SIRTF Mission Design

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NASA will launch the Space Infrared Telescope Facility (SIRTF) from Cape Canaveral Air Force Station on April 15, 2003 following two decades of development, several false starts, and recent project delays. The launch – the first aboard the Delta II 7920H launch vehicle – will place SIRTF into an Earth-trailing solar orbit where it will immediately enter a 90-day In Orbit Checkout and Science Verification (IOC/SV) period. Activities during the first 90 days are designed to commission the Observatory for the expected post-IOC/SV lifetime of 2.5 to 5 years. During this "nominal operations" phase, SIRTF will be performing the most advanced infrared astronomy to date. This paper presents how the mission has been designed to facilitate science data collection, with special emphasis on how the flight path meets, and in some cases far exceeds, the requirements of the various SIRTF systems.

INTRODUCTION

SIRTF is NASA's fourth and final "Great Observatory". The Great Observatories – a series of space telescopes including the Hubble Space Telescope, the Compton Gamma Ray Observatory, and the Chandra X-ray Observatory – are each designed to study a different part of the electromagnetic spectrum. SIRTF covers the infrared portion, where its detectors provide imaging, photometry, and spectroscopy over the 3-180 μm wavelength range[1]. SIRTF observing time is available to the entire scientific community, and as one of three Great Observatories flying over the next few years, SIRTF will often be sequenced to carry out complementary observations with the other two, a practice that will undoubtedly prove popular to the scientific community.

For SIRTF to be able to study objects that are as cold as a few degrees Kelvin, it must take stringent measures to reduce its own thermal signature. The SIRTF telescope is cooled to its extremely low operating temperature of 5.5 K (the telescope launches at room temperature) following a 45-day cooldown period. During this cooldown period, heat is removed through the combination of radiation to cold space and the advantageous routing of helium vapor boiled off from SIRTF's liquid helium cryostat to the warm telescope[2,3]. The solar orbit further aids SIRTF's thermal design since it distances the Observatory from

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the heat input of the Earth-Moon system, as well as keeping it far clear of the Earth's trapped radiation environment.

In addition to the thermal advantages afforded by the solar orbit, SIRTF's flight path design has been driven largely by the long term need to accommodate the capabilities of the telecom subsystem, and the short term need to survive the launch/ascent environment. Telecom performance and target visibility windows are also key drivers during the IOC/SV period. This paper discusses how well the flight path design, when coupled with the telescope's pointing constraints, meets the telecom requirements, as well as those imposed by the need to minimize solar illumination during ascent. Following sections describing SIRTF's recent history and its mission phases, discussion will focus on: how the solar orbit combines with the pointing constraints to form lengthy visibility windows for science and calibration targets; the steps taken to minimize the impact of both the launch vehicle 2nd stage and the Observatory's dust cover on science observations; how come the spacecraft can get away without having an onboard propulsion system; and other special topics.

RECENT HISTORY

As recently as the eve of Thanksgiving 2002, SIRTF's project schedule was continuing apace to accommodate a planned launch on January 9th, 2003 – the first day of a 60-day launch period extending through March 9, 2003 (plans were also being developed for a possible launch on the 29th of January). As chronicled in the December 6, 2002 issue of Science, NASA postponed SIRTF's launch when it became apparent that a GPS satellite, damaged during erection on the same launch pad, could place SIRTF's launch in jeopardy as steps were taken to repair the damage[4]. It wasn't immediately known how long the delay would last, but since it generally requires 6 weeks between launches on the same pad, the early bet was that SIRTF's launch would slip past March 9th. Fortunately, targets for an "insurance" launch period were delivered to Boeing some two weeks prior to the postponement on the off chance that something might cause launch to slip past March 9th. This new Target Specification listed requirements for a launch on any day between April 15th and May 20th (the 7920H <u>can</u> meet SIRTF injection requirements for every day between April 15th and September 9th), May 20th chosen as an end date because it was roughly 6 weeks prior to the open of the MER-B launch period, the next launch on SIRTF's pad.

Most team members saw the delay as a great risk reduction opportunity because it allowed for continued system simulation and testing, the delivery of numerous updated software components prior to launch, increased training sessions, and more time to finish documentation. At first glance, the Mission Design team did <u>not</u> welcome the delay because it meant that roughly a year of work geared toward designing the "winter" (January through March) flight path and understanding its attributes was down the tubes. Furthermore, there were now just a few months to completely redesign the mission for a "spring" launch. As time passed, however, it became apparent that the tools built to implement the winter launch scenario and the knowledge gained in the design process would be largely applicable to the spring launch problem. In fact, the targets for the Detailed Test Objectives (DTO) version of the spring launch Target Specification were both solved for and verified in one weekend thanks to the versatility of the search software coupled with the ability to reuse the previous year's Preliminary Mission Analysis (PMA) injection solutions as a starting point for the new solutions.

Not all of the spring launch mission design products have been completed as of this writing, but none of the missing items (mostly documentation) are considered flight critical. Where necessary, some results presented in this paper will be for the winter launch scenario, with additional discussion of the differences between those items and the corresponding items for the spring launch.

MISSION OVERVIEW

SIRTF's extreme sensitivity – which derives from the combination of its state-of-the art infrared detector arrays and the fact that cryogenic space telescopes are intrinsically sensitive – will give SIRTF a tremendous gain in capability over previous infrared space telescopes. SIRTF will use its unprecedented sensitivity to study four main science themes:

> Protoplanetary and Planetary Debris Disks – the study of material around nearby stars which is indicative either of a planetary system in formation or of a more mature planetary system which replenishes the circumstellar matter.
>
> Brown Dwarfs and Super Planets – understanding the formation, composition, and structure of objects with masses between 0.001 and 0.1 times that of the sun, objects which are too low in mass to have star-like brightness but which glow faintly in the infrared due to the heat generated as they form.
>
> Ultraluminous Galaxies and Active Galactic Nuclei – the exploration of the most luminous objects in the nearby and distant Universe, objects which may radiate predominantly at infrared wavelengths and have thousands of times the power output of our own Milky Way galaxy.
>
> The Early Universe – the study of the formation and evolution of galaxies, looking back to an epoch when the Universe was no more than one-fifth of its current size and age.‡

SIRTF's state-of-the art infrared detector arrays are housed in three science instruments: the Infrared Array Camera (IRAC), the Multiband Imaging Photometer for SIRTF (MIPS), and the Infrared Spectrograph (IRS). The instruments are installed in the cryostat as shown in Figure 1, with their individual Fields of View (FOVs) projecting on the celestial sphere as shown in Figure 2.

Figure 1 Instruments Installed in the Cryostat

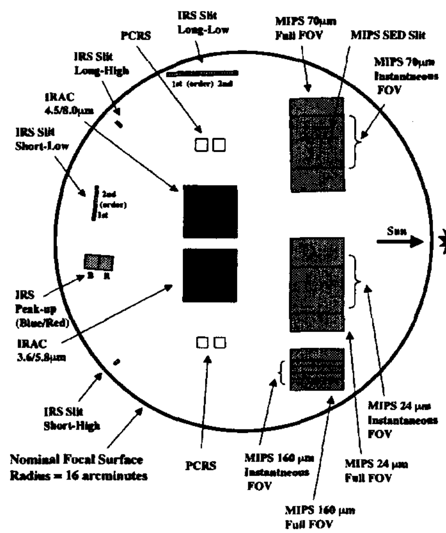

Figure 2 Focal Plane FOV Sky Projections

MISSION PHASES

Perhaps the most significant driver on SIRTF's mission design is the fact that the superfluid liquid Helium cryogen begins boiling off as soon as the Ground Service Equipment is disconnected just before liftoff. This cryogen is required to last for 32 months, with lifetime projections currently showing that it could last for as long as 62 months[2]. Regardless of how long it actually lasts, once it's gone the telescope

‡ Gallagher, D. B., Irace, W. R., and Werner, M. W., "Development of the Space Infrared Telescope Facility (SIRTF)," 2002 Proc. SPIE 4850.

will begin to heat up and science observations from at least two of the instruments (IRS and MIPS) will no longer be possible, and observations from the third (IRAC) will be degraded. For this reason, routine science observations need to begin as soon as possible after launch, but not before several events critical to the success of the mission have taken place.

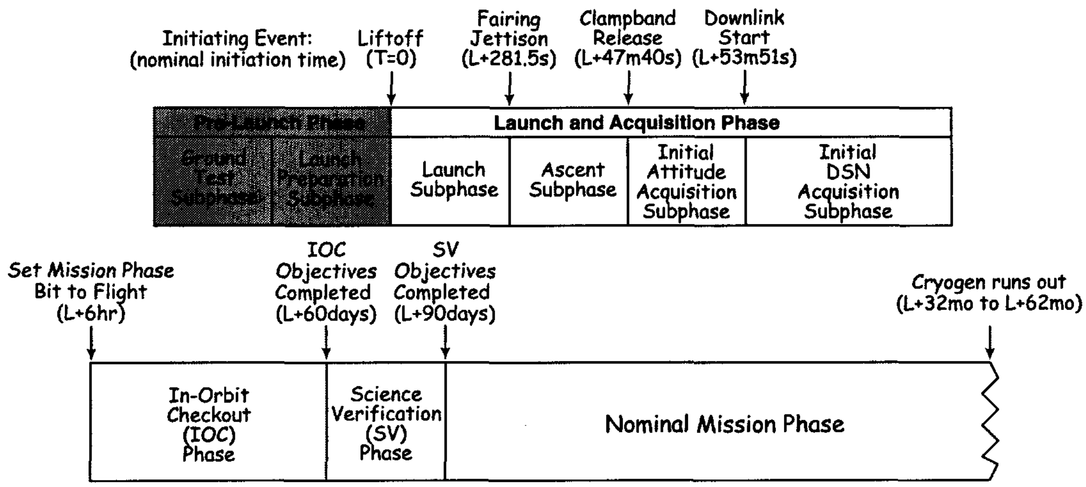

Figure 3 Mission Phases

In order for the Observatory's thermal design to function as intended, either one of two vent valves must be activated while the 2nd stage is thrusting. This activation occurs during the Ascent Subphase (see Figure 3) and is keyed to the Observatory's sensing that the Payload Fairing has been jettisoned. There are several layers of redundancy built into the Observatory components (both hardware and software) to make sure those valves get activated, but there will be several tense moments on the ground until the first telemetry indications are received showing that the valves activated according to design. If for some reason telemetry indicates that activation did not occur, then contingency activation commands will be uplinked from Canberra during the initial DSN station pass. One main benefit of the spring launch is that this first DSN pass occurs less than an hour after liftoff, whereas it didn't occur until nearly three hours after liftoff for the winter launch (although plans were being implemented to contract a non-DSN station in Hartebeesthoek, South Africa to uplink those contingency commands less than an hour after liftoff.) See the April 15, 2003 launch/ascent groundtrack (Figure 4) to get a sense of the timing of these early events.

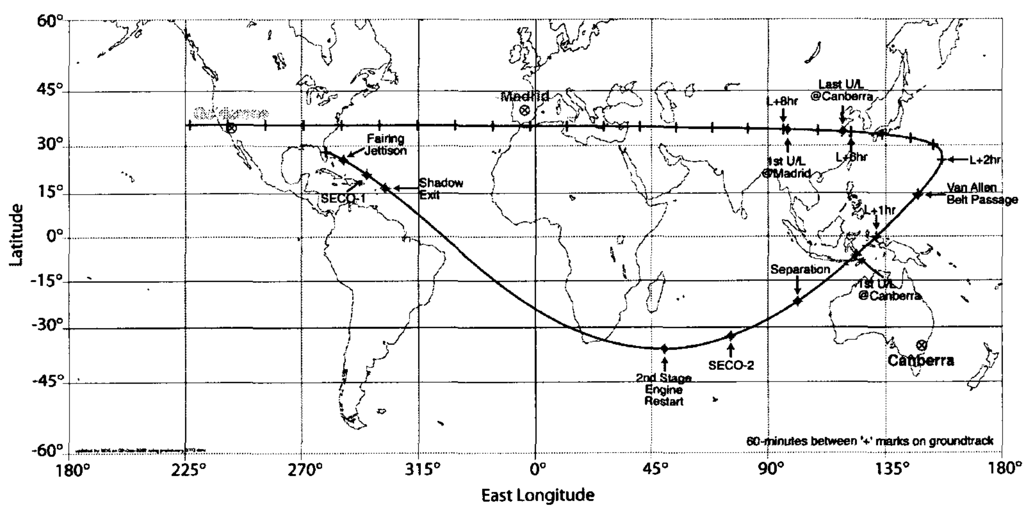

Figure 4 Groundtrack for SIRTF launch (107° Dogleg) on April 15th

The routine science (Nominal Mission) phase cannot begin until the Observatory is "commissioned", a process that is carried out during the in-orbit checkout (IOC) and science verification (SV) phases[5]. The emphasis for the IOC phase is to verify that the Observatory survived launch and is functioning correctly, as well as to demonstrate that the facility meets its Level 1 requirements. IOC is particularly challenging because the telescope nominally takes 45 days to cool to its operating temperature of 5.5 K and IOC itself must be completed in 60 days. During SV, the emphasis switches to characterizing the observatory's in-orbit performance, demonstrating autonomous operations, conducting early release observations, and exercising the ground systems software, processes, and staffing sufficiently to commission the facility for routine operations.[§]

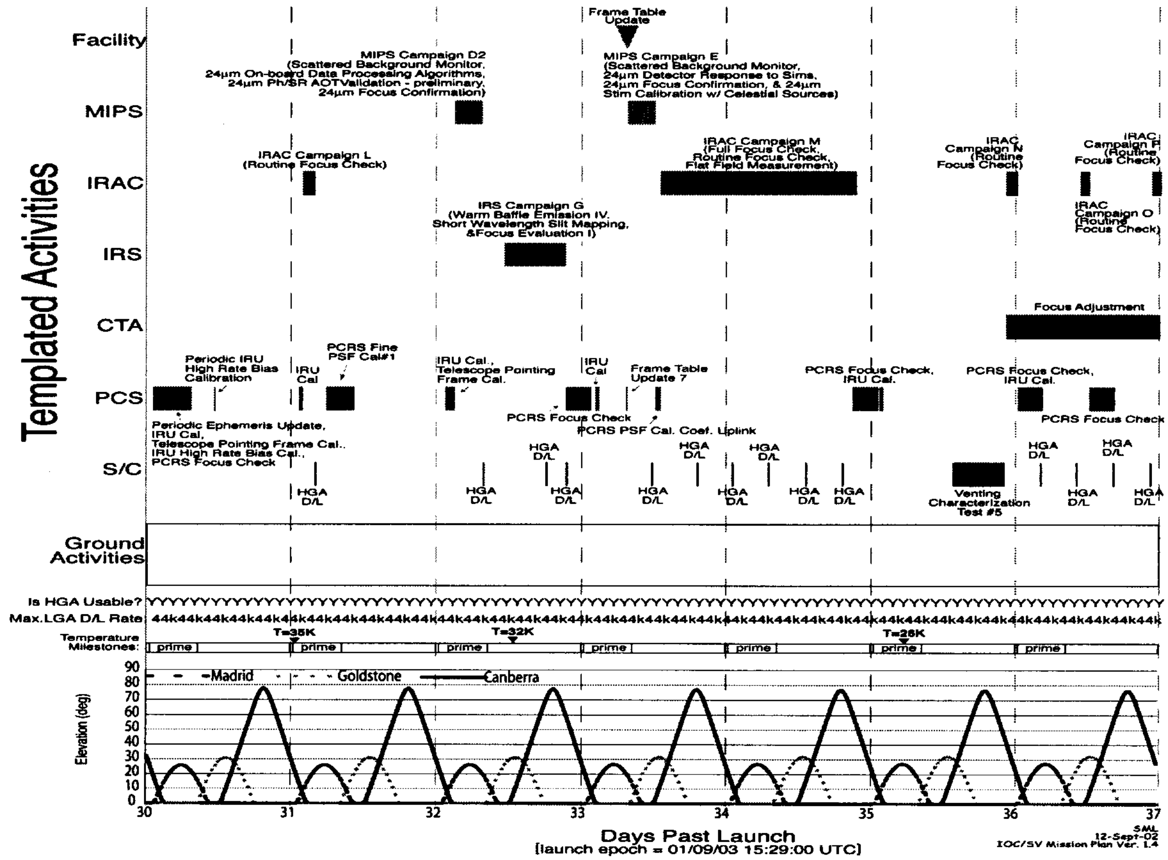

Figure 5 IOC Timeline

The activities needed to commission the Observatory and the constraints affecting their placement in the IOC/SV schedule are now well known because of many months of intense planning. Most of the command sequences implementing these activities onboard the Observatory had been built, tested and validated for the January 9th launch, and are just now being rebuilt for an April 15th launch. Fortunately, most of the targets required for either science or calibration activities during IOC/SV are located in the Continuous Viewing Zone (see Figure 7), which means that new targets do not need to be found for the majority of activities which in turn greatly reduces the time needed to revalidate the command sequences. See Figure 5 for a sample of the IOC/SV Timeline that was built for a January 9th launch. The version of the IOC/SV timeline seen in Figure 5 is built by hand using the Adobe Illustrator drawing program once a constraint-free schedule has been put together using two separate scheduling programs (Microsoft Project

[§] Miles, J. W. and Kwok, J. H., "The SIRTF In-Orbit Checkout and Science Verification Plan," 2002 Proc. SPIE 4850.

and JPL's APGEN activity plan generation tool) working in tandem. This so-called "Illustrator Timeline" is widely used throughout the Project as it is the best tool for keeping everyone informed of the "big picture".

The timeline above clearly shows that the majority of prior planning was geared toward ensuring that Observatory activities and constraints were satisfied. Ongoing Operational Readiness Testing has given a clearer understanding of how the workflow will go on the ground. The next version of the Illustrator timeline will show the major Ground Activity timelines and process flows. These include data flow scenarios through the DSN and back through JPL to the Science Center, negotiated DSN station allocations, IOC re-planning and sequence build schedules. Another notion that is immediately apparent in the timeline is that only one instrument is "active" at a time. This is not only true during IOC/SV but during the nominal mission as well. Only allowing one instrument at a time to be on and taking data is a major part of SIRTF's design.

Once routine science begins, the Observatory is required to have an extremely high observational efficiency, with activities such as downlinking data detracting from observing time (later discussion will point out how the solar orbit and the telecom subsystem design enhance the observing efficiency). Science Instruments (SIs) will be active one-at-a-time for three to seven day periods. Since each SI requires a different maximum telescope temperature at which it can operate, there are SI cycling scenarios that can be conceived which maximize the helium lifetime. For example, if the cycle goes IRS→IRAC→MIPS and the telescope temperature is allowed to fluctuate during each seven day period, the helium lifetime can be as long as 5.93 years.[2]

Data is ingested onboard at an average rate of nearly 90 kbps and downlinked to the DSN approximately every 12 hours. SIRTF downlinks data at 2.2 Mbps – the highest rate ever supported at the DSN for a deep space mission – via its bodyfixed High Gain Antenna (HGA). Figure 6 shows how SIRTF's link performance plays out as a function of distance from Earth. Also shown are range markers at three critical junctions during the mission, with the Project's DSN antenna request superimposed between each marker. Link margins are calculated assuming 90% weather and a 20° station elevation at Canberra. The maximum range supportable for each of the telecom configurations is determined when the link margin drops to 2 dB.

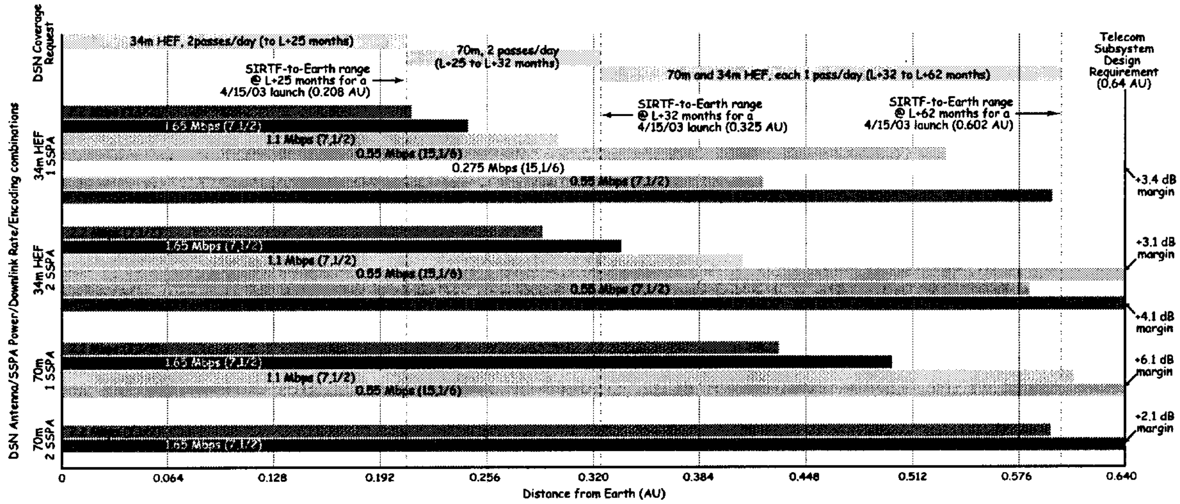

Figure 6 HGA Link Performance for Various Telecom Configurations

When overhead is taken into account it takes approximately 34 minutes to downlink 12 hours worth of data (4 Gbits) at 2.2 Mbps. A full hour is requested for each DSN pass, however, to give time to retransmit missed packets from previous passes before they are eventually overwritten in mass memory. Sequences are uplinked to the spacecraft simultaneous with downlink. Two-way coherent doppler data are collected during every pass for Orbit Determination (OD) purposes. This radiometric data collection profile allows JPL Multi-Mission Navigation to easily meet SIRTF's navigation requirements of 0.015° angular location accuracy and 2 KHz frequency predict accuracy (translates to 70 m/s velocity knowledge accuracy[6]. These requirements derive from how well the orbit needs to be known in order to point the 70m DSN antennas. SIRTF has no more stringent OD accuracy requirements than these, but solar system science benefits the more accurately that SIRTF's flight path is known. Navigation has come up with several strategies to ensure that the best orbit solution is available both on the ground and aboard the spacecraft at all times. The first strategy is to characterize the non-gravitational force model (aka, "small forces") as accurately as possible. The main non-gravitational force, solar radiation pressure, is computed using a detailed material properties model of the Observatory in conjunction with a robust attitude history profile (both in "predict" and "as run" modes). The spacecraft team also delivers information about ΔV due to momentum dumping (which also relies on the pointing history when this contribution is added to the small force model). Helium venting is characterized during several special tests during IOC that are designed to ascertain if there is any observable bias to the vent signature. Outside of that, venting is treated as a stochastic acceleration on the order of 4.0×10^{-12} km^2/s^2 in an essentially random direction in the small force model.

The OD solution is also kept as accurate as possible because new ones are delivered no more than one-month apart and always based on the latest radiometric data and small force input. Navigation also takes advantage of the dense tracking schedule early in the mission (continuous coverage for the first 2 weeks, 85% coverage for the remainder of IOC) to gather as much doppler data as possible. During the nominal mission when tracking passes are 12 ±2 hours apart, it is likely that one pass will be from a northern hemisphere complex (either Madrid or Goldstone) and one from the southern hemisphere complex (Canberra), which aids the OD process. After L+32 months when the maximum supportable downlink rate to the 34m High Efficiency Feed (HEF) antennas drops below 2.2 Mbps, it will take longer to downlink the same amount of data. The OD solution will naturally benefit from the increase in radiometric data that comes as a by-product.

THE SOLAR ORBIT

"Solar orbit" refers to low energy trajectories ($C_3<1$) whose orbit around the sun is very similar to the Earth's. The orbit that SIRTF will be injected into has a period that is slightly longer (372 days) than the Earth's. As a result, SIRTF will drift further behind the Earth over the course of the mission. The particular solar orbit that SIRTF flies is called an "Earth-trailing" orbit (as opposed to the "Earth-leading" orbit where the orbital period is slightly shorter than the Earth's).

Trajectory Constraints

As mentioned in the introduction, SIRTF's flight path design is driven largely by the telecom subsystem design, which in turn is subject to the pointing constraints that ensure the health and safety of the Observatory. These pointing constraints are shown graphically in Figure 7. After Dust Cover Ejection, the Observatory boresight (Observatory +X axis) cannot be pointed any closer than 80° toward the Sun (otherwise sunlight could get down the barrel). This constraint forms an exclusion region centered on the Sun known as the "Sun Avoidance Zone". Furthermore, +X cannot be pointed more than 120° from the sunline. This constraint serves both to keep sunlight off the radome covering the HGA and to insure that the flux incident on the solar arrays is maintained within levels needed for powering the Observatory. The pointing exclusion region created by this constraint is centered on the anti-Sun line and is known as the "Anti-Sun Avoidance Zone". The region of sky between these two Avoidance zones is the Operational Pointing Zone or OPZ. The edges of the OPZ move roughly 1°/day as SIRTF orbits the Sun. This means that targets in the plane of SIRTF's orbit (which is nearly coplanar with the ecliptic) are within the OPZ for 40 days at a time. As can be seen in Figure 7, targets stay within the OPZ longer and longer the further they are from the orbit plane. Targets that are more than 80° from the orbit plane can always be seen by SIRTF. These targets lie within the Constant (Continuous) Viewing Zone or CVZ.

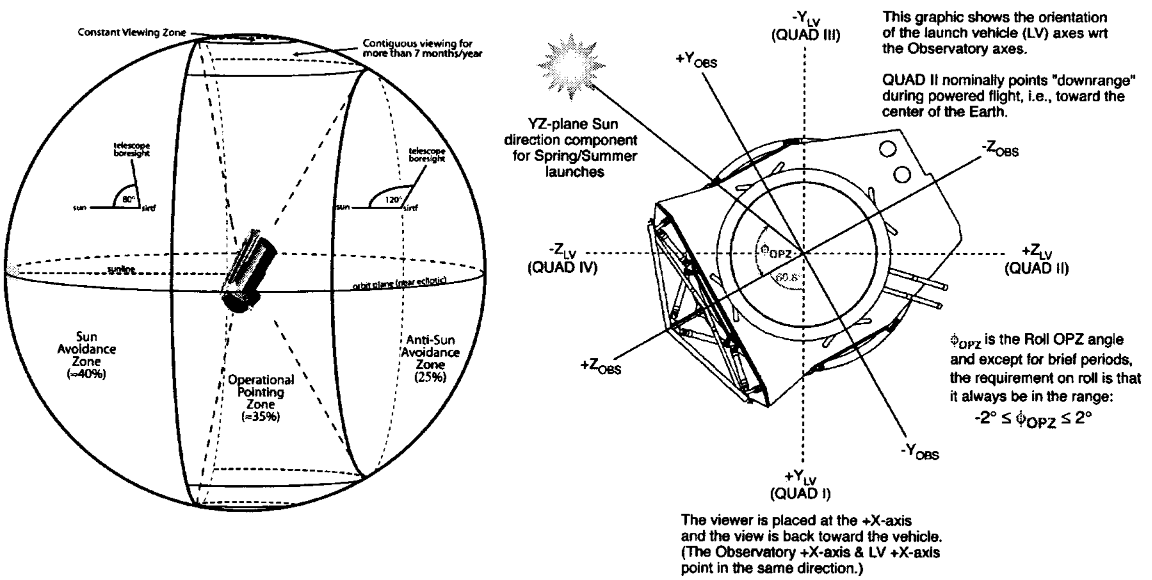

Figure 7 SIRTF OPZ and Coordinate System Description

Target "attitudes", either for putting science targets on the SI Fields-of-View or when orienting the Observatory for communications, are acquired via rotational motion about the Observatory axes shown in Figure 7. (Figure 7 also explains how SIRTF is oriented inside the launch vehicle.) "Pitch" is defined as rotational motion about the +Y axis. "Yaw" is rotational motion about the +Z axis (solar panel normal). "Roll" is rotational motion about the +X axis (telescope boresight). Rotational motion about these axes is constrained as defined in the previous paragraph. In terms of these Pitch-Yaw-Roll rotational motions, the OPZ can be defined as:

- Pitch angles from -10° to +30°
- Unlimited Yaw from 0° to 360° when +Z is pointed at the Sun (0° pitch)
- Roll angles from -2° to +2°

The High Gain Antenna (HGA) is canted 8° from the –X-axis towards the +Z axis. This allows the HGA to be used earlier in the IOC/SV period. The impact of the OPZ constraints and the HGA alignment on the trajectory design is that the Sun-Probe-Earth (SPE) angle must remain between 52° and 92° when HGA communications are required (from Launch+24 days to End of Mission)[7]. The trajectory is further constrained to have a maximum range of 0.64 AU from the Earth in order to satisfy the "safemode" communications design requirement.

The number of days after launch at which HGA communications are "required" to begin has always been a topic of much debate. Starting around the time of the project Critical Design Review, it became apparent that high rate (HGA) communications would be required within 30 days of launch, so Day 30 was adopted as an additional orbit design criterion. Late in the game, however, IOC planners adopted Day 24 as the date that the HGA would become available, regardless of whether or not the trajectory geometry would allow (this decision was made when the baseline trajectory geometry for a January 9th, 2003 launch easily allowed a transition by Day 24). Now that the baseline trajectory (April 15th, 2003 launch) does not allow transition until Day 30 (see Table 2) an alternative HGA Earthpoint scenario had to be devised. (A later discussion details how this problem was solved.) Table 1 gives a list of the telecom and pointing constraints used for trajectory optimization. Some of the constraints in Table 1 have been changed from what was mentioned above in order to provide an extra level of conservatism and to accommodate for injection error from the Delta.

Table 1

TRAJECTORY OPTIMIZATION CONSTRAINTS

Constraint #	Long Term Orbit Design Constraints
1-1	The maximum distance from Earth will not exceed 0.64 AU
1-2	The HGA will be useable by Day 30 (HGA 1st use is at SPE = 52.5°)
1-3	The maximum Sun-Probe-Earth angle (SPE) will be less than 90°
1-4	Once we're able to use it, the HGA will be available for high rate communications for the rest of the mission, i.e., the orbit geometry will not cause an OPZ violation when pointing the HGA at the Earth. This implies that after Day 30, the allowable range of Sun-Probe-Earth angles is 52.5° ≤ SPE ≤ 90°.
	Ascent Trajectory Performance, Timing and Geometry Constraints
2-1	The ascent trajectory will be designed so that the Observatory spends no more than 20 minutes in the shadow of the Earth after liftoff.
2-2	After payload fairing jettison and while attached to the 2nd stage, the Observatory will be outside of an OPZ-compatible attitude for at most 10 minutes (cumulative duration).
2-3	For launches where liftoff occurs in darkness, the Observatory will be placed in an attitude that points its +Z-axis at the Sun by the time of shadow exit.
2-4	The probability of command shutdown (PCS) of the Delta second stage shall be greater than or equal to 99.7% for all launch opportunities.

SIRTF Solar Orbits

The trajectory constraints imposed on the mission limit the family of Earth-trailing solar orbits available to SIRTF. Injection targets resulting in suitable trajectories all have common characteristics when viewed in the proper coordinate system. Figure 8 plots the outgoing $\mathbf{V}_\infty$ vector in a coordinate frame that is formed by the Earth-Sun Line and the ecliptic plane at the time of injection. Using this new coordinate system, it turns out that the SIRTF outgoing $\mathbf{V}_\infty$ vector will always have similar angular magnitudes for each and every launch day no matter when the launch happens throughout the year[6]. Ecliptic Clock is defined in Figure 8 as the angle in the ecliptic plane between the Earth-Sun line and the projection of the outgoing $\mathbf{V}_\infty$ vector. Ecliptic Cone is the angle between the outgoing $\mathbf{V}_\infty$ vector and the ecliptic plane, positive values indicating that the outgoing vector is above the ecliptic. To meet SIRTF's trajectory constraints it has been determined that Ecliptic Clock for all launch dates is about 172° ±2°, and that the magnitude of Ecliptic Cone must be between roughly 44° and 52°, with positive values being indicative of a "summer" launch and negative values indicative of a "winter" launch. Ecliptic cone angles with magnitudes at the larger end of the acceptable range result in trajectories that can use the HGA earlier and do not bump up against the maximum SPE constraint, but drift away from Earth at a faster rate. SIRTF cannot launch in and around the equinoxes because the 7920H does not reach large enough parking orbit inclinations to achieve the required values of Ecliptic Cone (DLA) during these periods.

SIRTF INJECTION TARGETS

Trajectory optimization for SIRTF was a 3-part process. The starting point of the trajectory optimization process was a state vector (see TIP discussion on next page) provided by Boeing[7] that satisfied the design constraints given in Table 1. The first step after Boeing provided the new state vector was to use it to create a series of trajectories for a given launch date, each with different launch times (RLA), which were then searched to see if they satisfied the constraints in Table 1. Second, if possible, only trajectories with a high gain antenna (HGA) transition date on or before Day 26 were considered (Day 26 was arbitrarily chosen and unfortunately did not quite match the required transition date that the IOC planners eventually chose). If there were no trajectories with a transition date before Day 26, then all trajectories were considered. Finally, of the remaining trajectories, the one with the smallest 'Max Range' to Earth over the course of the 5 year 2 month mission was selected.

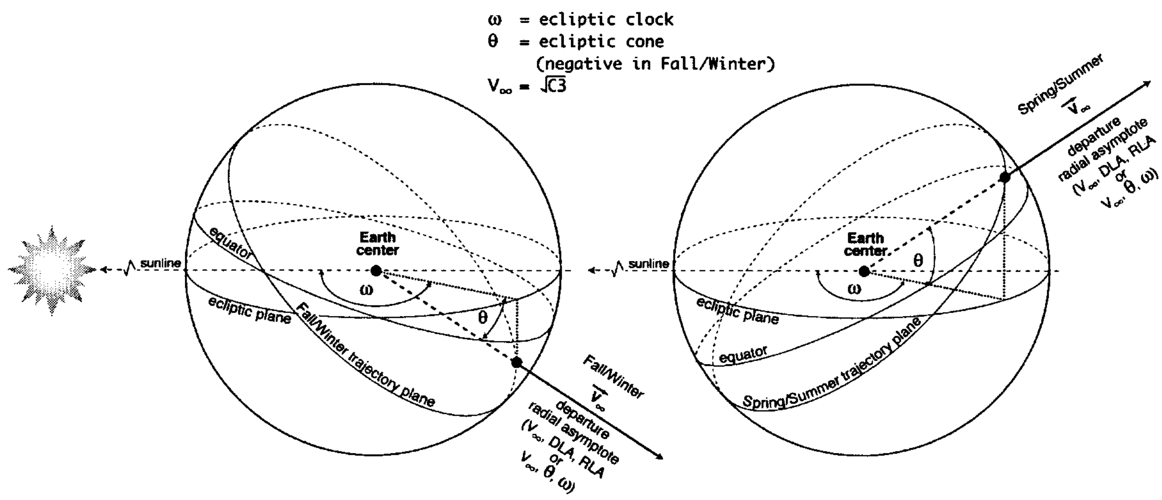

Figure 8 Launch/Injection Trajectory Plane Geometry Showing Ecliptic Clock and Cone

The SIRTF launch period extends from April 15th to May 20th and uses only two different ascent profiles for all of the launches (see Figure 4). Since SIRTF is not going anywhere in particular (unlike a planetary mission), it can use the same launch vehicle ascent profile for consecutive launch dates assuming that the injection targets satisfy the trajectory design constraints. This is desirable because it makes solar geometry calculations easier, as well as simplifying trajectory verification and project interaction with the launch vehicle contractor. Another desirable feature is that the relative timing of launch vehicle events does not change from day to day for a given ascent profile, which is very important to SIRTF because the timing of several critical Observatory actions (most notably the opening of the cryostat vent valves) are tied to launch vehicle-initiated events.

Table 2 gives one-line summaries of the SIRTF trajectories for every other launch in the launch period (there is only one launch attempt per day using an instantaneous launch window). The launch vehicle targets in these tables are given at the Target Interface Point (TIP) and are given in EME 2000 coordinates. TIP time is defined to occur 10 minutes after SECO II (Second Engine Cutoff II). The launches from April 15th to May 2nd use a 107° launch azimuth with a dogleg ascent to a parking orbit inclination (POI) of 36.3°; the launches from May 3rd to May 20th use a 105° azimuth with a planar ascent to a POI of 31.5°. SIRTF uses a C_3 of 0.4 km^2/s^2 because it meets all of the design criteria and offers the best solution to minimizing injection error and maximizing mass margin. All of the data in these tables are for a 5 year 2 month mission.

As mentioned previously, the ecliptic cone angle has a large affect on how acceptable an orbit is to the SIRTF mission. The 'ecliptic cone' column in Table 2 shows how the cone angle increases for each day that the same ascent profile is used. If this value gets too large, the trajectory constraints can no longer be met, and a new ascent profile would need to be used. The 'ecliptic clock' column also demonstrates how the V_∞ vector for the Earth-trailing trajectories tends to be in the anti-sun direction (at about 172°).

Since HGA communications are now required by Day 24, one can see from Table 2 that the nominal trajectory geometry on certain launch dates (April 15th-19th, May 3rd, and May 4th) does not meet the requirement. One proposed solution was to open up the OPZ pitch boundary (from +30° to +31.5°), which would allow the minimum SPE at HGA first use to decrease (to 50.5°). To implement this solution would have required an enormous amount of analysis in the re-verification of the thermal and power subsystems, which the Project was reluctant to do. Fortunately, Ramona Tung of the SIRTF telecom team came up with a simpler and more elegant solution. Ramona proposed pointing the HGA boresight up to 1.5° away from the Earth (instead of directly at it as during normal HGA communications). Since the HGA gain pattern is only down a few dB at 1.5° off-boresight, and since SIRTF is relatively close to the Earth (when compared to the 0.64 AU telecom subsystem design requirement), there is more than enough performance to implement this proposed solution for the 2.2 Mbps downlink rate. This alternate communications plan will be utilized from Day 24 until such time as the HGA can safely be pointed at the Earth.

Table 2

ONE-LINE TRAJECTORY SUMMARIES

Launch Date	Time Spent in Shadow (sec)	C_3 (km^2/s^2)	DLA (deg)	RLA (deg)	Ecliptic Clock (deg)	Ecliptic Cone (deg)	Predicted Transition Day LGA 88 Kbps -to- 44 Kbps	Predicted Transition Day HGA	Max. SPE (deg)	Max. Range (AU)
15-Apr-03	584	0.4	36.3	216.5	172.5	47.2	23.8	25.7	90.0	0.6013
17-Apr-03	561	0.4	36.3	218.3	172.4	47.9	23.9	26.7	90.0	0.6015
19-Apr-03	557	0.4	36.3	220.0	172.4	48.5	29.6	24.2	90.0	0.6013
21-Apr-03	558	0.4	36.3	221.6	172.1	49.1	28.7	21.7	90.0	0.6014
23-Apr-03	561	0.4	36.3	223.0	171.8	49.6	28.0	19.0	89.9	0.6028
25-Apr-03	563	0.4	36.3	224.5	171.5	50.2	27.1	15.8	89.6	0.6058
27-Apr-03	566	0.4	36.3	226.1	171.3	50.7	25.9	12.1	89.3	0.6102
29-Apr-03	567	0.4	36.3	227.6	171.2	51.3	24.2	8.1	88.8	0.6157
1-May-03	563	0.4	36.3	229.5	171.4	51.9	23.0	7.8	88.2	0.6222
3-May-03	735	0.4	31.5	228.5	171.4	47.2	24.2	26.4	89.9	0.6055
5-May-03	730	0.4	31.5	230.5	171.7	47.8	29.5	23.6	89.4	0.6113
7-May-03	722	0.4	31.5	232.6	172.2	48.5	29.0	20.9	88.9	0.6164
9-May-03	715	0.4	31.5	234.7	172.8	49.1	28.4	18.5	88.7	0.6194
11-May-03	712	0.4	31.5	236.5	173.2	49.7	28.2	17.0	88.8	0.6181
13-May-03	718	0.4	31.5	238.0	173.1	50.1	27.8	15.7	89.2	0.6134
15-May-03	725	0.4	31.5	239.5	173.0	50.5	27.0	12.8	89.3	0.6114
17-May-03	730	0.4	31.5	241.0	173.0	50.9	26.2	9.9	89.4	0.6103
19-May-03	739	0.4	31.5	242.4	172.9	51.2	25.6	7.8	89.5	0.6093

The Earth-trailing orbit is plotted in Figure 9 using a rotating coordinate system. The orbit is best viewed in the rotating frame because in the inertial frame it is practically indistinguishable from Earth's orbit around the Sun. This plot keeps the Earth-Sun line fixed and plots the trajectory in the Sun-Earth-SIRTF plane. Plotting the trajectory in the rotating frame clearly shows how the Observatory slowly drifts away from the Earth. The small loops in the orbit occur at perihelion when SIRTF's speed has increased enough to gain ground on the Earth. Earth-trailing trajectories that do not meet SIRTF's SPE constraints have much larger loops.

INJECTION DISPERSION ANALYSIS

Without any ability to perform a trajectory correction maneuver, it is extremely important that the optimized trajectory be robust enough that, even when accounting for 3σ injection errors, the trajectory will meet the design criteria given in Table 1.

The Project desires a confidence level of 3σ that the final trajectory will meet the mission requirements. In an effort to meet this level of confidence, the Project requested a 99.7% Probability of a Commanded Shutdown (PCS). This means that there is a 99.7% chance that the final engine cutoff will be commanded rather than because the launch vehicle simply ran out of fuel. For the April 15th - May 2nd launches, the Delta has 61.3 m/s velocity margin after taking into account propellant needed for a 99.7% PCS and all other launch vehicle reserve items. The May 3rd - May 20th launches have 117.0 m/s velocity margin.

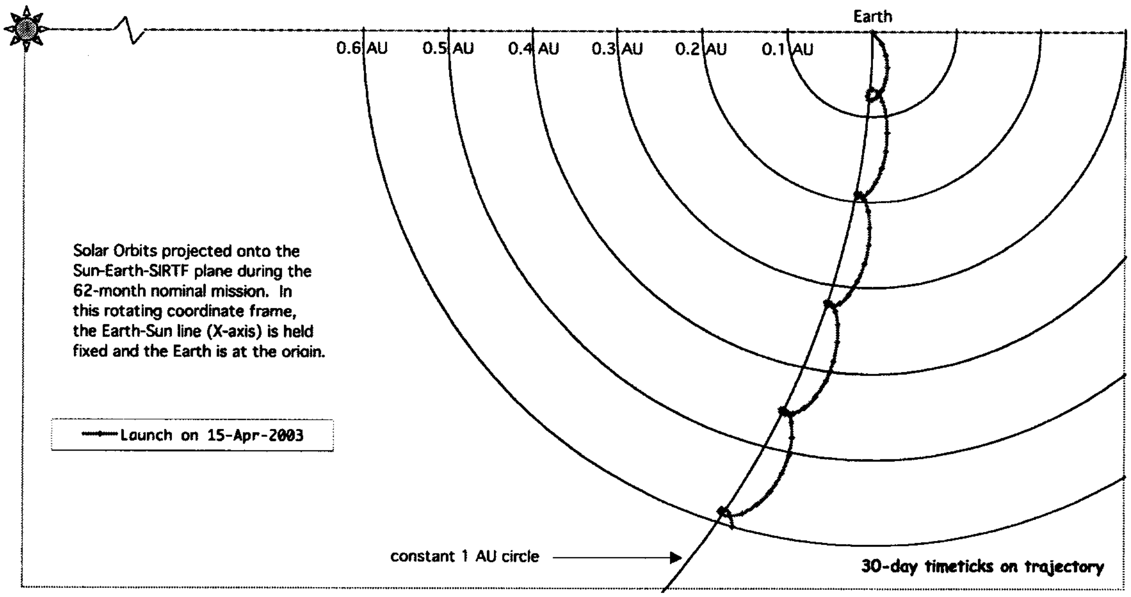

Figure 9 SIRTF Baseline Trajectory in Rotating Coordinate Frame

Boeing provides an injection covariance matrix (ICM) and a velocity deficit data provided for a SIRTF launch on the Delta 7920H that the SIRTF project has used to analyze injection dispersion. The velocity deficit data relates to the PCS mentioned above by giving the probability that the launch vehicle will be short by a certain amount of ΔV. The injection dispersion data that was provided corresponds to the state at SECO II. Consequently, this injection error analysis refers to how perturbations in the SECO II state translate into long-term effects in the SIRTF orbit.

Injection Dispersion Using Velocity Deficit

Judging from the velocity margin presented above, the Delta has more than enough performance to guarantee a PCS of at least 99.7%. However, before the true velocity margin was known it was decided to perform an injection error analysis using both the ICM and velocity deficit data. Since the velocity deficit data and the ICM are sampled independently of each other, a 99.7% PCS implies that for every 1000 times that the ICM is sampled during a Monte Carlo run, the velocity deficit data is only sampled (on average) 3 times. In order to ensure that the velocity deficit data was sampled enough to obtain an accurate *numerical* calculation of the injection error, 1 million possible injection states were calculated using the ICM and the velocity deficit data[8]. The ICM is sampled using random numbers from a normal distribution. The velocity deficit data, however, is sampled using random numbers from a uniform distribution. As a result of combining samples from 2 different types of random distributions, the typical formulas for calculating standard deviations are not applicable. In order to get the 3σ high and low values for C_3, DLA, and RLA a counting method was employed. That is, the highest 0.135% of the C_3 values from 1 million samples were thrown out to get the 3σ high value of C_3, and the lowest 0.135% of the C_3 values from 1 million samples were discarded to get the 3σ low value of C_3.

The 3σ values were also calculated using a slightly different method. Ten sets of 100,000 perturbed states were created by sampling the velocity deficit data and the ICM. For each set, the previously described counting technique was used to determine the 3σ high and low values. The 3σ values for C_3, RLA, and DLA from each of the ten sets were then averaged to come up with the final 3σ values ("averaging" method). The results from these 2 methods ("counting" and "averaging") can be seen in Table 3. (The results in this section are for a direct ascent launch in the winter. Although the new baseline is an April launch using a parking orbit, the conclusions made using these dispersion results are still valid.) The effect of including the velocity deficit data (that is, the possibility that a commanded shutdown may not occur) is to make the 3σ values un-symmetric. Note that the C_3 can be as much as 0.16287 km2/s2 *below* the nominal value, but only as much as 0.046805 km2/s2 *above* the nominal value for C_3).

Table 3

3σ CALCULATIONS USING VELOCITY DEFICIT

Parameter	3σ Low Using "1 Million States" method	3σ High Using "1 Million States" method	3σ Low Using "Averaging" method	3σ High Using "Averaging" method
Error in C_3 (km^2/s^2)	-.1672	.04677	-.16427	.04682
Error in DLA (°)	-.0849	.3533	-.08484	.34731
Error in RLA (°)	-.4116	1.0632	-.41148	1.03086

Injection Dispersion Without Velocity Deficit

One of the problems with using a 99.7% PCS is that, in SIRTF's case, the error in C_3 can be almost half the target value. Also complicating the analysis is the fact that all of the perturbed states must be integrated and the important trajectory characteristics (SPE angle, range to Earth, HGA transition day, etc.) analyzed. Integrating one million states takes a very long time (weeks). Fortunately, SIRTF has enough velocity margin to guarantee better than 99.99% PCS, for both the winter and spring launches. Because of this, taking velocity deficit into account is nothing more than an academic exercise since it will not affect the statistics and therefore can be ignored.

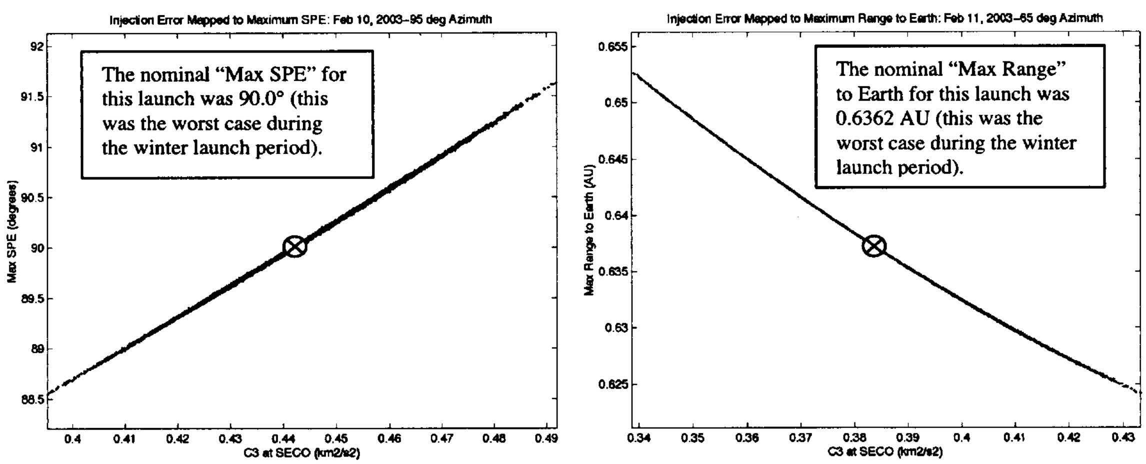

Figure 10 3σ Dispersions on SPE and Range for 5 year, 2 month Mission

Using just the ICM, 10,000 states were generated and then integrated for 62 months. The maximum SPE and Range from each of these integrations were then sorted numerically. Again, the top 0.135% and the bottom 0.135% were eliminated to determine the 3σ high and low values. Figure 10 provides plots of the maximum SPE and range values vs. C_3 from the 10,000 integrations falling within the 3σ distribution. Recall that the injection dispersion data is obtained using the injection state at SECO. Therefore, the nominal C_3 values plotted in Figure 10 are slightly different than the C_3 at TIP. The data in Figure 10 corresponds to the winter launches that lead to the worst-case nominal values of SPE and Range, which are the same or worse than the SPE and Range values associated with each nominal launch throughout the spring launch period. Had SIRTF launched on February 11, Figure 10 shows that a 3σ launch could have violated the maximum range constraint of 0.64 AU. In this worst-case scenario, the Project was willing to accept the small probability that the range constraint would be violated since it is more important to meet the maximum SPE constraint at all times (no HGA communications are possible when the SPE is greater than 92°). Although the injection dispersion analysis for the spring launch has not yet been completed, the 3σ maximum SPE is expected to be less than the aforementioned constraint of 92°. This expectation is based on the analysis that led to the results in Figure 10, the fact that the C_3 target is unchanged and because the nominal SPE values for all spring launches are 90° or less.

SOLAR ILLUMINATION

SIRTF has a requirement to limit excursions outside of the OPZ to a cumulative total of 10 minutes after fairing jettison otherwise its low emissivity surfaces would be damaged and the thermal performance degraded. Table 4 gives a list of launch relative times that are relevant to meeting this requirement and calculating violations of the OPZ. After SECO I and before shadow exit, the launch vehicle begins an attitude adjustment to point the Observatory within the OPZ. The launch vehicle then reorients itself approximately 1500 seconds later to the second engine restart attitude (which is also OPZ-compliant). After SECO II the launch vehicle puts the Observatory into an attitude that is optimized for communications. Following separation from the launch vehicle, the Observatory first captures any tip-off rates induced at separation (maximum 0.25 °/s per axis) and, within 4 minutes, will sun-point the +Z-axis and then hold this attitude until the Star Trackers are turned on and inertial reference established. Before inertial reference is acquired, the sun-pointed attitude will allow initial low rate communications at the Canberra DSN station, however as soon as inertial reference is established the Observatory will be commanded to an optimized LGA communications attitude which allows the highest LGA data rate possible (88 Kbps).

Table 4

ASCENT TIMES RELAVENT TO SOLAR ILLUMINATION

Event	107° Azimuth	105° Azimuth
Fairing Jettison	281.5 sec	281.5 sec
SECO I	436.5 sec	429.8 sec
Earth Shadow Exit[a]	557-567 sec	712-745 sec
Second Eng. Restart	2315 sec	2425 sec
SECO II	2591 sec	2703 sec
Clampband Release	2860 sec	2970 sec

[a] Range of Shadow Exit times for all launches

The attitude profiles used during the coast phase and after SECO II must be such that the 10-minute allowance is not violated for any of the SIRTF launch dates. Creating a new attitude profile for every day of the launch period would make the verification process more complicated and add risk. A study was performed to determine how long a given profile could be used from one day to the next while not compromising the 10-minute limit and minimizing the work for the launch vehicle contractor[9]. The final decision was to program the Delta to use the same attitude profile for 7 consecutive launches. After 7 days the attitude profile must be reset or else the 10-minute constraint could be violated during launch.

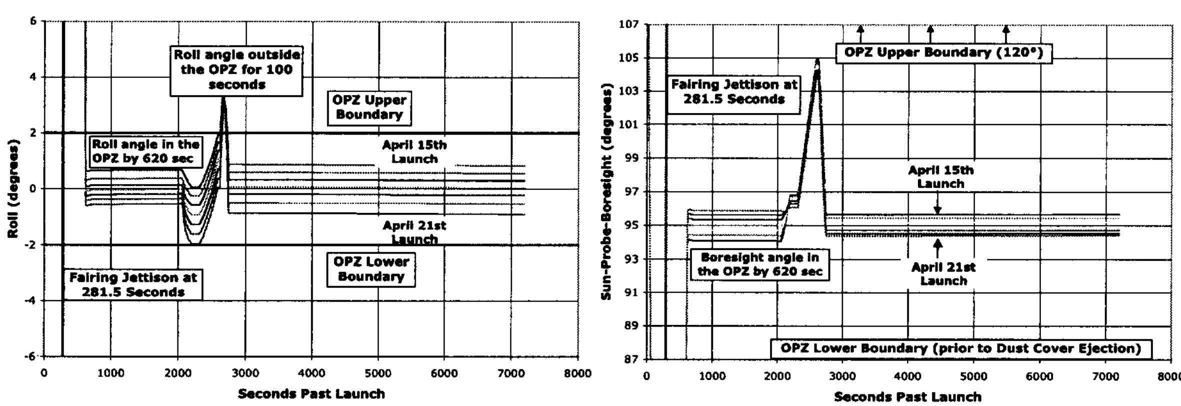

Figure 11 Solar Illumination Angles for First 7 Days of Launch Period

The section defining the OPZ stated that the roll angle should be 0° ±2°. The constraint on the Sun-Probe-boresight angle before dust cover ejection, however, is more restrictive than mentioned above. The telescope boresight must not be pointed any closer than 87° toward the sun while the dust cover is attached or else condensation may form, but the upper limit of 120° on the boresight angle must still be maintained. Figure 11 gives the boresight and roll angles from launch to L+2 hours for the first 7 days of the launch period. Recall that after 7 days, the attitude profiles are reset, and the same trends will occur for the next seven-day period. While the figure shows that the 10-minute allowance is not violated, if the same attitude profile were to continue to be used, this requirement would eventually be not be met.

DUST COVER EJECTION (DCE)

Dust Cover ejection is one of the most critical events of the early SIRTF mission. SIRTF has a 1-meter diameter dust cover on the boresight of the Observatory that protects the SIRTF instruments from contamination during launch and from the high spacecraft outgassing rate during the first few days of the mission. After L+4 days, the outgassing rate will have subsided enough to allow the dust cover to be ejected. The nominal direction for DCE coincides with the Observatory +X-axis.

In addition to the requirement to eject after L+4 days, there are a number of other requirements associated with DCE. One of the requirements is for dual DSN station coverage during ejection, so the DCE attitude must be "communication positive" via one of the two Low Gain Antennas. (The 2 LGAs are aligned with the +Y and –Y-axis.) There is also a PCS requirement on DCE that limits pitch angles to be between –3° and +15°. However, this analysis used –2.5° as the lower limit. The Observatory must also be in an attitude that allows the ejected dust cover to meet certain trajectory requirements that minimize impact on science. To minimize science impact, the dust cover must either remain outside of the OPZ or be more than 20,000 km away from the Observatory during the nominal mission. Table 5 summarizes the DCE characteristics that are relevant to the dust cover trajectory design[10]. The ΔV for DCE is listed as 0.98 m/s, but this is actually the velocity of the dust cover relative to the Observatory. This means that the Observatory will experience a change in velocity of about .007 m/s. It may be possible to actually verify dust cover ejection by looking at the Doppler history of SIRTF during dust cover ejection.

Table 5

CHARACTERISTICS OF DCE

ΔV of Dust Cover Ejection	0.98 +0/-0.2 (m/s)
Ejection Direction	Along X-axis ±4° in XZ plane
Dust Cover Mass	6.15 kg
Dust Cover Area	0.82 m^2
Solar Momentum Transfer Value of Dust Cover	1.09

DCE Method and Results

To find the optimal DCE attitude, a parametric search was performed in which the full range of communication positive DCE attitudes were considered[11]. The Observatory was first placed in the "+Y LGA Earthpoint Attitude" (The Z-axis points at the sun, and the X-axis is perpendicular to the Sun-SIRTF-Earth plane which minimizes the angle between the LGA boresight and the Earthline.). From this starting attitude, several yaw/pitch combinations were tested for DCE (each keeping one of the LGA boresights within 60° of the Earth to satisfy the requirement to be communication positive). The attitudes were calculated by starting from the "+Y LGA Earthpoint Attitude" and then rotating first through the yaw angle (about the +Z-axis) and then the pitch angle (about the +Y-axis). The dust cover ΔV was applied along the +X-axis direction of each orientation. For each set of yaw/pitch combinations, the dust cover trajectory was propagated and compared against the nominal SIRTF trajectory. The initial conditions are the most important factor in determining the dust cover trajectory, but solar radiation pressure is also an important factor to consider. When calculating solar radiation pressure on the rotating dust cover, a conservative approach was taken, whereby the solar radiation pressure was multiplied by the cosine of 45° to account for the constantly varying dust cover geometry with respect to the solar wind.

Figure 12 gives the range from the dust cover to SIRTF for a series of allowable rotations. This plot presents only the best results from the parametric search where the LGA on the +Y-axis is used and corresponds to a launch on April 15th. The legend for Figure 12 should be read such that "Range –47.3:2.5" refers to a SIRTF attitude with a yaw of –47.3° and a pitch of –2.5° at the time of dust cover ejection. The data given in Figure 12 suggests that the optimal orientation would be to yaw 47.3° and then pitch –2.5° (from the "+Y LGA Earthpoint Attitude"). Using this orientation, the dust cover remains well outside of the 20,000 km constraint for all by the first 100 days of the mission. (Although not shown in Figure 12, the dust cover is well outside of the OPZ during the first 100 days.) The same search was performed for additional launch dates, and it was determined that the same pitch (47.3°) and yaw (-2.5°) orientation was optimal for all of the SIRTF launch dates

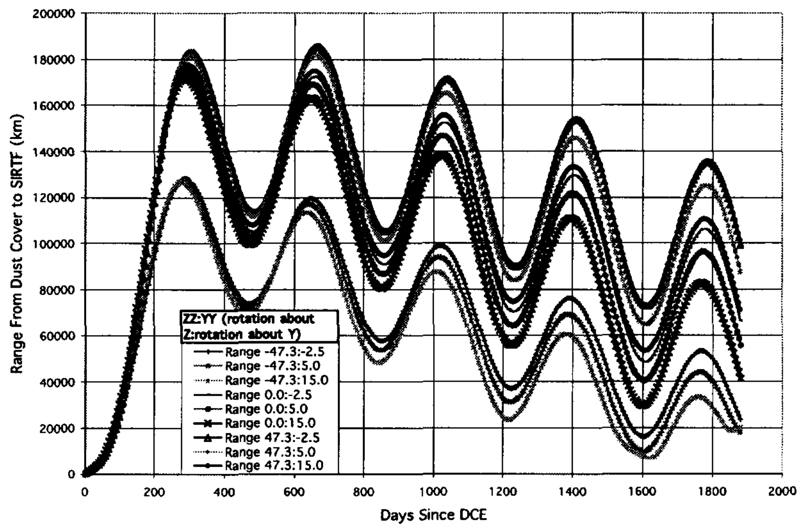

Figure 12 Resulting Range From SIRTF to Dust Cover for Various DCE Orientations

Dust Cover Ejection Error

As noted in Table 5, there are uncertainties in the velocity magnitude and direction of the dust cover at ejection. The nominal speed of ejection is 0.98m/s, but it can be as low as 0.78 m/s. The nominal ejection direction is along the x-axis, but can be off-axis by 4 degrees in the XZ plane (although 6° was used in this study to add conservatism). In order to ensure that the dust cover will meet its trajectory requirements, dust cover trajectories were studied covering the full range of ejection error scenarios relative to the optimal orientation. Although a number of launch dates were analyzed for this ejection error study, the data presented here only refers to the April 22nd launch. The DCE associated with the April 22nd launch had the worst range characteristics (the dust cover got as close as 50,000 km over the course of the 5 year 2 month mission). Figure 13 gives the range from the dust cover to SIRTF for a wide range of ejection scenarios. Again, "Range .98:-6.0" refers to an ejection velocity of 0.98 m/s and an angular ejection error of –6°. The figure shows the impact of ejection error on the resulting dust cover trajectories and clearly demonstrates that the dust cover ejection attitude is robust enough to sustain an off-nominal ejection. (Again, the dust cover is well outside the OPZ during the first 100 days of Figure 13.)

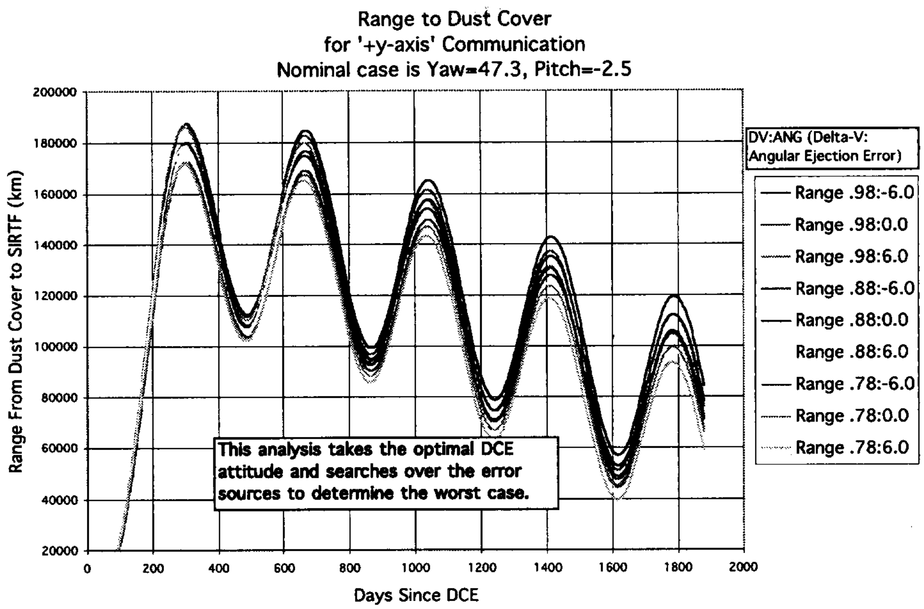

Figure 13 Resulting Range From SIRTF to Dust Cover While Accounting for Ejection Error

DELTA SECOND STAGE ORBIT

Just as important that the dust cover get far enough away from SIRTF so as not to interfere with science, is that the second stage not be in SIRTF's field of view during observations. Once the second stage separates from SIRTF, the launch vehicle will perform a series of evasive maneuvers to put some distance between itself and SIRTF. The final engine restart will be a depletion burn of the second stage. Collectively, these maneuvers are referred to as the Contamination and Collision Avoidance Maneuver (CCAM). The CCAM is essential to the SIRTF mission as it is the only way to guarantee that the second stage will get sufficiently far from the Observatory. While there is no exact requirement on the range that should be maintained between SIRTF and the second stage, the SIRTF science team has recommended that 100,000 km be used. The original CCAM plan did not meet this recommendation so the ΔV associated with the CCAM was reoriented to find a more optimal orientation for the maneuver. The new CCAM was designed in such a way as to put the second stage into an Earth-leading orbit (i.e. in the exact opposite direction of SIRTF).

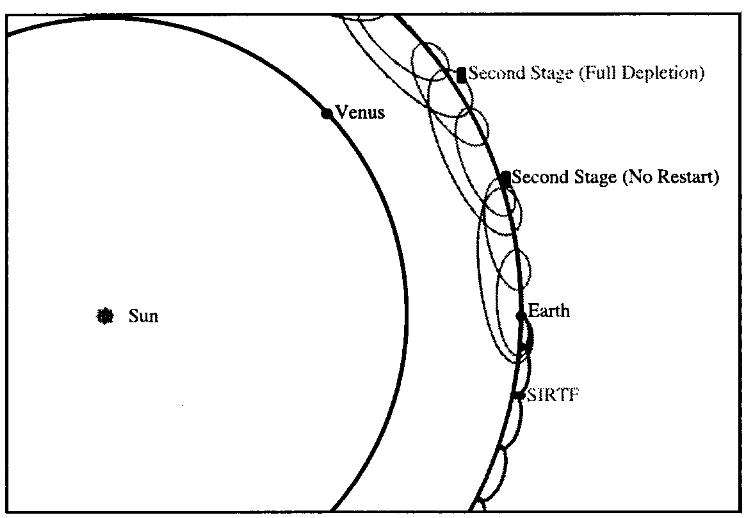

Figure 14 Second Stage Trajectories (After Depletion) as Compared to the SIRTF Trajectory

The series of maneuvers that make up the CCAM include two restarts of the second stage engine. Of course, there is the concern that the final restart of the second stage during CCAM may not occur. As it turns out, this is not a problem because the first firing of the second stage engine (which amounts to a 5-second burn) during CCAM is enough to put the Delta into an Earth-leading orbit. The results of the new CCAM can be seen in Figure 14. Both the SIRTF and second stage trajectories are plotted in a rotating coordinate system with the Earth-Sun line fixed. The two restart scenarios (a completely successful CCAM or a failure of the final depletion burn to occur) of the CCAM have been plotted and clearly show the second stage in an Earth-leading orbit. Since SIRTF is in an Earth-trailing orbit, there is no need to worry about the second stage interfering with science.

ROC

The Reserved Observations Catalog (ROC) is a tabular list of targets and observing modes taken from the Science Operations Database (SODB). These targets and observing modes have been specified in detailed observations from the SIRTF Guaranteed Time Observers programs, the First Look Survey program, and the Legacy Science program. The ROC can be used to determine if any observations planned with SIRTF are in conflict with those already reserved. In general, the SIRTF Science Center will not allow a duplication of observations listed in the ROC. As such, the ROC offers a convenient way to gather "days in view" statistics on real world targets. Figure 15 below shows the EMO 2000 coordinates of the roughly 5500 "fixed" targets in the ROC. As can be seen, there are targets all over the sky, with especially high concentrations along both the Galactic and Ecliptic planes. The Ecliptic targets fall into two main groups, one between Ecliptic longitudes of 60° and 75° and another 180° away from that.

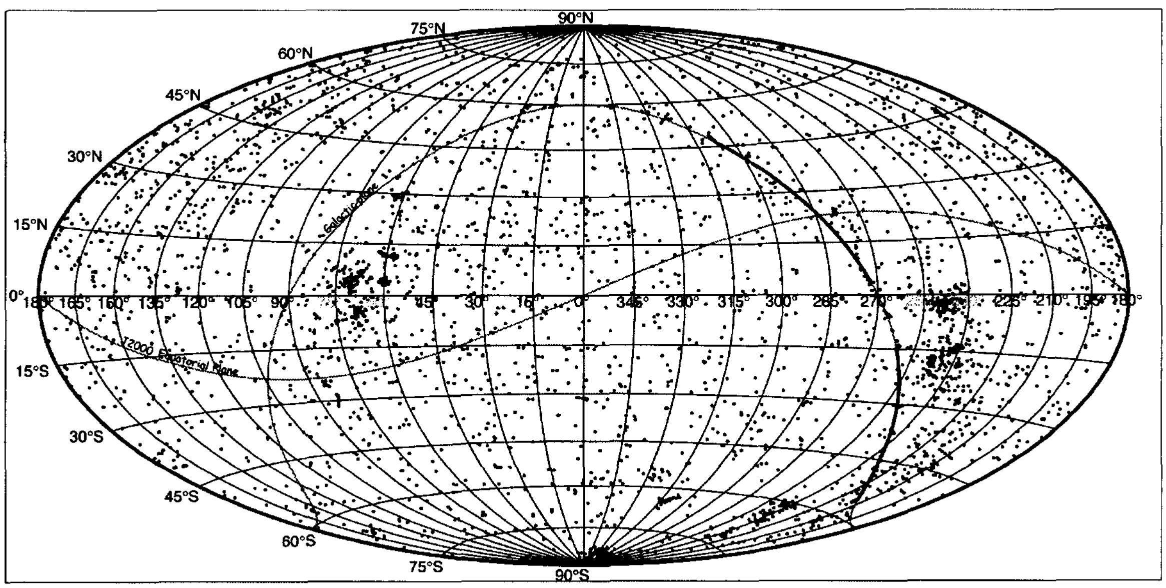

Figure 15 Earth-Mean-Orbit and Equinox of J2000 (EMO2000) Locations of the ROC Targets

An electronic file containing the entire catalog data was searched to calculating OPZ crossing statistics (start day in view, end day in view, total number of days in view, and the number of days between OPZ crossings) for the entire 5 year, 2 month mission. Partial crossings (ones where the object was already deep inside the OPZ at the start of the trajectory data or where an object was still inside the OPZ at the end of the trajectory data) were not included in the statistics. Figure 16 below shows the results of this study by plotting the average number of days in view per year as a function of ecliptic latitude. Only the average numbers are shown because the overwhelming majority of targets take the same amount of time, within ±1 day, to cross through the OPZ every time they cross it. Exceptions can occur for targets at the edge of the OPZ boundaries, i.e., at ±80° and ±60° ecliptic latitude.

LONG TERM SIRTF ORBIT

SIRTF can be expected to have many interactions with the Earth over the course of its existence. It's difficult to say exactly what the long-term orbit will look like since there are uncertainties in what SIRTF's actual injected orbit will be, as well as uncertainties in the planetary ephemeredes over the next 200 years. Momentum dumps performed throughout the mission will also affect the post-injected orbit. All of these factors contribute to uncertainties in SIRTF's orbit over the next 200 years. That being said, it is still worthwhile to look at some of the long-term predictions of SIRTF's orbit.

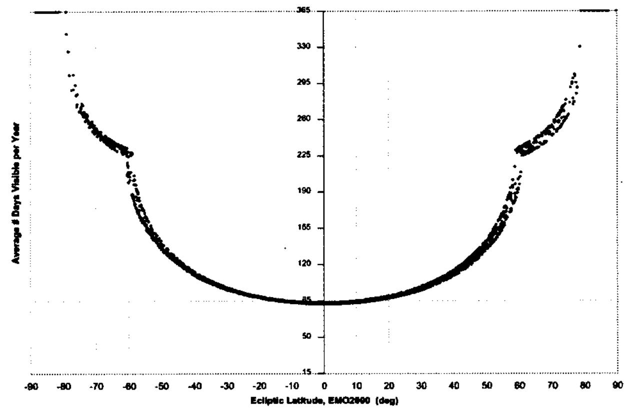

Figure 16 Ave Days in View per Year for ROC Targets as a Function of Ecliptic Latitude

The April 15th trajectory was integrated for 200 years past launch. The Observatory will trail the Earth for a period of about 50 years. After 50 years, SIRTF will finally "catch up" to the Earth and be bounced back into an Earth-leading orbit. This 50-year cycle can be easily calculated since SIRTF's period is 7 days longer than the Earth's. For the next 150 years SIRTF has many closest approaches of the Earth, although it remains in an Earth-leading orbit. SIRTF's range to the Earth over these 200 years is given in Figure 17. Each of the minima is effectively an Earth gravity assist that perturbs SIRTF's orbit. The period of SIRTF decreases to the point that the Earth gravity assists begin to occur about every 8-10 years by the end of the 200-year integration. Table 6 lists how SIRTF's heliocentric orbital elements change as a result of each of the perturbations. This particular integration is interesting in that the perihelion continues to decrease so much that it's conceivable SIRTF may one day have significant gravity interactions with Venus.

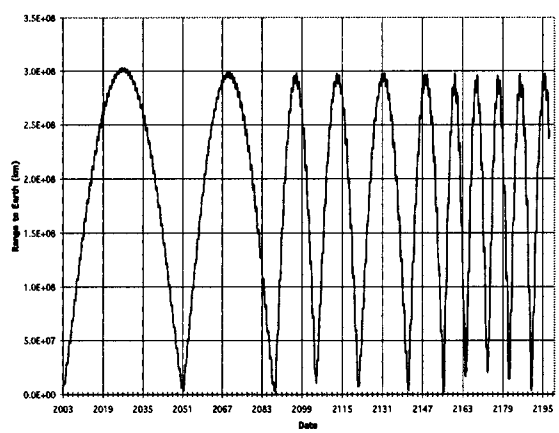

Figure 2 SIRTF Range to Earth Over the Next 200 Years

Table 6

HELIOCENTRIC ELEMENTS OVER 200 YEARS

Time Range	Aphelion (AU)	Perihelion (AU)	Helio. Period (days)	Helio. Eccent.
2003-2051	1.0388	0.9798	372.9	0.0291
2052-2088	1.0077	0.9478	355.7	0.0305
2089-2104	1.0033	0.9100	344.3	0.0485
2105-2121	1.0037	0.9112	344.7	0.0481
2122-2141	1.0048	0.9210	347.6	0.0433
2142-2155	1.0023	0.8986	340.9	0.0543
2156-2164	0.9967	0.8553	327.9	0.0760
2165-2173	0.9966	0.8540	327.5	0.0767
2174-2181	0.9966	0.8540	327.6	0.0767
2182-2190	0.9969	0.8565	328.3	0.0754

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