities per year (Figure 10).

A "random release" joint Space Station mission has also been considered. "Random release" refers to the right ascension (RA) constraint on Triana's release point. In this scenario, the Shuttle is free to release Triana on any orbit, of any mission, as long as the Triana Project is allowed to still specify where in the orbit the observatory is released. This way, the Triana Project can constrain Triana's RA at release to lie within a given hemisphere, and, consequently, its apogee (post GUS burn) to lie within a given hemisphere. The GUS ballast, in this case, is set such that Triana is injected into a highly elliptical orbit (HEO) with a period of 14 days, twice the moon's orbital period, so as to minimize the moon's impact on

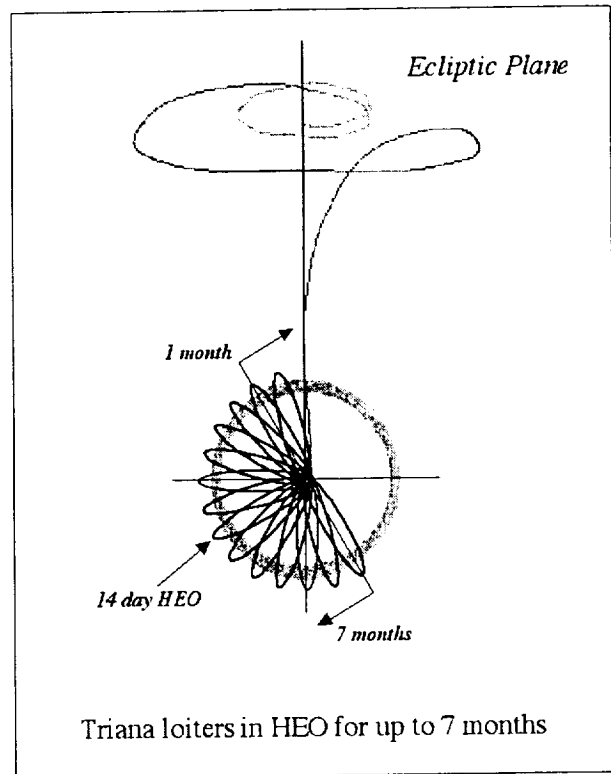


Figure 11: Illustration of "random release" Shuttle mission scenario

the orbit. This way, Triana can loiter while the Earth-sun line precesses around (at roughly 1° per day) to line up with Triana's apogee (Figure 11). Triana's hydrazine system is then used to send Triana the rest of the way to L1. Since the release and GUS ΔV corrections, as well as the final TTI maneuver, can all be done at perigees, this scenario does not differ, considerably, from the baseline scenario, in terms of total ΔV costs.

Looking for an ELV

In light of the lack of success in finding a spot on any near-term Shuttle flight, the Triana Project has explored various expendable launch vehicle (ELV) options, as well, in hopes that an opportunity might ultimately present itself. To that end, Triana's energy requirement can be summarized in one of two ways. Either the observatory, itself, needs to be boosted to a C_3 of $-0.7 \text{ km}^2/\text{s}^2$, or the Triana/GUS stack needs to be placed in a sufficiently high-energy LEO such that the ΔV provided by the GUS is enough to put Triana on the proper trajectory. These relationships are shown in Figures 12 and 13, with the difference being the weight and the required velocities.

Domestically, Delta II ELVs have the capability to boost Triana directly onto its transfer trajectory [4]. The Triana Project considered them at length. Even a flight out of Vandenberg Air Force Base, on the U.S. West Coast, where the resulting inclination would have been in excess of 60°, was considered. Generator was able to find solutions at inclinations as high as 80°. A Delta II appears to be a very viable option, but has never come to fruition, primarily due to a lack of such funding on the Triana Project. Triana's Shuttle launch was meant to be "free".

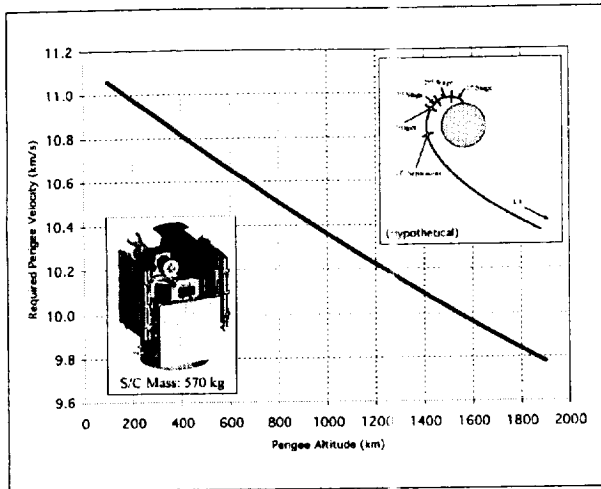


Figure 12: Energy requirement for Triana observatory (C_3 of -0.7)

Discussions with United Start, a Delaware based corporation owned by the American company Assured Space Access, Inc. and the Russian company ZAO Puskovkie Uslugi (Launch Service Provider) [5] have led to the conclusion that a 3-stage version of the Ukrainian Tsyklon vehicle, being proposed by United Start, would be capable of putting the Triana/GUS stack into an orbit with a perigee of 120 km and an apogee of 200 km at an inclination of 51.6° . Figure 14 shows that, as long as the orbit's perigee is within roughly 60° of Triana's TTI point, the Tsyklon/GUS combination is enough to get Triana to L1. It is assumed that the Tsyklon vehicle places Triana/GUS in an orbit whose RAAN is specified by the Triana Project.

Triangular Transfer Trajectories

The final and possibly the most difficult to accommodate ELV considered for use by the Triana Project is the French Ariane 5. What makes this opportunity difficult is the fact that Triana would need to be co-manifested with some other payload, and the Ariane's standard product is a rather specific geostationary transfer orbit (GTO). The Ariane "constraints" would put Triana into an orbit whose line of apsides is as much as 45 minutes (11.25° in RA) off the Earth-sun line and 23.4° off the ecliptic [6]. Compared to the Shuttle tolerance of 3.8° in RA, 11.25° is excessive. What makes this scenario possible is a "triangular" transfer trajectory first proposed by Purdue University as a possible Shuttle contingency option [7]. These trajectories have departing asymptotes that are much farther off the Earth-sun line than the baseline trajectory (which is right along the Earth-sun line), easily encompassing the 11.25° (Figure 15).

Putting Triana into an orbit with a 7.5 day period (roughly) would allow the triangular transfer trajectories to be achieved, ultimately, from anywhere within the line of apsides RA range (Figure 16). It would just be a matter of letting the Earth-sun line precess to the proper spot, while waiting in up to 2 phasing loops.

As for the inclination issue, it's possible to enter into a Lissajous at L1 from any of the given ecliptic inclinations, but doing so determines the z-amplitude of the

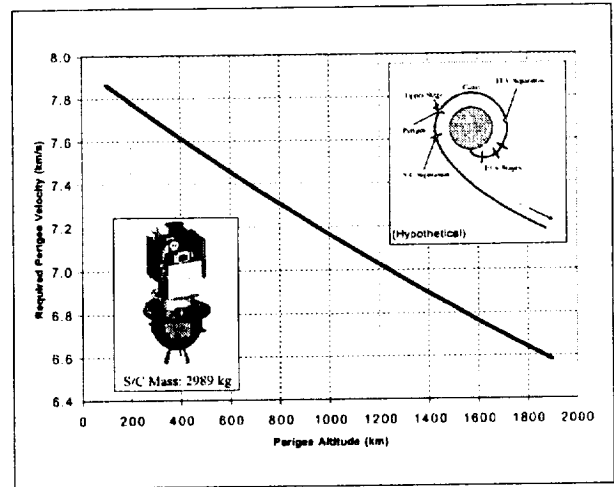


Figure 13: Requirement placed on LEO state for use by Triana/GUS

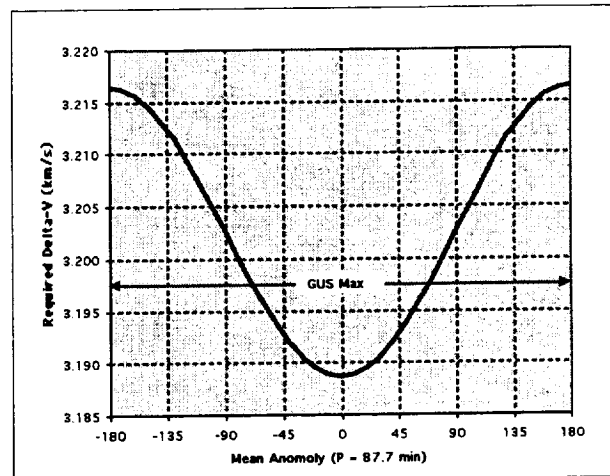


Figure 14: Tsyklon/GUS "energy balance" for getting Triana to L1

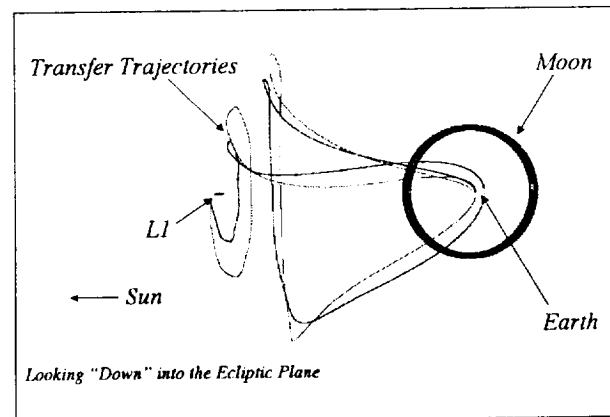


Figure 15: "Triangular" transfer trajectories for use in getting to L1

resulting Lissajous (Figure 17). A ΔV would be required to lower (or raise) the z-amplitude to match the mission orbit. The cost of doing so was shown to be manageable (10^3 's of m/s). There is an additional issue with particularly low inclinations in that there will be a communications loss as the observatory passes in front of the sun. All of these nuances are ultimately manageable [8].

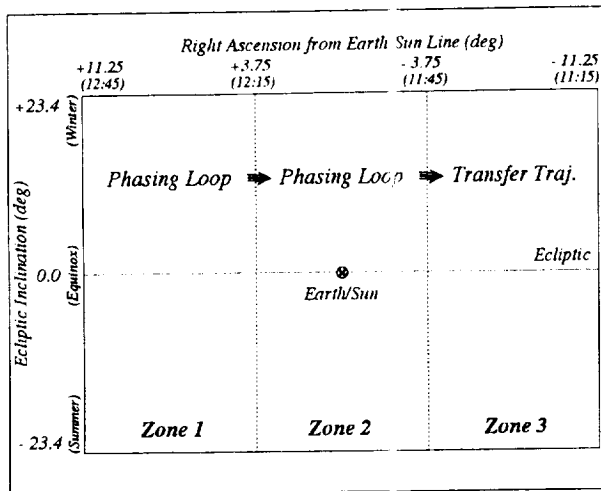


Figure 16: Line of apsides with respect to the Earth-sun line (Ariane)

Conclusion

There are several ways of getting a satellite, such as Triana, to L1, and they're not all equal. Clearly the most sensible solution is to have a dedicated launch vehicle for any satellite that is going to L1, or any Lagrange point for that matter. From the standpoint of targeting, Lagrange point missions are essentially no different than interplanetary missions. They're relatively hard to hit. Anything that makes that task more difficult than it already is should be avoided.

The sensible approach notwithstanding, Goddard Space Flight Center has shown that there are several options for getting Triana to L1, apart from the baseline Shuttle deployment scenario. It was shown that there are feasible ways of flying Triana on a rendezvous/retrieval type Shuttle mission and that the TTI point RA constraint can, if necessary, be lifted, through the use of phasing loops, allowing for even greater flexibility. The inclination of the LEO orbit from which Triana departs was also shown to be relatively unimportant. This was evident in the Delta II study, which looked at inclinations as high as 80°. Other considered options include a version of the Ukrainian Tsyklon vehicle and a co-manifested flight on an Ariane 5 launch vehicle. The latter option would involve the use of phasing loops and a "triangular" transfer trajectory. Such flexibilities in mission planning approaches make a plethora of options ultimately available.

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 [3] G. Marr, S. Cooley, et al.; "Triana Trajectory Design Peer Review" (Package); September 26, 2001.
 [4] Delta II Payload Planners Guide - www.boeing.com
 [5] United Start Corporation - www.unitedstart.com

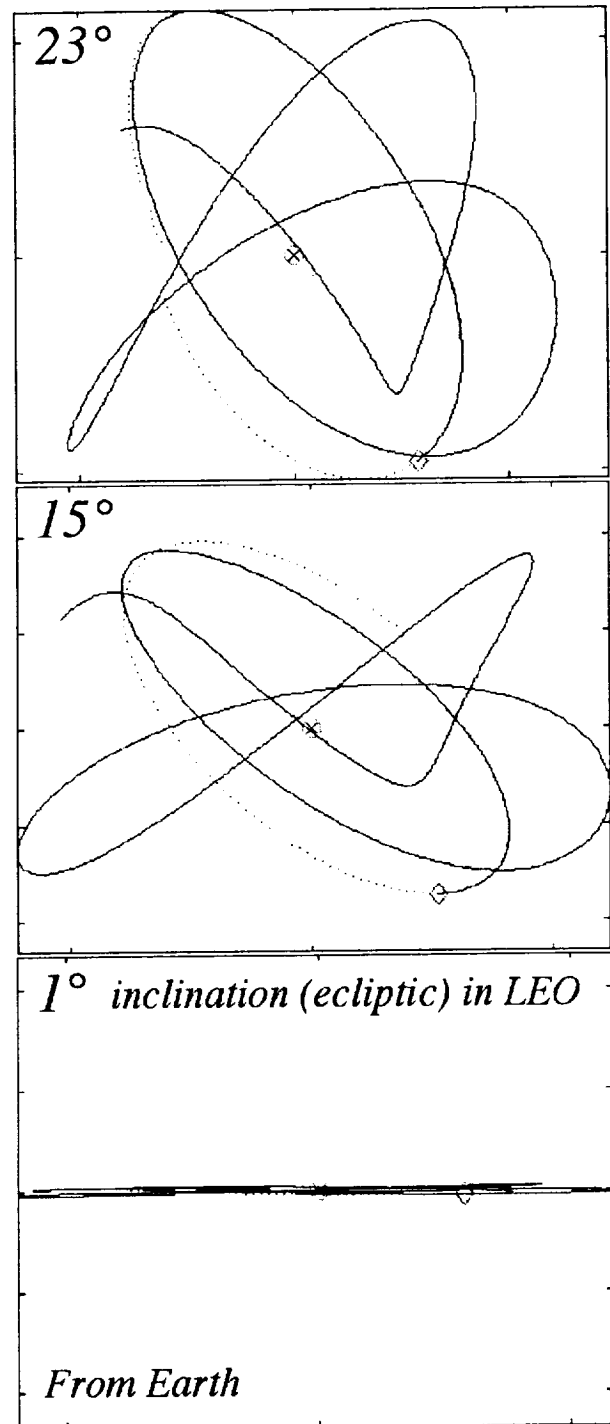


Figure 17: "Triangular" transfer trajectories for different inclinations

[6] Ariane 5 User's Manual - www.arianespace.com
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