Design of a Precision Pointing Control System for the Space Infrared Telescope Facility

Banavar Sridhar, Jean-Noël Aubrun, and Kenneth R. Lorell

ABSTRACT: This paper describes the design of a precision pointing control system for the Space Infrared Telescope Facility (SIRTF). SIRTF mission requirements and their impact on control system design are discussed along with the original features of the control strategy. Simulation of the total system is described, and the most significant results are presented.

Introduction

The National Aeronautics and Space Administration (NASA) is proposing to build a long-life, cryogenically cooled, orbiting infrared observatory, to be called the Space Infrared Telescope Facility (SIRTF). Designed to take advantage of the success of the Infrared Astronomical Satellite (IRAS), SIRTF will have a wider variety of focal plane instrumentation and a larger aperture, making it about 1,000 times more sensitive than IRAS. This sensitivity will make it possible to observe targets of scientific interest in any portion of the celestial sphere. However, in order to fully take advantage of this capability [1], an extremely precise and stable pointing and control system is required.

The Lockheed version of the baseline SIRTF design, shown in Fig. 1, assumes a Shuttle launch of a dedicated spacecraft flying in a 600 km orbit with 28-degree inclination. Control for large and small angle slews, earth-sun-moon avoidance, and a first level of disturbance attenuation will be provided by the vehicle's attitude control system. In the proposed Lockheed design, residual motion of the telescope optical axis, due to a variety of disturbances and error sources, can be effectively removed by a second level of stabilization. The additional performance is provided by an active image stabilization (AIS) system, which utilizes both feedback from the focal plane fine-guidance sensor to drive the telescope's secondary mirror.

SIRTF Mission Requirements

There are a number of aspects of the SIRTF mission that have a direct effect on the design of the pointing and control system (PCS). These are listed below, with each followed by a brief description:

1. High sensitivity of focal plane instrumentation: SIRTF's ability to rapidly take data on even the weakest sources must be supported by a high-performance PCS, able to rapidly and efficiently reorient the telescope to acquire and track new targets.

2. Precision pointing and image stability: The performance of SIRTF's focal plane instrumentation must be matched by an extremely precise PCS, which must also eliminate the jitter in the image, once the telescope is correctly pointed.

3. Operation at temperatures below 10 K: Cryogenic operation of the telescope makes the problem of misalignment between an external fine-guidance sensor and the telescope optical axis much more severe. Therefore, a focal plane fine-guidance sensor will probably be required. In addition, the sensitivity of the cryogenic cooling system to aperture thermal inputs is such that the telescope must

from the focal plane fine-guidance sensor to drive the telescope's secondary mirror.

1. Sunshade
2. TDRSS Antenna
3. Dewar Outer Shell
4. Solar Panel
5. Spacecraft Support Module
6. Shuttle Pallet Lockdown
7. Multiple Instrument Chamber Cover
8. Momentum Dump Coil

Fig. 1. Space Infrared Telescope Facility spacecraft.

These requirements are directly affected by SIRTF's operational modes, because slewing maneuvers—especially the rapid small angle slews necessary for scanning diffuse sources—will excite unacceptable structural vibrations in the system.

System Definition

The SIRTF pointing and control system, shown in Fig. 2 [2], utilizes rate integrating gyros as attitude sensors, and a cluster of six single-gimbal control moment gyros (CMG's) as actuators. In order to provide updates to the gyros, estimate their drift rates, and automatically identify targets, the PCS incorporates a focal plane fine-guidance sensor (FGS) that is capable of tracking multiple stars simultaneously. By comparing the current positions of the tracked stars with their desired positions, algorithms in the fine-guidance sensor computer can compute the attitude error in all three axes.

Another important feature of the PCS is the active secondary mirror of the SIRTF's Cassegrain telescope. This mirror is controlled in two axes to provide the spatial chopping function, a technique used in infrared astronomy to enhance the signal-to-noise ratio of weak sources. The secondary
SECONDARY H I R R O R  C H G  ( I O F  6 )
CCD F G S A T FOCAL PLANE

ATTITUDE CONTROL E L E C T R O N I C S

Fig. 2. Pictorial diagram of PCS.

The mirror is thus equipped with a high-performance control system that can also be used to provide active image stabilization with little or no additional complexity. The mirror's controller is driven by error signals generated by the attitude gyros and the focal plane fine-guidance sensors. The mirror's movements are commanded to reduce the telescope line-of-sight errors that could not be compensated for by the attitude controller.

Flexible appendages, such as TDRSS antennas and solar panels, were modeled using data pertinent to the space telescope, with proper scaling for SIRTF use.

The use of rigid bodies interconnected by gimbals, springs, and dampers is adequate to model the principal structural flexibility effects. Only the lowest modal frequencies can be attained in this way, but they are the ones usually responsible for the major degradation in pointing and stability performance. Thus, effects connected with structural dynamics of the telescope structure, or of higher modes of the appendages and the SSM, are not modeled. Such modeling would require a precise definition of the spacecraft — an undertaking which is beyond the scope of the present study. The model for the cryogen slosh is similar to the one used for IRAS [3]. It is likely to represent a worst-case situation in which all the fluid behaves as a lump mass, but does not attempt to represent the actual complexity of cryogenic fluid dynamics under zero-g conditions.

Spacecraft Dynamic Model

The primary purpose of the SIRTF dynamic model is to represent the major components of the dynamic behavior of the spacecraft. As can be seen in Fig. 4, SIRTF consists of seven interconnected bodies. Body 1 is the spacecraft support module (SSM), which contains the attitude control actuators (CMG's) and the attitude gyros. Body 2 is the telescope, which includes the dewar, cryogen tanks, mirrors, and instruments. Body 3 is the cryogen (superfluid helium), which is free to rotate about the telescope axis. Bodies 4 and 5 are the communication antennas (TDRSS). Bodies 6 and 7 are the solar panels. The telescope (including instrument chamber and cryogen tanks) is connected to the SSM by special isolators that give the system some additional flexibility. Overall telescope-motion natural frequencies related to these isolators were derived from ground experimental data.
Fig. 4. SIRTF dynamic model showing interconnection of bodies.

When angular rates become large, TER-FLEX can also provide the solution to the complete nonlinear dynamic equations. This option was only exercised once during our work, to verify the behavior of cryogen slosh and the validity of its linear representation. Computer-aided control synthesis and analysis software (such as the Lockheed-developed program MAPLE) was used to perform the various analyses.

**Pointing and Control System Performance Requirements**

There are several basic requirements for a pointing and control system designed for use with an orbiting, infrared observatory. The system must have full three-axis attitude control with backup capability. It must be able to provide inertial pointing in any attitude, and must automatically avoid pointing the telescope at the sun, earth, or moon, so that sensitive instrumentation and cryogenic cooling are not compromised. In addition, there are some specific performance requirements that the pointing and control system must meet. These are listed below, each followed by a brief explanation:

1. **Absolute pointing accuracy of 1 arcsec:** This accuracy is required so that the telescope can be pointed at infrared sources that have no visible radiation. The pointing control must therefore be operated by using stellar-inertial updates to the attitude gyros, obtained by tracking nearby visible guide stars with the focal plane fine-guidance sensor.

2. **Image stability of 0.1 arcsec rms:** The resolution of SIRTF's instrumentation will be directly affected by the stability of the image at the focal plane. The width of spectrometer slits, for example, and the ability to stare for extended periods of time at very weak sources are important reasons for maintaining a high degree of image stability.

3. **The ability to slew 120 degrees in 8 min (0.25 deg/sec average):** This relatively easy-to-meet requirement is based on the need to reorient the telescope three times per orbit without viewing the earth's limb.

4. **The ability to make small angle slews, up to a maximum of 7 arcmin, in a time frame of 2 sec or less:** This requirement arises from the need to scan the focal plane over diffuse infrared sources in order to map them. Short slew times are important to maximize the efficient utilization of the instrument, since its operational lifetime is limited by the cryogen system. However, the control torques required may result in significant excitation of structural modes that severely impacts image stability. The need for this maneuver becomes the primary reason for using the AIS.

**Attitude Control System**

Figure 5 shows a block diagram of the attitude control system. Probably the most important concept in this diagram is the command generator, which produces both a feedforward torque as well as position and rate commands \( \theta \) and \( \dot{\theta} \). The use of the command generator permits the attitude control system to perform slews, especially small angle slews, in a relatively short time frame. Since the spacecraft has potential problems with flexible appendages, the command generator is used to produce the commanded time histories for attitude angle and rate, along with the corresponding varying torque profile (e.g., sine-versine) tailored to substantially reduce structural excitation. Estimates for the inertial attitude angle \( \theta \) and rate \( \dot{\theta} \) are provided by the rate integrating gyros. To eliminate bias and drift errors, the gyros are updated using information from the fine-guidance sensor (not shown in the figure).

**Active Image Stabilization System**

The block diagram in Fig. 6 illustrates the details of the active image stabilization control loop. In particular, it shows how output from the fine-guidance sensor is combined...
with gyro signals (which are corrupted by a stabilization system. Fig.
scale-factor error represented by the gain at sensor null, except when requested to
control system that attempts to keep the
being different from
herent in a gyro feedforward system. Since
move by the combined gyro and fine-
move sensor inputs in the outer loop
ance sensor commands. The use of fme-
mance sensor has an effective
profile, which has an effective
power spectrum decays rapidly with fre-
quency. The sine-versine profile, which has
power spectrum is very rich in
harmonics that can excite vibration modes.
In a slew maneuver, the torque time his-
tory, or torque profile, has a strong impact on the
modal excitation of the spacecraft, and thus on the settling time. The time-optimal
torque profile minimizes the maximum
torque; it is also known as the bang-bang
torque profile because it utilizes maximum accelera-
tion, and integral of the angle. If e is
the vector of attitude errors, and T is the feed-
back torque, the control law takes the form:

\[ T(t) = C_1 \dot{e} + C_2 e + C_3 \int e \, dt \]

The control design involves the selection of matrices \( C_1 \), \( C_2 \), and \( C_3 \), which can be obtained by using optimal control or pole placement methods. In the present design, the emphasis was more on settling time and damping, so the latter technique was selected and is briefly described below. Assuming a pure rigid-body model, of composite inertia tensor \( I \), the dynamics of the error \( e \) are described by

\[ \ddot{e} = I^{-1} \tau_f \]

Thus, the error equation can be written as

\[ \ddot{e} = I^{-1} C_1 \dot{e} + I^{-1} C_2 e + I^{-1} C_3 \int e \, dt \]

If \( \alpha \) is the desired integrator pole, \( f \) the
closed-loop frequency, and \( \xi \) the damping
dratio corresponding to motions about the \( i \)th
controlled axis \( i = 1, 2, 3 \) of the spacecraft, then the \( C \) matrices must be such that

\[ C_1 = -I[\alpha + 2\xi \omega] \]
\[ C_2 = -I[2\xi \omega \alpha + \omega^2] \]
\[ C_3 = -I[\alpha \omega^2] \]

where the \( I \) denote a diagonal matrix, and \( \omega = 2\pi f \). This control law is the three-axis equivalent of the standard PID controller. In this case, the resulting controls are coupled, i.e., errors on one axis produce torques on all three axes. However, because of this coupling, the system can deal efficiently with existing misalignments between the spacecraft principal axes of inertia and the control system reference axes. In the model studied for SIRTF, the off-diagonal terms in the inertia tensor were, in fact, very significant, thus motivating this particular control design approach.

Simulation and Results

The full spacecraft dynamics, together with the attitude control and active image stabilization system, were simulated using the LISSA computer program [2]. The simulation included nonlinear effects such as torque saturation and CMG bearing stiction. The complete model contained a total of 32 states — 6 for the main body of the spacecraft, 2 for the cryogenic slosh, and 24 for various flexibility effects.

Tables 1 and 2 display the eigenvalues of the dynamical model of the spacecraft (open-
loop roots) and those of the total system, i.e., when attitude and image stabilization control systems are activated (closed-loop roots). The corresponding modes or subsystems asso-
ciuated with a particular root are identified. The natural structural damping is usually low and has been adjusted in the model to be at or below 1 percent of critical damping. Very little additional damping is introduced by the PCS in the roots corresponding to the tele-
scope and the TDRSS antennas. However, up to 10 percent is introduced in those three solar-panel modes that couple with spacecraft rotations (antisymmetric modes). Sym-
metric modes are not affected by the PCS, and, conversely, do not cause pointing errors when excited. The PCS mainly controls the rigid-body modes, introducing more than 50 percent damping in all three rotations with a bandwidth of about 0.5 Hz. The sine-
guidance sensor bandwidth is less than 0.5 Hz (corresponding to a 1 Hz sampling rate). Finally, although the slosh frequency is truly zero, it was set at a value incrementally larger than zero to avoid numerical in-

February 1986
Table 1
Open-Loop Poles

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Damping</th>
<th>Subsystem</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.6E-5</td>
<td>0.0</td>
<td>Rigid-Body</td>
</tr>
<tr>
<td>1.8E-5</td>
<td>0.0</td>
<td>Slosh</td>
</tr>
<tr>
<td>2.8E-5</td>
<td>0.0</td>
<td>Solar-Panel</td>
</tr>
<tr>
<td>2.2E-3</td>
<td>0.002</td>
<td>TDRSS</td>
</tr>
<tr>
<td>0.7558</td>
<td>0.008</td>
<td>Antenna</td>
</tr>
<tr>
<td>0.7892</td>
<td>0.009</td>
<td>Mirror Servo</td>
</tr>
<tr>
<td>0.8327</td>
<td>0.010</td>
<td>Integrator</td>
</tr>
<tr>
<td>0.8737</td>
<td>0.008</td>
<td>Integral Control</td>
</tr>
<tr>
<td>1.0730</td>
<td>0.008</td>
<td>Solar-Panel</td>
</tr>
<tr>
<td>1.0759</td>
<td>0.008</td>
<td>TDRSS</td>
</tr>
<tr>
<td>1.4091</td>
<td>0.005</td>
<td>Antenna</td>
</tr>
<tr>
<td>1.4281</td>
<td>0.005</td>
<td>Mirror Servo</td>
</tr>
<tr>
<td>1.4462</td>
<td>0.005</td>
<td>TDRSS</td>
</tr>
<tr>
<td>1.4610</td>
<td>0.005</td>
<td>Solar-Panel</td>
</tr>
<tr>
<td>1.9992</td>
<td>0.004</td>
<td>Telescope</td>
</tr>
<tr>
<td>2.0390</td>
<td>0.004</td>
<td>Telescope</td>
</tr>
</tbody>
</table>

stabilities in the simulation. This had no measurable effect on the results.

Various simulation cases were run to study the effectiveness of the control system in maintaining performance requirements in the presence of on-board disturbances (actuator noise and nonlinearities, cryogen slosh, momentum desaturation, among others) and external disturbances (gravity gradient and aerodynamic torques). However, because of their overwhelming importance to the SIRTF mission and their sensitivity to the control system design, small slew maneuvers were studied in detail and will be discussed next.

Results concerning small angle slews are summarized in Figs. 7 and 8. These 7 arcmin slews have a slew time varying from 2 to 6 sec. Figure 7 corresponds to the case of a sine-versine torque profile. It shows the plot of the time it took after the start of the slew maneuver for the pointing error to decay to, and remain below, 0.1 arcsec. This pointing error is defined as the difference between the commanded and actual pointing angles. Thus, the error could settle below 0.1 arcsec before being on the target. However, as long as the telescope line of sight itself is not on target (i.e., its attitude has not yet reached the prescribed final value), no observation can be made. Thus, the minimum achievable time to reach the target is, by definition, equal to the prescribed slew time. This fact is graphically represented by a straight line. Points above this line mean that structural vibrations excited during the slew period need extra time to damp out after the end of the slew (settling time). Points below the line mean that the telescope was already tracking the prescribed profile before the end of the slew.

The time to reach target (TTRT) has been plotted for the telescope line-of-sight error (U-LOSX) and for the actual focal plane error when active image stabilization is used (C-LOSX). The TTRT first decreases, due to a lessening of structural excitations, to about
6 sec for U-LOSX (or 3 sec for C-LOSX). Increasing the slew time beyond these values will further reduce the residual oscillations but will not improve the TTRT. The AIS will make it possible to achieve a 3-sec TTRT instead of a 6-sec TTRT.

Figure 8 is identical to Fig. 7 except that it corresponds to a bang-bang torque profile. In this case, lengthening the slew time does not significantly improve the TTRT. This is because the bang-bang power spectral density decreases slowly with increased slew time, as indicated previously. The excitation of the solar panels and antennas is significant and reoccurs at the very end of the slew when the torque is abruptly turned off. The settling time is therefore never zero when a bang-bang profile is used, and the TTRT always exceeds the commanded slew time. Slew times from 2 to 9 sec were simulated, and the dramatic effect of active image stabilization was evident, as the TTRT was reduced from 10 to 3 sec.

Figure 9 illustrates typical time histories of solar panel bending about the x-axis (SPX), TDRSS antenna bending about the x-axis, telescope pointing error (ULOS), and focal plane pointing error after compensation by the AIS (CLOS), for a bang-bang slew of 7 arcmin about the x-axis. By comparison, Fig. 10 shows similar time histories for a sine-versine torque profile. Although the feedback loop stabilizes the spacecraft in both cases, and eventually achieves the required pointing accuracy, the choice of the torque profile greatly influences the amount of structural vibration excited by the maneuver and, thus, the availability of the telescope for observations.

Conclusion

This paper has described the design and performance simulation of the Space Infrared Telescope Facility pointing and control sys-
tem. The system design is constrained by numerous considerations, such as image stability, maneuver capability, cryogen lifetime, and structural flexibility. The primary design consideration was the need to rapidly execute small angle reorientations of the telescope's optical axis. The size and type of attitude control actuator were impacted, as well as the need for an additional level of stabilization involving active optical elements. The flexibility of the SIRTF spacecraft was simulated using a simplified multibody model that provided an approximation of the primary bending modes.

The rather conventional PID attitude control system design, with a bandwidth of 0.5 Hz, was substantially enhanced to meet the small angle maneuver requirements through the use of three techniques:

1. A feedforward loop to improve time response
2. Torque shaping to minimize structural excitation
3. Active image stabilization to remove residual pointing error and jitter

Simulation results indicate that the system has the desired performance and can be designed utilizing techniques and hardware well within the state of the art.

References


Jean-Noël Aubrun received his Diploma of Engineering from the Ecole Superieure de Physique et Chimie de Paris in 1960 and his Ph.D. in physics from the University of Paris in 1964. He also holds advanced degrees in thermodynamics, mechanics, optics, and mathematics from the same university. He worked at NASA Ames and Ford Aerospace before joining Lockheed in 1975. For the past ten years, Dr. Aubrun has been deeply involved with the large space structures control problem. He developed the low authority control theory for which he was awarded the Outstanding Control Engineer Award by IEEE CCS (San Francisco Chapter) in 1980. He is currently a Senior Staff Scientist at Lockheed and was nominated Senior Member of the Research Laboratory in 1984.

Kenneth R. Lorell was born in Baltimore, Maryland, on February 10, 1944. He received a B.S. degree in physics from Harvey Mudd College in 1965 and a Ph.D. degree in aeronautical and astronautical sciences from Stanford University in 1971. From 1971 to 1973, he held a National Research Council Postdoctoral Fellowship at the NASA Ames Research Center. From 1973 to 1982, he continued research at NASA Ames in the areas of microprocessor-controlled systems, CCD star trackers, and the applications of automatic control to infrared astronomy. He is currently a Senior Staff Scientist at the Lockheed Palo Alto Research Laboratory. Dr. Lorell's research interests include development of special low-energy dissipation control systems and mechanisms for cryogenic applications, high-performance controllers for active optical components such as beam steering mirrors, and the analysis of the interaction between structural dynamics, optical performance, and figure/alignment control systems.