Spitzer Space Telescope Mission Design

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ABSTRACT

This paper gives a description of the mission design, launch, orbit, and navigation results for the Spitzer space telescope mission. The Spitzer telescope was launched by the Delta II Heavy launch vehicle into a heliocentric Earth trailing orbit. This orbit is flown for the first time and will be used by several future astronomical missions such as Kepler, SIM, and LISA. This paper describes the launch strategy for a winter versus a summer launch and how it affects communications. It also describes how the solar orbit affects the design and operations of the Observatory. It describes the actual launch timeline, launch vehicle flight performance, and the long term behavior of the as flown orbit. It also provides the orbit knowledge from in-flight navigation data.

Keywords: Spitzer, SIRTF, Mission Design, Earth trailing orbit, solar orbit

1. Introduction

On August 25th, 2003, 1:35:39 EST, the Spitzer space telescope, formerly known as the Space Infrared Telescope Facility (SIRTF), roared into the night sky of Cape Canaveral Air Force Station in Florida, USA. To some, this is the beginning of a journey of discovery that will extend our knowledge in the formation of solar systems, galaxies, and the early universe. To the mission designers, this is the final proof of an innovation in simplicity that enables a NASA flagship mission.

2. Flight System Description

Figure 1 depicts the Spitzer space telescope. It is composed of a spacecraft bus, a telescope, a cryostat, and 3 instruments. The telescope is a Ritchey-Chrétien design, with an 85 cm primary mirror. It is the largest infrared telescope ever launched into space. Not shown is the telescope dust cover that was ejected 4.86 days after launch. The three instruments are housed in the Multiple Instrument Chamber (MIC) and cooled by liquid helium to near absolute zero (-459 degrees Fahrenheit or -273 degrees Celsius). The Infrared Array Camera (IRAC) is a four-channel imager with simultaneous viewing at 3.5, 4.5, 6.3, and 8.0 microns. The Multi-band Imaging Photometer for SIRTF (MIPS) has five distinct optical trains that can image simultaneously at 24, 70, and 160 microns, or obtain low-resolution spectra from 50 to 100 microns. The Infrared Spectrograph (IRS) has four separate optical trains that cover the spectral range from 5 to 40 microns. The MIC and the liquid helium tank are housed inside a

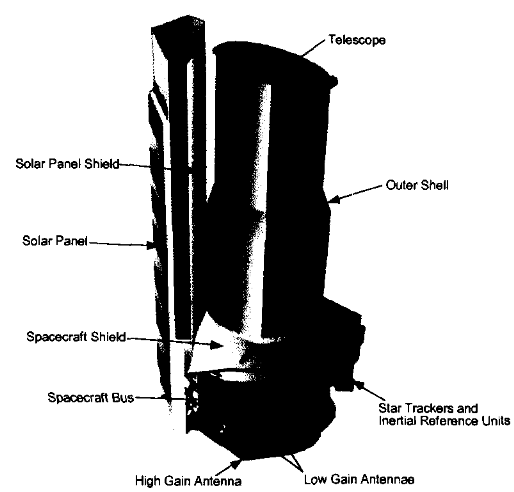

Fig. 1 Spitzer Space Telescope

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vacuum shell, and enclosed by an outer shell. The telescope and the cryogenic system is referred to as the Cryo-Telescope Assembly (CTA). The Spacecraft (S/C) consists of the solar panel and the spacecraft bus that provides structural and mechanical support, thermal control, power generation and distribution, pointing control, command and data handling, reaction control, telecommunications, and flight software. Redundant star trackers are used for celestial reference, coupled with redundant inertial reference units and sun-sensors. Reaction control is accomplished with reaction wheels, and nitrogen cold gas is used to off-load momentum built-up in the reaction wheels.

Communication is achieved via a 1.35 meter High Gain Antenna (HGA) for downlink data rates up to 2.2 million bits per second (Mbps). The HGA is fixed to the bottom of the S/C bus and canted 8° towards the solar panel. There are a set of receive and transmit Low Gain Antennas (LGA) on both sides of the S/C bus for low data rates. The LGA's are used during early In-orbit Checkout (IOC) when the geometry of the trajectory relative to the Sun-Earth line precludes pointing the HGA at Earth. This point will be discussed further later. The LGA can support downlink rates of 88 thousand bits per second (kbps) out to a range of 2×10^6 km which occurs around 24 days from launch, and 44 kbps out to a range of 2.8×10^6 km which occurs around 41days from launch. On the other hand, the instruments can record data at an average rate of 90 kbps. There is a total of 16 billion bits (gbits) of on-board solid state memory storage. The LGA's are also used for safemode communications with an uplink rate of 7.8125 bps, and a downlink rate of 40 bps. During safemode, the Observatory rotates at 0.05 degree per second with the solar panel face on to the sun while transmitting simultaneously through both LGAs. Due to interference effects when transmitting simultaneously through the LGAs, there is a large region in the LGA pattern that has its deepest null roughly halfway between the two transmit antenna boresights. These two null region leads to two communication outages each revolution during safemode.

3. Launch Vehicle

Figure 2 depicts the Delta rocket used by Spitzer. It is a new configuration designated as 7920H built by Boeing, formerly McDonnell Douglas. It is a two-stage Delta II with 9 strap-on solid rocket motors (SSRM) to augment the first stage. Rather than the 40" diameter SSRMs for the standard Delta II, 7920H uses the 46" SSRMs from the commercial Delta III. As with the standard Delta II, 6 of the SSRMs are ignited at liftoff, and 3 are ignited after burnout of the first 6. The first stage is powered by a Rocketdyne RS-27A main engine and two vernier engines, using a mixture of kerosene and liquid oxygen. The second stage is powered by an Aerojet AJ10-118K engine using hypergolic bi-propellant, a mixture of hydrazine and nitrogen tetroxide.

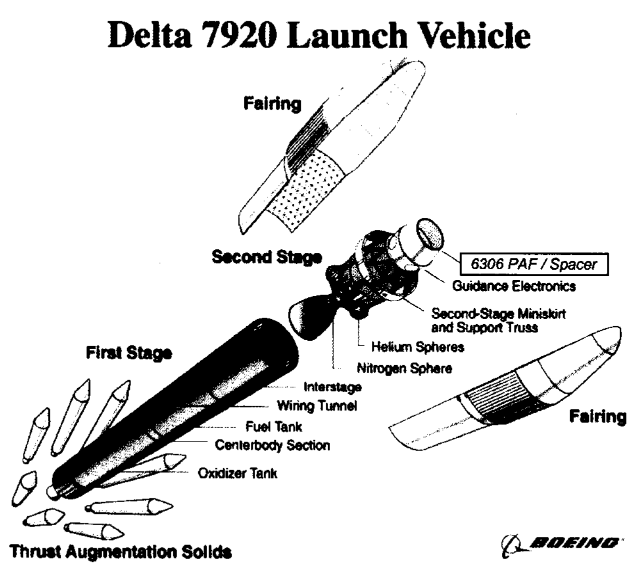


Fig. 2 The Delta 7920H-9.5 launch vehicle

4. Launch Phase

The launch trajectory is composed of 3 parts, ascent, coasting, and injection burn. Table 1 gives the sequence of events during the launch phase. Figure 3 depicts the ground track of the launch trajectory. There were several spacecraft critical events during launch. Two cryo-venting valves (number 7 and 8) were programmed to open to allow helium gas venting during ascent. The event was triggered by fairing jettison at 4 minutes 44 seconds after launch. After the spacecraft was separated from the second stage, the spacecraft transmitter was turned on at L+54 minutes, and the Deep Space Network (DSN) at Canberra acquired the signal almost immediately. Another critical event is for the telescope to acquire inertial reference at 1 hour 20 min. However, due to either stray light from the Earth albedo, or other unexpected environment such as a highly charged particle hit, the star tracker failed to acquire, and the spacecraft initiated safemode 1 hour 26 minutes after launch and remained in safemode for 14 hours 40 minutes when it was commanded to transition to standby mode.

The launch vehicle was instrumented with two cameras, one downward looking to record and transmit ascent events, and one upward looking for separation events. The separation video was to be captured by the Ocean-going Telemetry and Test Resource (OTTR), a commercial boat with telecommunication equipment that was stationed in the Indian Ocean east of South Africa. Due to equipment handling error, the video was not recorded. At the same time, United Space Network (USN) station at Dongara, west Australia, was to track the separation telemetry and video. Due to a miscommunication of the coordinate system used in transmitting the trajectory information, the station antenna was pointed in the wrong direction resulting in the loss of the separation video and some telemetry data not available (DNA). The Guam Tracking Station (GTS) acquired the telemetry for the Contamination and Collision Avoidance burn (Second Restart Stage II) and the final depletion burn (Third Restart Stage II), and confirmed that all sequenced events executed nominally. The navigation team later confirmed that the second stage placed the Spitzer telescope almost perfectly into the escape orbit and that the errors were well under the 3σ uncertainties (table 2). The attitude control team also confirmed that separation tip-off rates were minimal and were well under the requirements (table 3).

Table 1 Spitzer launch sequence

Event	Time after Liftoff (sec) Predicted	Actual
Liftoff	0.0	0.0
(3) Ground Ignited Solid Motors Burnout	76.2	75.4
(3) Ground Ignited Solid Motors Burnout	76.7	75.8
(3) Altitude Ignited Solid Motors Ignition	79.0	79.0
Jettison (3) Ground Ignited Solid Motors	80.5	80.8
Jettison (3) Ground Ignited Solid Motors	81.5	81.8
(3) Altitude Ignited Solid Moters Burnout	155.9	155.0
Jettison (3) Altitude Ignited Solid Motors	159.5	159.8
Main Engine Cutoff (MECO)	263.5	264.6
Stage I-II Separation	272.0	273.8
Stage II Ignition	277.5	279.3
Jettison Fairing	282.0	283.8
Second Engine Cutoff 1 (SECO 1)	431.9	437.1
Stage II Restart Ignition	2424.0	DNA
Second Engine Cutoff 2 (SECO2)	2695.9	2706.1
Separate Spacecraft	3000.0	DNA
Second Restart Stage II	3920.0	3922.8
Second Engine Cutoff 3 (SECO 3)	3925.1	3928.6
Third Restart Stage II	4300.5	4303.4
Second Engine Cutoff 4 (SECO4)	4308.6	4309.1

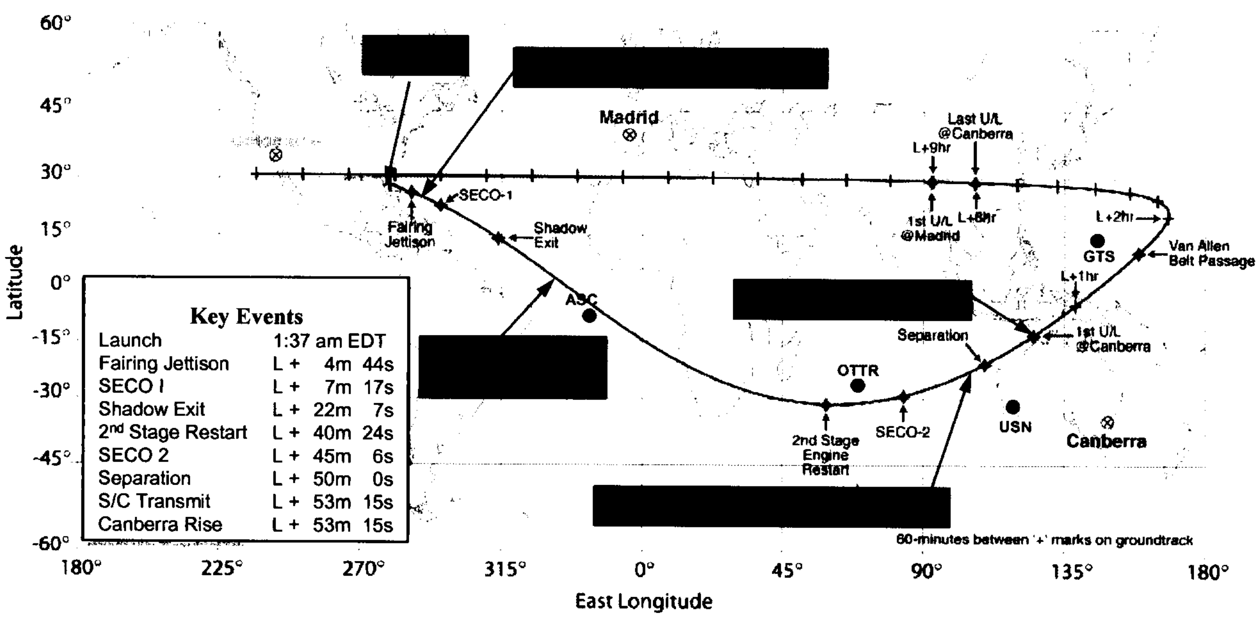


Figure 3 Ground Track of the launch trajectory

Table 2 Parameters of the achieved orbit

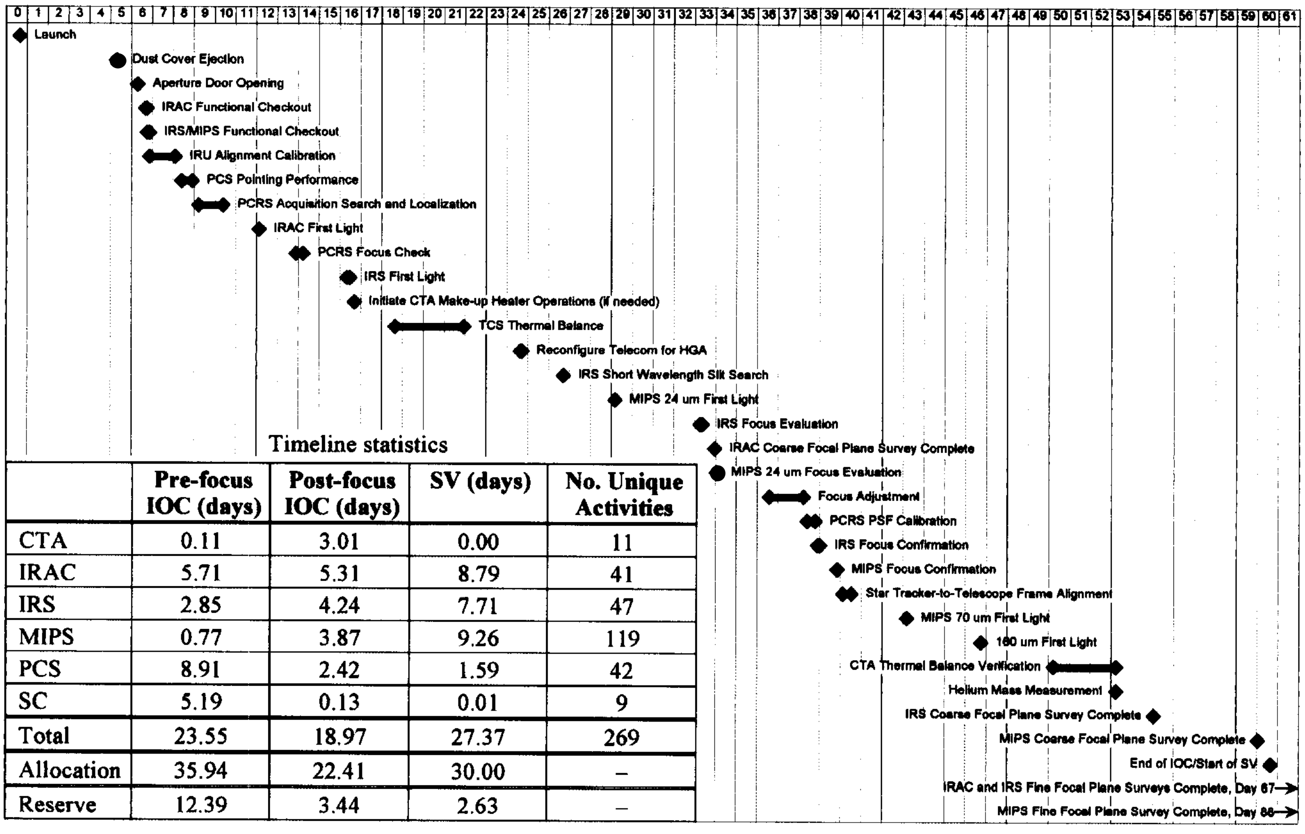
Orbit Parameter	Actual	Targeted	3σ uncertainty
C_3 (km^2/s^2)	0.393	0.400	-0.183
Declination (deg)	31.47	31.48	-0.03
Right Ascension (deg)	310.98	310.95	+1.14

Table 3 Separation tip-off rates

	Actual tip-off rates (deg/sec)	Requirement (deg/sec)
x-axis	0.011	≤ |±0.25|
y-axis	0.003	≤ |±0.25|
z-axis	-0.038	≤ |±0.25|

5. In-Orbit Checkout and Science Verification Phase

The launch phase was followed by the In-orbit Checkout and Science Verification (IOC/SV) phase. The IOC phase was planned for 60 days, and the SV phase for 30 days. Figure 4 gives the summary of the IOC activities. Two other critical events occurred during IOC. Dust Cover Ejection was planned for 4 ½ days after launch, and the Aperture Door was opened the following day. The Pointing Calibration Reference Sensor (PCRS) is a fine guidance sensor in the MIC and is the cold sensor that saw first light, followed by IRAC, IRS, and MIPS. During IOC/SV phase, the spacecraft went into safemode 3 times for a total duration of 4 ½ days. The IOC was completed 62.7 days after launch, and had rather faithfully followed this timeline. The SV phase was completed 98.3 days after launch, which includes 4.4 days of stand-down and recovery due to a solar storm. Miles et al 2004 provide a comprehensive description of the IOC/SV plan execution.



	Pre-focus IOC (days)	Post-focus IOC (days)	SV (days)	No. Unique Activities
CTA	0.11	3.01	0.00	11
IRAC	5.71	5.31	8.79	41
IRS	2.85	4.24	7.71	47
MIPS	0.77	3.87	9.26	119
PCS	8.91	2.42	1.59	42
SC	5.19	0.13	0.01	9
Total	23.55	18.97	27.37	269
Allocation	35.94	22.41	30.00	–
Reserve	12.39	3.44	2.63	–

Figure 4 IOC/SV mission timeline

6. Sky Coverage

The Spitzer telescope design and the solar orbit provide very efficient viewing geometry. The solar panel, the solar panel shield, and the aperture shade are designed to allow the telescope to point within 80° of the Sun. At the same time, the solar panel and the solar cells are sized to provide sufficient power when the telescope is pointed 120° from the Sun. Figure 5 illustrates the sky coverage of the Spitzer telescope. In this figure, the telescope is at the center of the celestial sphere, and the Sun is always to the left. Given this definition, one can imagine that celestial objects complete a full revolution in this sphere once a year as Spitzer orbits the Sun. Indeed, any object along the ecliptic longitude is visible for about 40 days at a time. Objects more than 60° latitude above or below the ecliptic are visible for a minimum of 7 months at a time. Objects within 10° of the ecliptic pole can always be seen by the telescope. That region is called the constant viewing zone (CVZ). The 40° band in this celestial sphere that the telescope can point to forms the "pitch" and "yaw" components of what is called the Operating Pointing Zone (OPZ). The OPZ also includes a ±2° roll component about the optical axis of the telescope

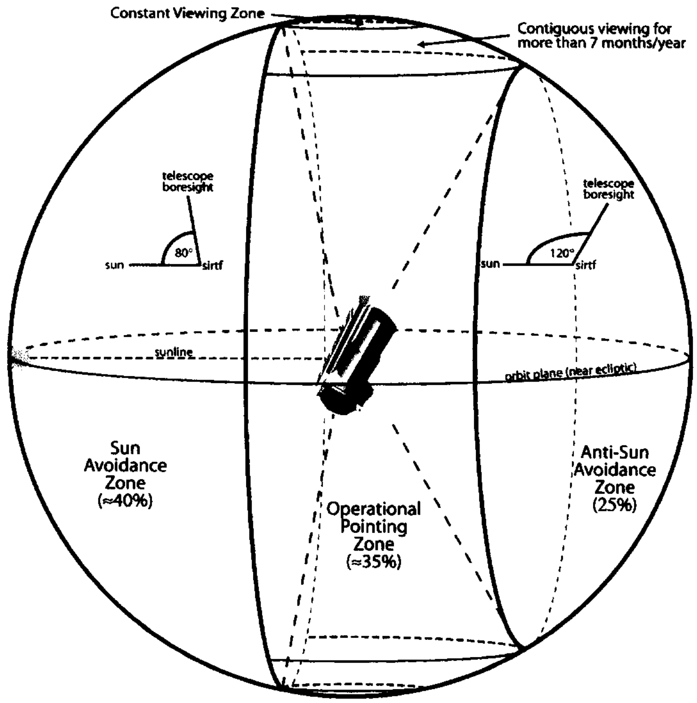


Figure 5 Spitzer telescope sky coverage

7. Trajectory and Navigation Design

7.1. The Spitzer Solar Orbit

Figure 6 plots the Spitzer solar orbit that was achieved by the launch vehicle. It is plotted in a rotating coordinate system where the Sun is at negative 1 AU, the Earth is at the origin, and the X-Y plane is the ecliptic plane. Tick marks in the plot are 1 month apart. The Spitzer solar orbit has an inclination of about 1 degree relative to the ecliptic plane and the loops are artifacts of plotting in a rotating frame. The Spitzer orbital period is about 373 days. So after 62 months, it would be about 0.6 AU from Earth. Because the perihelion between the Earth orbit and the Spitzer orbit are not aligned, for about one month in a year the Spitzer telescope would be moving closer to Earth.

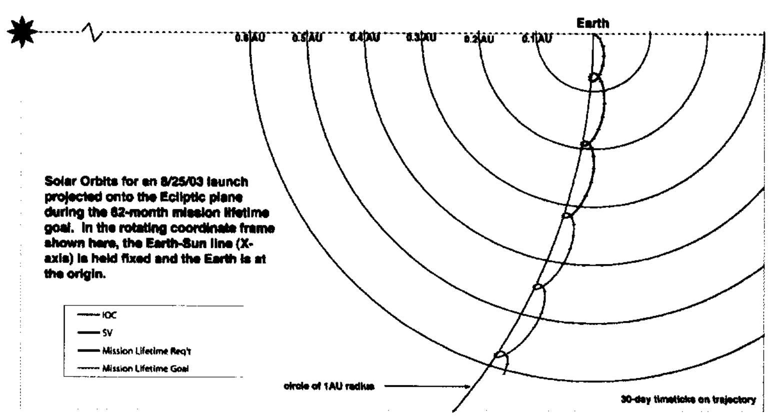


Figure 6 Spitzer as flown solar orbit

7.2. Orbit options

The Spitzer orbit has evolved over many years. The original concept of SIRTF in the early 80's was to use the Space Transportation System (Shuttle) and the Orbital Maneuvering Vehicle (OMV) to launch the observatory into a 900 km circular orbit. In late 1988, an alternative mission concept was conducted based on a 100,000 km altitude High Earth Orbit (HEO) launched by the new Titan IV/Centaur with the upgraded Solid Rocket Motor (SRMU). The telescope would weigh 5700 kg and have a 5-year cryogenic lifetime. In the summer of 1989, the new concept was adopted by NASA and the science community to become the baseline. In the fall of 1991, it became apparent to NASA and the project that the cost of the HEO design was not commensurable with the fiscal and programmatic climate. The engineering team and the instrument teams were charged with redefining the instruments, the mission, the telescope, the spacecraft subsystems, and the operations concepts to minimize cost and complexity. The work began in March of 1992 and the SIRTF teams emerged in July with a completely new design. The new design was based on using an Earth escape orbit, an Atlas IIAS launch vehicle, and a reduced cryogenic system that provides a mission life of 3 years.

The popular escape orbit at that time was the L2 orbit (L2 stands for libration point number 2). L2 is an anti-sun location situated along the Sun-Earth line at about 1.5×10^6 km from the Earth. At that location, the gravitational forces from the Sun and the Earth balance out the centrifugal force of an object moving at an angular velocity equal to that of the Earth around the Sun. An object at that location requires no additional force to maintain the Sun-Earth-object alignment. This orbit would have been ideal for astronomical telescopes such as Spitzer except for the fact that L2 is an unstable point. Every 3 to 6 months, a small maneuver is required to maintain station. Otherwise it would return to the vicinity of Earth and may even reenter the Earth's atmosphere.

To reduce complexity and mass, save cost, and minimize contamination by propulsive elements, the Spitzer project looked for an escape orbit that does not require station-keeping, and thus would eliminate the need for a propulsion system. And yet, this escape orbit must stay near the Earth to minimize communication requirement. The way to find such an orbit is to simulate an escape orbit with slightly varying energy and direction and find the distance at the end of, say, 5 years. As it turns out, the minimum drift rate orbit was found to have an escape energy of 0.4 km^2/s^2. In contrast, the HEO orbit requires two maneuver burns to achieve, resulting in an equivalent energy of about 22 km^2/s^2. The L2 orbit requires an energy of -0.6 km^2/s^2. Figure 7 provides a schematic comparison of the 3 orbits.

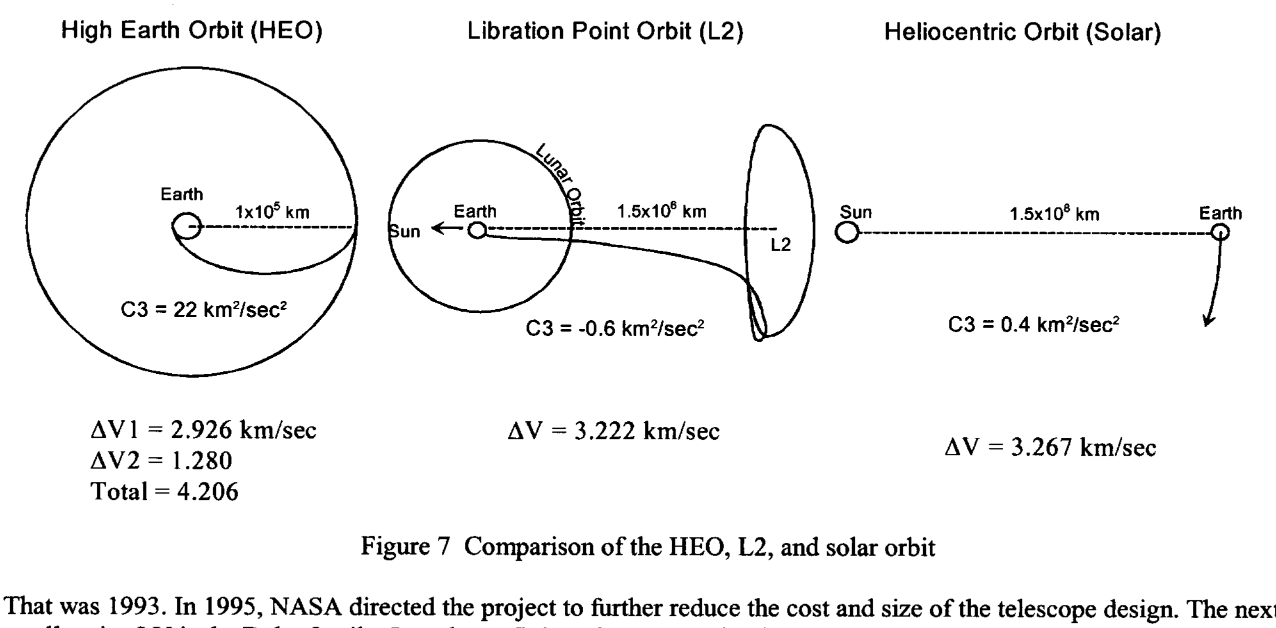
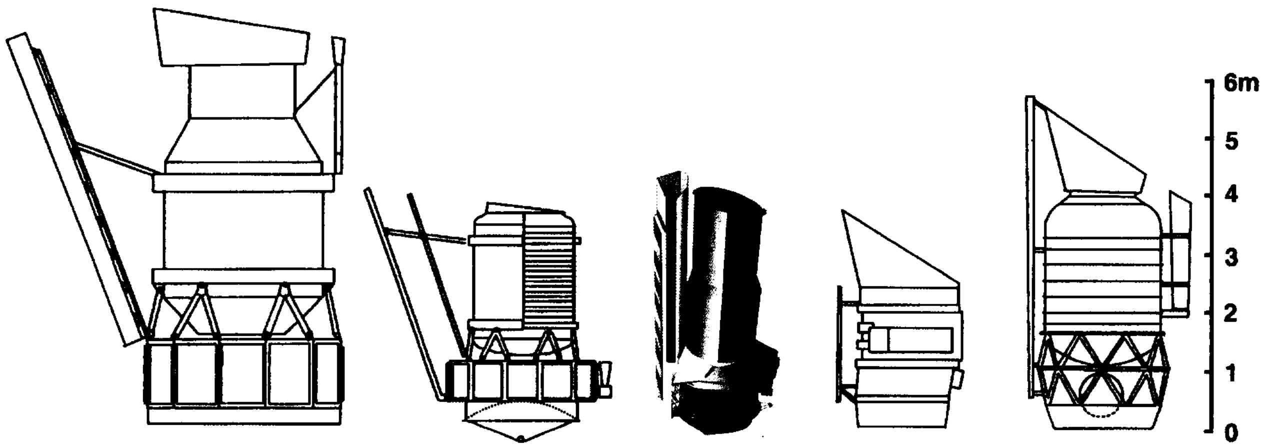


Figure 7 Comparison of the HEO, L2, and solar orbit

That was 1993. In 1995, NASA directed the project to further reduce the cost and size of the telescope design. The next smaller size LV is the Delta family. In order to fit into the mass and volume limit of the Delta II, the project adopted the innovative warm launch architecture. Prior cryogenic telescope missions such as Infrared Astronomical Satellite

(IRAS), Infrared Space Observatory (ISO), and Cosmic Background Explorer (COBE), have used a cryostat design similar to a thermos bottle, where the telescope and the instruments are all housed inside the cryostat. The warm launch architecture takes advantage of the thermal environment of the solar orbit and only the instruments are placed in the cryostat, leaving the telescope outside which means that the telescope will be launched at room temperature and cooled to its operating temperature of 5.6 K via a gradual on orbit cooldown process. This allows for a significant reduction in mass and volume compared to what was traditionally required in previous IR telescope designs. Finley et al, 2004 provides more details of the configuration of the warm launch architecture and its on-orbit performance.

Figure 8 compares the size, mass, and mission lifetime for three versions of the Spitzer telescope, and compares them to the two previous IR astronomy missions, IRAS and ISO.



Mission:	SIRTF (circa 1989)	SIRTF (circa 1993)	SIRTF (2003)	IRAS (1983)	ISO (1995)
Launcher:	Titan IV	Atlas IIAS	Delta II 7920H	Delta 3910	Ariane 44P
Orbit Type:	HEO	Solar Orbit	Solar Orbit	Sun Synchronous	1-day elliptical
Mass:	5500 kg	2460 kg	850 kg	1080 kg	2240 kg
Cryogen Vol.:	3800 liters LHe	920 liters LHe	360 liters LHe	520 liters LHe	2140 liters LHe
Lifetime:	5 years	3 years	5 years, 2 months	10 months	2 years, 5 months

Figure 8 Evolution of the Spitzer telescope and comparison to IRAS and ISO

7.3. Direct Ascent versus Parking Orbit

When the solar orbit was first conceived, a direct ascent launch trajectory was proposed. Planetary missions require parking orbits to achieve a specific set of escape conditions, namely, the energy, right ascension, and declination of the escape velocity at infinity, referred to as the launch asymptote. Since the solar orbit does not have to hit a particular planetary target, the declination of the launch asymptote becomes essentially a free parameter. This free parameter allows the use of a direct ascent launch trajectory. Direct ascent provides slightly more payload mass capability by eliminating gravity loss and reducing the among of propellant and attitude gas associated with using a parking

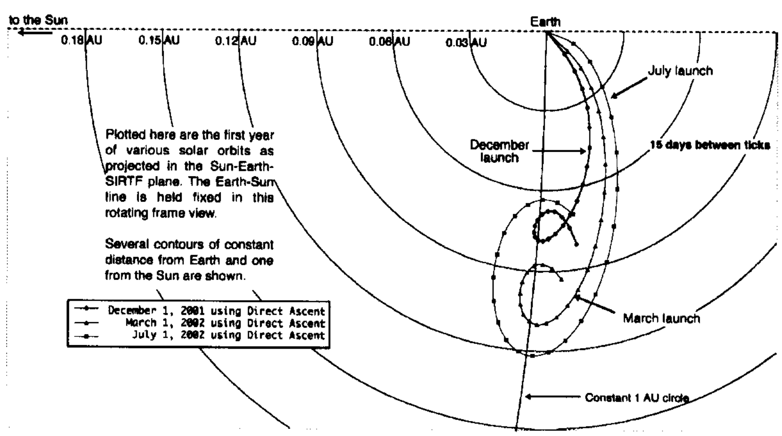


Figure 9 The orbit shapes when launched in different times of the year

orbit. However, the Sun plays a significant role in shaping the escape trajectory. Figure 9 shows three Earth trailing solar orbits launched in March, July, and December following direct ascent from Eastern Test Range to a DLA = -24.8°. The escape orbit relative to Earth is exactly the same but due to the seasonal location of the Sun relative to the escape orbit, the resulting solar orbits all have different size loops. This turns into a communications problem for Spitzer.

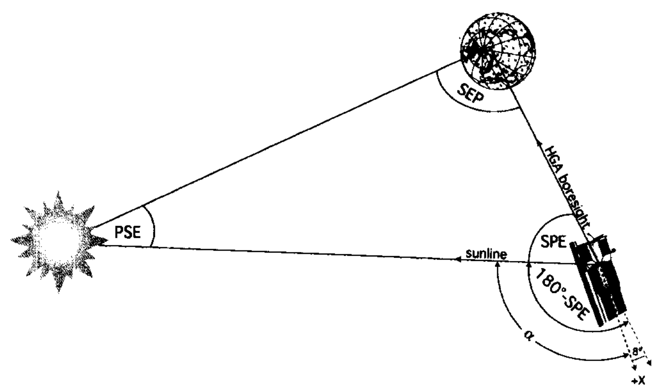


Figure 10 Definition of SPE angle

As pointed out earlier, the HGA is fixed to the bottom of the telescope and canted by 8° towards the solar panel. To communicate with Earth using the HGA, the telescope would stop observing and would slew to point the HGA at the Earth without violating the OPZ constraints. Figure 10 illustrates the geometry of HGA communications. The angle between the Spitzer (Probe) to Sun vector and the Spitzer to Earth vector is referred to as the Sun-Probe-Earth (SPE) angle. Had the HGA boresight been aligned with the telescope axis, the SPE angle must be 60° ≤ SPE ≤ 100° to stay within the OPZ. But because of the canting of 8°, the range of valid SPE is 52° ≤ SPE ≤ 92°. Figure 11 shows a plot of the SPE angle for the as-flown trajectory and one with a large loop. The reason to cant the HGA becomes apparent. It allows early use of the HGA. Had the HGA not been canted, then one has to wait until the SPE angle is 60° around day 70 from launch.

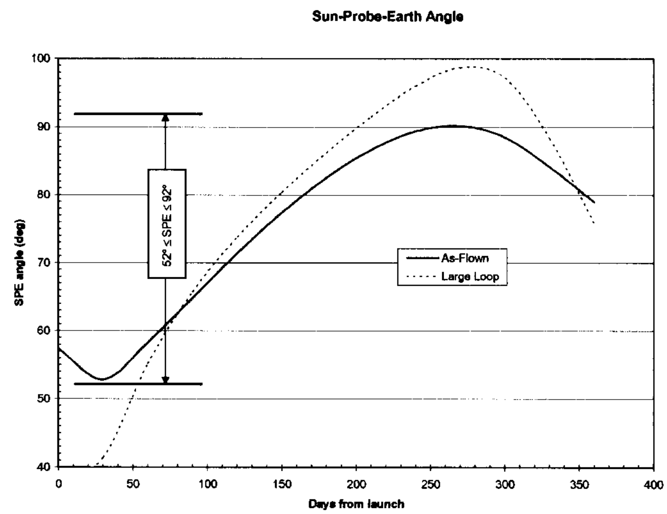


Figure 11 SPE angle for first year of Spitzer

However, canting the HGA caused a violation of the OPZ during high rate communication sessions for orbits with large loops since the SPE angle at around 8 months from launch is larger than 92°. When Spitzer was delayed from a winter launch to a summer launch, the direct ascent launch trajectory had to be abandoned, and Spitzer had to revert back to a parking orbit launch strategy. A parking orbit allows choosing a declination of the launch asymptote that results in an escape orbit with small loops similar to a direct ascent launch in the winter. Bonfiglio and Garcia, 2003 gives a more comprehensive description of the trajectory design and launch strategy between the winter and summer launches.

7.4. Navigation design

Unlike Earth orbital and interplanetary missions where frequent tracking and precision orbit determination are required to achieve certain targets or orbit event execution, the only navigation requirement on the solar orbit option for Spitzer is to have enough knowledge of the telescope location for DSN antenna pointing. At X-band frequencies, acquisition by the 70 meter antenna requires angular accuracy of approximately 0.015° for antenna pointing. A velocity accuracy of 70 m/s (2 Khz) is required to receive downlink signal. For the 34 meter antenna, the requirement is relaxed by a factor of 2.

Doppler tracking data is a by-product of telecommunications. During IOC/SV, there were almost 90 days of continuous tracking. Thereafter, the plan was to communicate 30 minutes every 12 hours. Therefore tracking data is available daily. Based on such strategy, Table 4 gives the orbit knowledge for three stressing cases: 1) when Spitzer is near Earth (during IOC/SV), 2) when Spitzer is at zero declination and the Earth rotation does not produce sufficient knowledge of the north-south component of the orbit, and 3) when Spitzer is at 0.6 AU (max distance). It is clear that the knowledge of the orbit is more than two orders of magnitude better than what is needed to point the DSN antennas.

Table 4 Orbit Knowledge

	Position (km)	Velocity (mm/s)	Longitude (deg)	Latitude (deg)
Near Earth	42	0.2	$3.2° \times 10^{-5}$	$1.1° \times 10^{-4}$
Zero Dec	762	0.3	$4.9° \times 10^{-5}$	$7.3° \times 10^{-5}$
Max Range	1011	0.2	$4.3° \times 10^{-5}$	$5.0° \times 10^{-5}$

7.5. Dust Cover Ejection Design

The ejection of the Spitzer dust cover was an interesting mission design exercise. The dust cover is spring loaded and when released, would have an initial speed of 0.98 m/s and an ejection direction along the telescope axis. This does not mean that the cover would continuously drift away from the telescope. Under the gravity of the Sun and the Earth, it is possible for the cover to return to the vicinity of the telescope. Since the telescope has no propulsive capability, one can only choose the ejection attitude to maximize separation distance. The dynamics of the cover and the gravitation interaction of the telescope and the cover were simulated with thousands of computed runs. The mission design team finally chose an ejection attitude that would maximize separation distance, maintain LGA communications through ejection, and allow the Observatory to remain pointed within the OPZ even in the worst-case angular momentum change following ejection. After the dust cover was ejected, attitude and Doppler data confirmed that the dust cover was ejected very close to plan. Figure 12 shows the actual and predicted dust cover trajectory. It remains more than 100,000 km from Spitzer over the course of the mission.

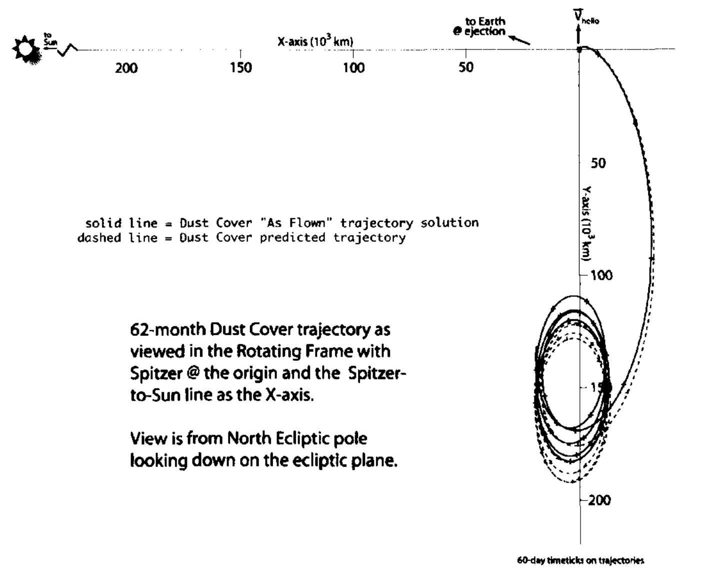


Figure 12 Dust cover trajectory relative to Spitzer

8. Conclusion

At the point of this writing, the Spitzer telescope has been performing almost flawlessly. The main reason for that is the team that built Spitzer is an extremely talented and dedicated group of professionals. But the authors could not help but think that the simplicity of the solar orbit has allowed a very robust design of the telescope in areas of pointing control, thermal control, fault protection, and mission operations. There have been many planetary missions, such as Voyager, Galileo, and Cassini, in which complicated trajectories are required to deliver the payload to the destination. Spitzer is the other extreme. The simplest trajectory has enabled the realization of the fourth Great Observatory.

9. Acknowledgement

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