

AN OVERVIEW OF THE POINTING CONTROL SYSTEM FOR NASA'S SPACE INFRA-RED TELESCOPE FACILITY (SIRTF)

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ABSTRACT

This paper discusses the pointing control system for NASA's Space Infra-Red Telescope Facility (SIRTF). After an introduction to the SIRTF mission and telescope, an overview is given of the pointing control hardware, pointing control architecture, pointing requirements and capability, attitude constraints and commanding, attitude observers and required calibrations.

INTRODUCTION

SIRTF is an infrared space telescope which is the last in NASA's Great Observatory series. This well-known series includes the Hubble Space Telescope for the visible frequencies, AXAF (Chandra) for X-ray, and the Compton Gamma Ray Observatory (CGRO) for gamma rays. SIRTF is scheduled for launch in the August 2003 time frame. The new space telescope will have unprecedented sensitivity in the infrared, leveraging a large defense-based investment in the infrared detector arrays, with additional development under NASA sponsorship. SIRTF will study the early universe, evolution of galaxies, birth of planetary systems, search for brown dwarfs, etc.

The orbit of SIRTF is unusual for a space telescope in the sense that it does not orbit the Earth. Rather, SIRTF orbits the Sun at 1 AU in an Earth-trailing orbit, which drifts away from Earth at about .12 AU per year. This Heliocentric orbit is ideal for infrared science which can avoid the effect of the Earth/Moon system as a huge heat disturbance source. To support the sensitivities required for infrared astronomy, SIRTF is cryogenically cooled down to below 5.5 degrees Kelvin. The consumption of cryogen fundamentally limits the life span of SIRTF, and drives the need for high operational efficiency. The nominal expected mission life is 2½ years, with a goal of 5 years. The SIRTF mission is managed for NASA by the Jet Propulsion Laboratory. The main engineering contractors are Lockheed Martin (for the Spacecraft and integration) and Ball Aerospace (for the telescope optics and cryogenic assembly).

This paper discusses the pointing control system for SIRTf, providing an overview is given of the pointing control hardware, pointing architecture, pointing requirements and capability, attitude constraints/commanding, required calibrations, and attitude observers.

OVERVIEW OF TELESCOPE

The telescope optics are shown in Figure 1. The primary mirror is 85 cm, and is of a Ritchey-Chretien design which ensures that the optics are well compensated for spherical aberration and coma. The optics are diffraction limited to 6.5 μm , and are designed to operate at or below 5.5 degrees Kelvin. The focal length is 10.2 meters with a focal ratio of $f/12$. The field of view is 32 arcmin (approximately the size of the full moon as seen on the sky), with a spectral bandpass between 3-180 μm .

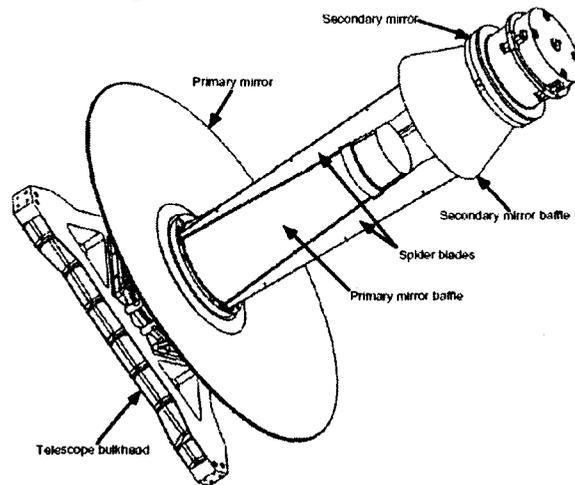


Figure 1: SIRTf telescope optics

The focal plane layout is shown in Figure 2. This particular figure looks down into the telescope and will look different when projected on the sky. It is seen that SIRTf carries three scientific instruments: the Infra-Red Array Camera (IRAC) which provides images from 1.8 to 27 μm ; the Infra-Red Spectrograph (IRS) which provides spectra from 4 to 200 μm ; and the Multiband Imaging Photometer for SIRTf (MIPS) which provides images and large area mapping from 20 to 200 μm . MIPS is unique in that it uses a scanning mirror to extend its field of view, and to coordinate with synchronized spacecraft scanning motions.

Also included in the focal plane are two Pointing Control Reference Sensors (PCRSs). The PCRS is a 4x4 pixel array, with 10 arcsecond pixels. There are two PCRS (each with an A and B side), of which the four central pixels are extremely well calibrated for pointing alignment purposes (i.e., providing 0.14 arcsec centroiding accuracy). Interestingly, the PCRS is the only real estate in the focal plane which is owned by the pointing control system. This restriction is intentional since the heat dissipation from a more significant pointing sensor in the cooled focal plane (e.g., such as HST's fine guidance sensor) would be prohibitive and significantly shorten the life of the mission.

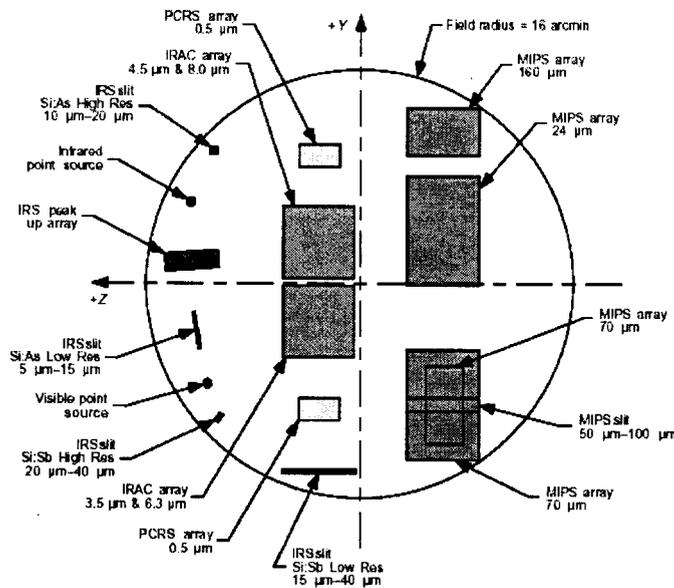


Figure 2: Focal plane layout

POINTING CONTROL HARDWARE

The SIRTf spacecraft is shown in Figure 3. The SIRTf pointing control hardware includes: 2 Kearfott SKIRU V gyro boxes (4 gyros per box), 2 LMMS AST 301 star trackers, 4 Ithaco B reaction wheels (all used simultaneously), 2 fine and 3 coarse LMMS sun sensors (the fine sensors are just finely calibrated versions of the coarse sensors), and 2 specially designed PCRS sensors. A cold gas Reaction Control System (RCS) is available which makes use of cold-gas thrusters for momentum dumping, but is not used for pointing purposes.

The LMMS AST 301 star tracker is modified from an earlier AST 201 model to provide higher accuracy. The main modifications are a reduced FOV, redesigned optics, larger star catalog, and an upgraded processor. The star tracker has a 5x5 degree FOV, tracks 50 stars (20 at the galactic poles), has an update rate of 2 Hz, and provides an overall NEA of 0.22" (x,y), 6.2" (z), and a bias of 0.62" (x,y), 21" (z). Only a single star tracker is used at any one time, and both are nominally boresighted in the same direction as the telescope boresight. The AST 301 is completely autonomous (requires no initialization) and outputs a full quaternion measurement of spacecraft attitude.

The SKIRU V gyros have been used previously on Chandra and various LMMS missions. They have an angle random walk of 56×10^{-6} deg/rt-hr, a bias stability of 0.0045 deg/hr, and they have been designed specially for SIRTf to have a small angle quantization of 0.0005 arc-sec.

The Ithaco Type B reaction wheels are commandable to a max torque of 0.04 Nm with a 8 bit quantization, and have a 19 Nms storage capability. The static imbalance is $2.16e-5$ Kg-m, the dynamic imbalance is $3.6e-6$ Kg-m², the torque ripple is 10% and the cogging torque is 0.002 Nm. All four reaction wheels are used simultaneously for pointing purposes, taking advantage of the null-space for momentum management.

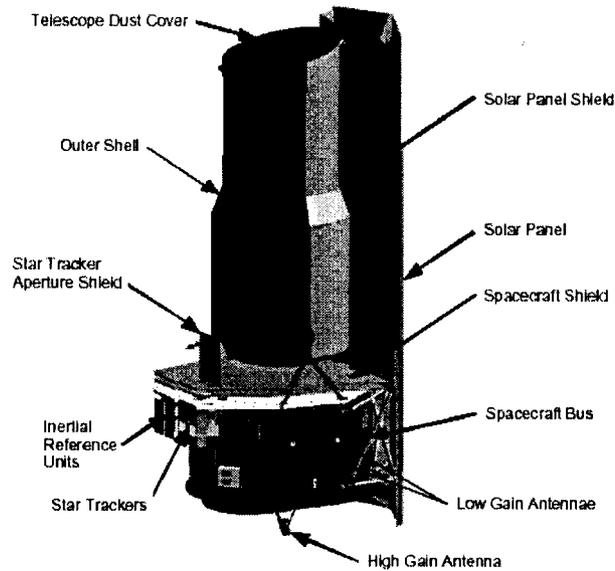


Figure 3: Spacecraft configuration

POINTING REQUIREMENTS AND CAPABILITY

The pointing requirements are outlined in Table 1, along with a recent assessment of the expected capability. It is seen that there is adequate margin on all pointing requirements. One of the most stringent requirements is for accurate incremental offset accuracy. This is needed to move sources accurately from the IRS pickup array to the centers of the narrow spectroscopy slits. Accurate incremental offsets are performed in-flight using a novel reconfigurable control approach [7].

Pointing Requirements and Capability		
	Requirement	Capability
Pointing accuracy	5"	2.34"
Incremental offset accuracy	0.56"	0.37"
Stability over 200 sec	0.3"	0.06"
Stability over 500 sec	0.6"	0.11"
*Scan stability over 15 sec	0.7"	0.23"
*Scan stability over 150 sec	1.0"	0.24"

* assumed to be at scan rates from 2 to 20 arcsec/sec

Symbol " denotes arcseconds

Table 1: Pointing requirements and capability [12][2], 1-sigma, radial; capability as of 1/20/03

KEY POINTING FRAMES

The main Instrument Pointing Frames (IPFs) of interest for pointing are shown in Figure 4. IPFs are defined by specific pixel locations in each science array, and which adopt the orientation of the pixel rows and columns. The quaternions for 128 such IPFs are stored in an on-board database, denoted as the “frame table”. A typical pointing command specifies that a particular frame from the frame table (denoted by its number) should be pointed to a particular location on the sky (denoted by its RA and DEC). The attitude commander applies a velocity aberration correction to the RA,DEC position and then computes an attitude which points the desired frame to desired location on the sky, subject to the geometric attitude constraints. Details on the attitude constraints are discussed next.

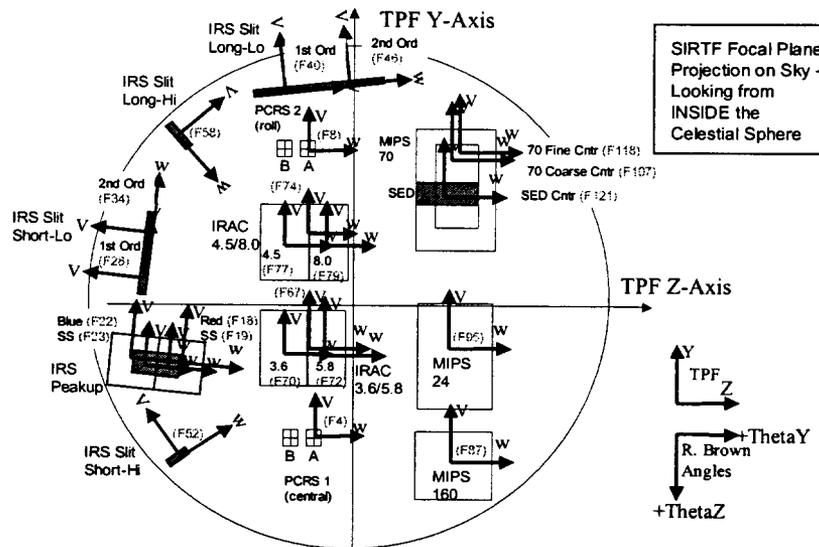


Figure 4: Key instrument pointing frame

ATTITUDE CONSTRAINTS

The attitude constraints for SIRTF are shown in Figure 5. The telescope is restricted to pitch at most -10 degrees toward the sun (sun avoidance on the CTA) and 30 degrees away from the SUN (power constraint). The roll angle is constrained to +/- 2 degrees. The yaw angle is unconstrained.

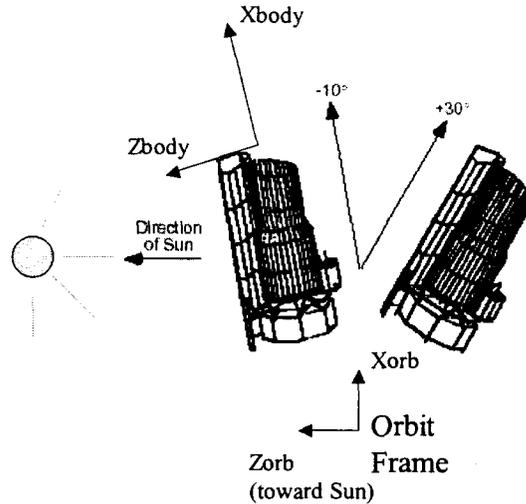


Figure 5: SIRTTF attitude pitch angle constraint

Mathematically, one can write these constraints concisely as follows. The constraint is written with respect to the cryogenic-telescope assembly (CTA) frame, which is defined by the sun-shield geometry (but is nominally aligned with the telescope boresight frame). Let the orbit-to-CTA frame transformation be denoted by D_{orb}^{cta} , and be decomposed into its Euler 3,2,1 sequence as follows,

$$D_{orb}^{cta} = R_1(\theta_1)R_2(\theta_2)R_3(\theta_3)$$

Then the attitude constraints a SIRTTF at any time instant can be written as,

$$-10^\circ \leq \theta_2 \leq 30^\circ$$

$$-2^\circ \leq \theta_1 \leq 2^\circ$$

Note, that the yaw angle θ_3 remains unconstrained.

Fixed Attitude Commanding

The attitude commander must take into account the constraints discussed above. For commanding a fixed attitude, the ground specifies

- (1) A frame table number (desired frame to point)
- (2) An RA,DEC (the desired sky location to point at)
- (3) A value for θ_1 , denoted as the roll constraint angle (RCA)

The attitude commander fixes the value $\theta_1 = RCA$ in the expression above for D_{orb}^{cta} , and then solves for the θ_3, θ_2 angles that point the boresight of the frame defined in (1) to the sky location in (2). Typically the RCA angle is specified as 0, unless one is holding the same attitude for many hours, and the change in sun direction (due to orbital rotation) must be taken into account.

Point-to-Point Attitude Commanding

The attitude constraint region is shown in Figure 6. Often SIRTTF starts at a fixed attitude within the constraint region, and desires to maneuver to another attitude within the constraint region (computed using the procedure from the previous section). The

procedure for the designing the attitude path is simply to connect the start and end points in Figure 6 with a straight line. This entire path is guaranteed to lie within the constraint because the end-points do, and the constraint region is convex. The reaction wheel torques are shaped to accelerate, coast and decelerate along this path.

POINTING CONSTRAINT REGION

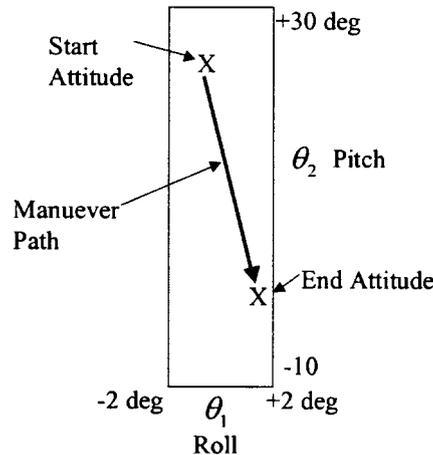


Figure 6: Attitude maneuvers using straight line segments in Euler angle space

POINTING FRAMES AND TRANSFORMATIONS

The key pointing frames and frame transformations for SIRTf are shown in Figure 7.

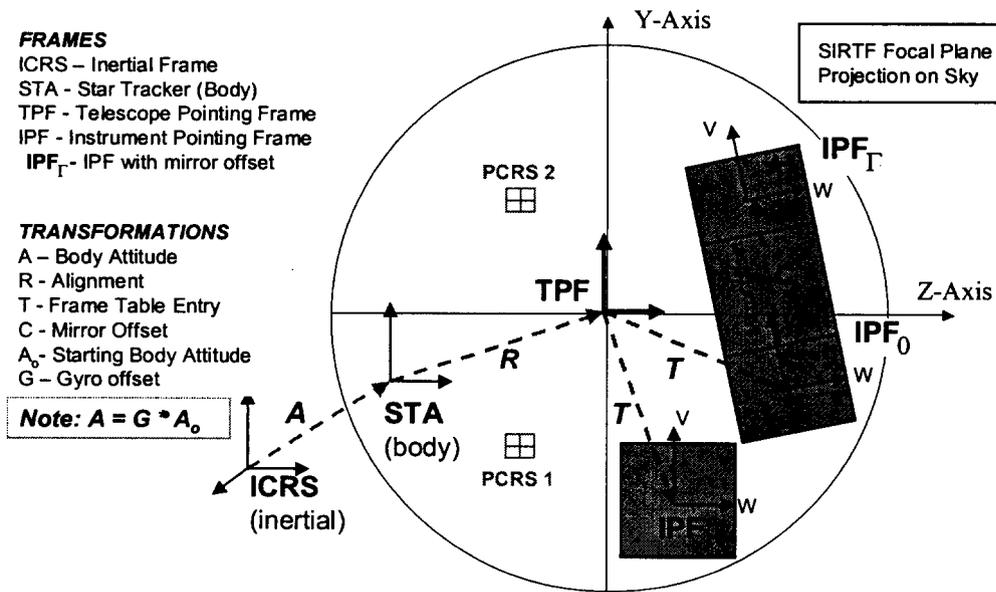


Figure 7: Main SIRTf Pointing Frames and Transformations

The International Celestial Reference System (ICRS) frame serves as SIRTf's principle inertial reference frame. With a suitable relabeling, the star-tracker instrument frame serves as the SIRTf Body frame (i.e., when spelled with its boresight as the x axis – see [10]). The mapping from ICRS to the Body Frame is denoted as the spacecraft attitude A . The Telescope Pointing Frame (TPF) has the telescope boresight as its x axis, and is defined rigorously in terms of the null points of the two PCRS sensors in [10]. The mapping from the Body Frame to the TPF is denoted as the alignment matrix R .

As mentioned earlier, Instrument Pointing Frames (IPF) are defined by specific pixel locations in each science array and which adopt the orientation of the pixel rows and columns. The mapping from the TPF to any specified IPF is denoted as T . The IPF frames are stored in an on-board "Frame Table" as 128 values for T (stored as quaternions), which is used extensively for commanding purposes. Certain important IPF frames are denoted as **Prime Frames** (e.g., located at the center of each of the instrument arrays). Other frames are called **Inferred Frames** and are defined by a pixel offset relative to a nearby Prime frame. The nominal orientations of the science instruments and their associated Prime frames in the telescope focal plane have been shown in Figure 4. Also seen are the associated w and v directions associated with each frame, which are used by the attitude commander for implementing fixed angle offsets.

The C matrix represents a scan mirror offset from a nominal starting position $\Gamma = 0$ to its current local mirror position $\Gamma \neq 0$ (where Γ is the commanded scan mirror rotation angle, in radians). For non-MIPS instruments, the C matrix is set to identity. For MIPS, the frame defined when the mirror is at position Γ is denoted as IPF_{Γ} . Note that as the scan mirror moves there is an entire family of IPF_{Γ} frames generated as a continuous function of the variable Γ .

The C matrix is not used for pointing purposes (although it is used for pointing reconstruction). Because of this the main pointing frames are A, R , and T which can be remembered because they spell the common word "art". These important frames will be discussed in more detail in the architecture section. The attitude A is time-varying due to telescope repositioning, and R is time-varying due to thermo-mechanically induced alignment drift. The mapping T is assumed constant due to the fact that the telescope focal plane is actively cooled. The mapping C is time-varying due to a time-varying scan-mirror offset angle Γ .

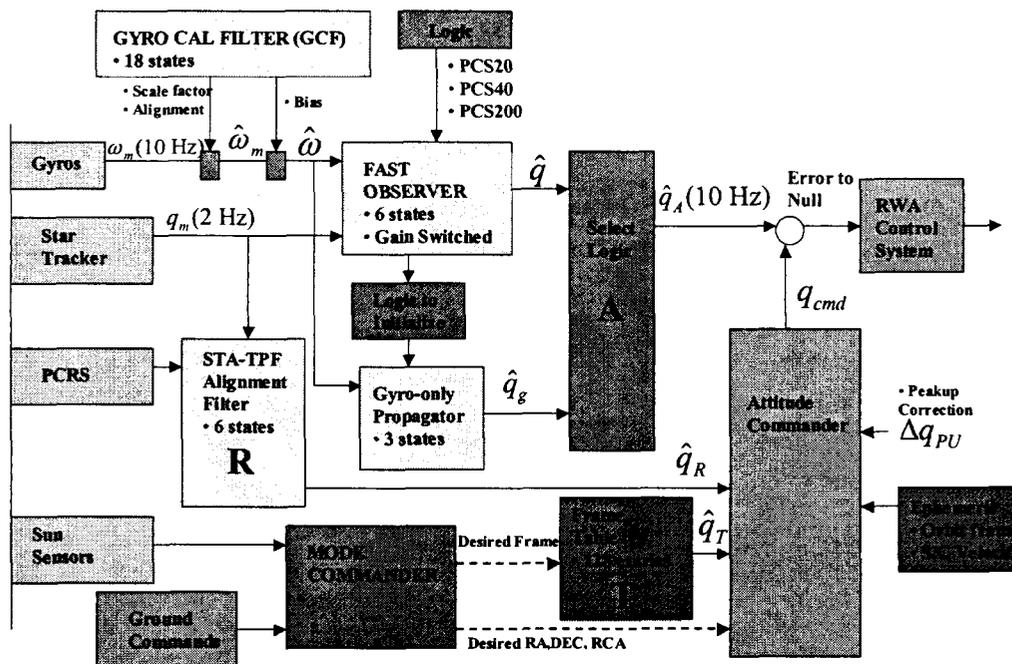


Figure 8: SIRTf Pointing Control System Architecture Schematic

POINTING CONTROL SYSTEM

A schematic of the pointing control system architecture is shown in Figure 8. The sensor signals shown on the left are mapped through the diagram to create a control error shown on the right. The controller acts to null the indicated error.

The gyro rate (actually an incremental angle) is sampled at 10 Hz and is first corrected for scale factor and alignment, and then for bias by the Gyro Calibration Filter (GCF). The compensated rate and star tracker quaternion (available at 2 Hz) are then input into the attitude observer. One of three time constants for the attitude observer can be chosen by use of gain switching. In addition, one has the option to propagate attitude purely by integrating the rate estimate. This requires logic to provide an initial starting attitude estimate from the attitude observer, after which the rate estimate is integrated numerically. Selection logic chooses whether the observer or gyro-propagated quaternion estimate is used for control purposes.

If one is commanding SIRTf over a long period based on gyro-only propagation (i.e., tens of minutes) an “attitude reset” command can be issued which resets the integrator with the observer attitude estimate at the time of the command, and continues propagating from the reset attitude. This causes a discontinuity in the attitude control position, but acts to null out any accumulated attitude error due to gyro drift.

The frame alignment R is recursively estimated on-board by the STA-TPF alignment filter. The STA-TPF alignment filter is a six state Kalman filter which was developed at JPL [9]. Its main input is a PCRS centroid and an attitude estimate, and its main output is a recursive estimate of R . A centroid is taken on a single PCRS once every 8 hours to

feed this filter and maintain the accuracy of R to $\frac{1}{2}$ arcsecond (y,z directions). Even though a single star is used at each update, the filter is able to estimate the twist alignment because successive updates alternate between putting a star on PCRS1 and PCRS2. The twist angle knowledge of R is maintained in this fashion to within 10 arcseconds error. A similar pointing filter on the ground, denoted as the Pointing Alignment and Calibration (PAC) filter, will be used during IOC which repeats the calculations of the STA-TPF alignment filter, but estimates an additional parameter related to the separation distance between the two PCRS sensors.

The TPF to IPF mapping T is stored in the on-board Frame Table. The Frame Table is a database of 128 quaternions which are outputted upon request for attitude commanding purposes. The attitude commander takes Frame Table quaternions and desired RA,DEC locations to compute the desired pointing attitudes. The SIRTf ephemeris is also provided to the attitude commander to compute the orbit frame (needed for constraint avoidance) and to compute a velocity aberration correction which is applied to the pointing direction.

Like the Hubble Space Telescope, SIRTf uses an attitude observer rather than a Kalman filter to avoid the long setting times required with the optimal smoothing time constant. Ironically, although the Kalman filter is optimal, it has a very sluggish pole (i.e., a real pole near the origin) which significantly lengthens settling times and makes it less desirable for use when efficiency is an issue. Instead, SIRTf uses 3 Fast Observers which are designed by solving an optimization problem which minimizes variance of the attitude estimate subject to a constraint that the poles of the filter lie to the left of a line in the left-hand Laplace s-plane. Fast Observers will be discussed in more detail later.

The GCF is an on-board Kalman filter with 18 states which was developed at JPL [11]. The GCF filter includes 9 linear scale factors and alignments, 3 attitude states, 3 bias states, and 3 absolute scale factor parameters. The GCF scale factor and alignment are calibrated using dedicated maneuvers on the average duration of $\frac{1}{2}$ hour per day per axis, which maintains calibration to 95 parts per million. The GCF bias is updated based on inertial hold data. Regular inertial holds are built into the commanded sequences such that there is a 100 second inertial hold every 3 hours (or every 15 minutes for high accuracy .0008 arcsec/sec bias cal). It is noted that since the attitude observer carries 6 states (2 states per axis) it provides an extra level of compensation for the gyro bias. However, this additional compensation is only used during observer based pointing and is not applied for gyro-only propagation.

The Frame Table entries are estimated using a ground-based Instrument Pointing Frame (IPF) filter. The IPF filter is a 37 state Kalman filter that was developed at JPL [10][14]. The IPF filter will be operated on the ground to determine IPF frames, plate scales and optical distortions. The IPF filter is expected to be exercised over 60 times during SIRTf's 3 month in-orbit checkout period.

FAST OBSERVERS

Interestingly, SIRTf does not use a Kalman filter for attitude determination. The reason for this is that a sluggish pole from the optimal Kalman filter significantly slows settling time. The solution is to design attitude observers that settle fast but still have good (but not necessarily optimal) smoothing properties. Such attitude observers are denoted as Fast Observers, and their theory is treated in [8]. Fast Observer design is briefly outlined here, as applied to the SIRTf pointing control system.

In terms of the Laplace s variable, a two-gain decoupled attitude observer that combines measurements from a gyro and star tracker can be written as follows,

Attitude Observer (Decoupled)

$$\hat{\theta} = \frac{(sk_1 + k_2)y + s^2(\omega_m / s)}{s^2 + k_1s + k_2}$$

$$\hat{b} = \frac{k_2(\omega_m - sy)}{s^2 + k_1s + k_2}$$

y - Angle meas (star tracker with NEA)

ω_m - Rate meas (Gyro, with bias and ARW)

θ - Angle (attitude)

b - Rate bias

Let the variance of the estimate $\hat{\theta}$ be written as a cost function $J(k_1, k_2)$ to be minimized,

$$J = \text{Cov}[\theta - \hat{\theta}] = J(k_1, k_2)$$

Then the optimal steady-state Kalman filter corresponds to the solution of the following minimization problem,

Steady-State Kalman Filter

$$\min J(k_1, k_2)$$

$$k_1, k_2$$

However, the Kalman filter solution does not place any constraint on the settling time, and the resulting filter can be quite sluggish. This is particularly true in fine pointing applications where the steady-state Kalman filter is often a split-root real pole design with one of the poles very close to the origin.

Consider instead the Fast Observer design which is defined by the solution to the following constrained minimization problem,

Fast Observer

$$\min J(k_1, k_2)$$

$$k_1, k_2$$

subject to

$$\text{Real (poles of } s^2 + k_1s + k_2) \leq -\frac{1}{\tau}$$

Here, the variance is minimized subject to a constraint that the poles be sufficiently fast. Specifically, the poles are constrained to be located to the left of a specified line in the Laplace plane. This ensures that the response will be on the order of τ seconds. A globally optimal analytic solution to the Fast Observer problem is given in [8], based on solving the corresponding Kuhn Tucker conditions.

Interestingly, for sufficiently fast Fast Observers, the solution is always a double pole located on the real axis at $-1/\tau$, so that $k_1 = 2/\tau$ and $k_2 = 1/\tau^2$. For slower Fast Observers, the design is more complicated but can still be calculated analytically.

The SIRTf pointing control system uses 3 Fast Observer designs with the time constants $\tau = 20, 40, 200$, respectively. The values for these designs is given in Table 2 and Table 3. The k_1, k_2 gains from these designs are input into a free running second-order filter structure using gain-switching logic. The gains for the (x) axis (i.e., the noisy twist axis) observer are not switched, but are kept constant and consistent with a 200 second time constant for maximum smoothing.

Observer Gains for (y,z) axes		
τ	k_1	k_2
200	.031225	.00013113
40	.05	6.25e-4
20	.1	.0025

Table 2: Fast Observer gains for (y,z) axes

Observer Gains for (x) axes		
τ	k_1	k_2
200	.01	2.5e-5

Table 3: Fast observer gains the (x) axis

OTHER POINTING ISSUES

There are many interesting issues related to the SIRTf pointing system which have not been covered here. These areas include the pointing criteria developed for high-resolution spectroscopy [6], reconfigurable control for accurate offset pointing [7], focal plane

survey [10][14], pointing reconstruction [13], among others. The reader is referred to the literature for further details.

CONCLUSIONS

SIRTF is NASA's new space telescope which is scheduled to be launched in August 2003 time-frame. The on-board infra-red science instruments include cameras, scanning arrays, and spectrographs. A brief overview of SIRTF's pointing control system has been outlined in the paper. It has been seen that accurate attitude estimation, alignments and calibrations have been designed to meet a wide range of challenging pointing, jitter, scanning, incremental offset, and efficiency requirements.

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