Pre-launch performance testing of the Pointing Calibration & Reference Sensor for SIRTF

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ABSTRACT

We present the performance results of the as-built Pointing Calibration and Reference Sensor (PCRS) for the Space Infrared Telescope Facility (SIRTF). A cryogenic optical (center wavelength 0.55 microns) imager, the PCRS serves as the Observatory's fine guidance sensor by providing an alignment reference between the telescope boresight and the external spacecraft attitude determination system. The PCRS makes precision measurements of the positions of known guide stars; these are used to calibrate measurements from SIRTF's star trackers and gyroscopes to obtain the actual pointing of the SIRTF telescope. The PCRS calibrates out thermomechanical drifts between the 300 K spacecraft bus and the 5.5 K telescope. We have demonstrated that the PCRS meets its centroiding accuracy requirement of 0.14 arcsec 1-σ radial. The PCRS was installed inside the SIRTF Cryo-Telescope Assembly in July, 2000 and has logged over 1000 hours of failure-free operation ever since. We have verified that the PCRS has survived all box-level environmental requirements, including the 1.4 K operating temperature, random vibration, pyroshock, and EMI/EMC, necessary to survive launch and operations over SIRTF's 2.5 year lifetime. Currently, the PCRS is undergoing testing as part of the recently integrated Observatory in preparation for a January, 2003 launch.

Keywords: infrared, cryogenic, optical, telescope, SIRTF, guidance, centroiding, pointing, helium, instrument

1. INTRODUCTION

The Pointing Calibration and Reference Sensor (PCRS) is a cryogenic instrument with a center wavelength of 0.55 μm colocated with the SIRTF science instruments inside the Multiple Instrument Chamber (MIC). It serves as the Observatory's fine guidance sensor by providing an alignment reference between the telescope boresight and the external spacecraft attitude determination system[1]. The PCRS makes precision measurements of the positions of known

Figure 1a: The Flight Cold Assembly, on the bench and during its installation into the Multiple Instrument Chamber.

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guide stars with an accuracy of 0.14 arcsec 1-σ radial; these are compared with measurements from SIRTF's star trackers and gyroscopes to obtain the actual pointing of the SIRTF telescope. This procedure calibrates out thermomechanical drifts between the 300 K spacecraft bus and the 5.5 K telescope. Currently, we estimate that we must perform this thermomechanical drift calibration once every eight hours.[2]

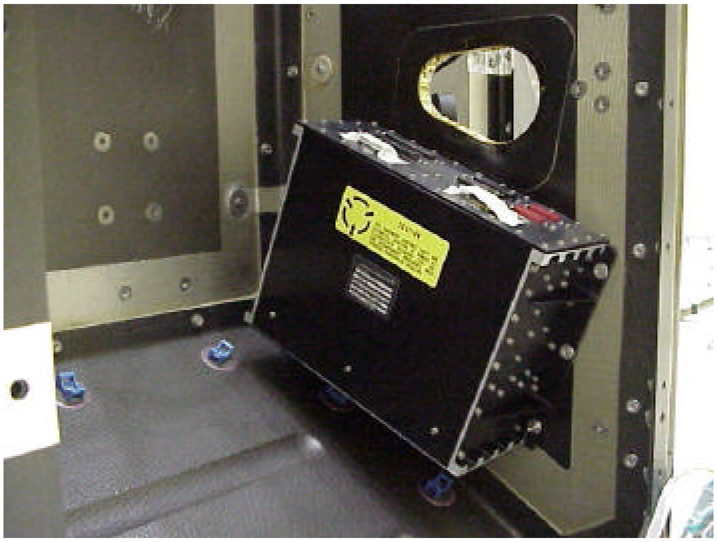


Figure 1b: The Flight PCRS Warm Electronics, being fit checked in the SIRTF spacecraft bus.

The PCRS also calibrates out uncertainty in the roll angle about the telescope boresight axis. We have two separate PCRS apertures located symmetrically about the SIRTF coordinate origin. To measure the roll angle, we first capture a star in one aperture, then scan the star over to where we think the other aperture is. The difference between where the star lands on the second array and the array center defines the roll angle error, which is then calibrated out.

The third usage of the PCRS is to initialize the pointing system for science observations that require high precision attitude knowledge. For example, the Infrared Spectrograph (IRS) requires accurate placement of the target in a spectrometer slit. The PCRS can be used to first peak up the guidance system on a known visible star and then precisely offset the pointing to place the infrared target in the spectrograph. This peakup capability will be offered to SIRTF observers as an alternative to the IRS peakup mode.

The instrument consists of a Cold Assembly (CA) and Warm Electronics (WE). See Figure 1. The Cold Assembly, which resides with the other science instruments in the 1.4 K MIC, contains relay optics, filters, detector arrays, and cryogenic readout/multiplexers. Hence, even though the PCRS most resembles the science instruments, it is an integral part of the Observatory's pointing control system. The Warm Electronics, which is installed in the ~300 K spacecraft bus, supplies the voltages and currents necessary to power the Cold Assembly, along with the A/D converters, power supply boards, and FPGAs required to digitize the data and perform preliminary processing on it before sending it to the main spacecraft computer. Table 1 summarizes the general instrument characteristics.

Characteristic	**Value**
center wavelength	550 nm
filter bandpass	520-600 nm; defined by Schott BG39 + OG515 Filters
magnitude range	V= 7 – 10
detector type	Silicon PIN
detector format	4x4 pixels
readout type	Raytheon CRC-696
array size	40x40 arcsec
read noise	118 electrons
well depth	250,000 electrons
dark current	< 0.1 electron/sec
integration time	0.5 – 25.5 sec
centroiding accuracy in "sweetspot" region	0.14 arcsec 1-σ radial
centroiding accuracy outside "sweetspot" region	0.5 arcsec 1-σ radial
radius of "sweetspot"	2 arcsec

Table 1: PCRS general characteristics.

2. INSTRUMENT DESIGN

2.1 Centroiding Performance

Although it has only 16 pixels, each 10 arcsec across, the PCRS is still able to achieve a centroiding accuracy of 0.1 arcsec 1-σ per axis. This accuracy, better than 1/100 of a pixel, is accomplished by making a high resolution map of the pixel responses and matching the responses coming out of the central four pixels to the map. We only use the inner ±2 arcsec of each array as the calibrated region in which high precision centroiding is available (the "sweetspot").

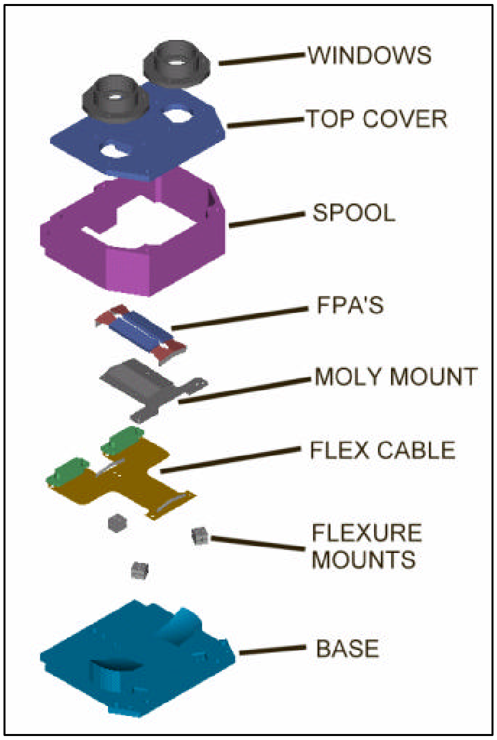
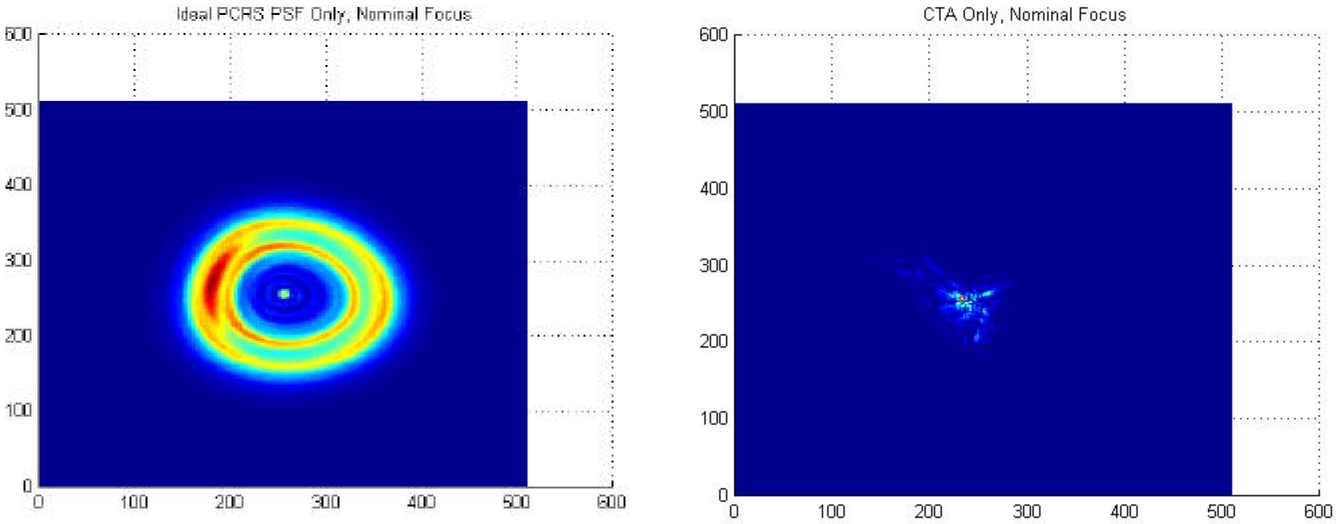


Figure 2: Exploded view of the PCRS Cold Assembly.

The centroiding algorithm, which was custom written for this application, uses a modified Newton's method routine to match the signals coming out of the four inner pixels to the four pixel response maps. We generated the maps for each array by raster scanning a simulated star across each pixel with fine steps. The resulting grid of data was fitted to a set of Chebyshev polynomials. We chose Chebyshev polynomials because they decrease with each successive coefficient,allowing us to gracefully truncate them to save space and increase processing speed. The algorithm minimizes the χ^2 derived from comparing the four pixels' measured values to the pixel response map, which is now represented by the Chebyshev polynomials. The algorithm computes the centroid fast enough to be run each time the detector collects an image. After any cosmic rays have been removed from the data, the resulting set of centroids are then averaged together to provide a final star position.

By defocusing the highly irregular non-diffraction limited image from the telescope, we smoothed out the PCRS's point spread function (PSF). See Figure 3. This resulted in a much more uniform sub-pixel response, which allowed us to centroid with greater precision using fewer mapping points than if the PSF exhibited great variability across each pixel. By performing a series of discrete offsets across the array using a high precision translation stage to move the simulated star, we assessed how well the centroiding algorithm works. These tests yielded an average accuracy below that of the required 0.1 arcsec 1-σ per axis. We therefore


Ideal PCRS PSF Only, Nominal Focus

CTA Only, Nominal Focus

Figure 3: PCRS model point spread functions both with and without the defocus. The PSF without defocus is irregular since it is operating at 0.55 µm, well below the SIRTF 3 µm diffraction limit.

conclude that the PCRS will meet its accuracy requirement in the calibrated region.

The remainder of the inner four pixels, plus the outer 12, are used strictly for acquisition purposes. The measured centroiding error should the star fall on these areas outside the sweetspot is approximately 0.5 arcsec 1-σ radial. This result accords well with what one would expect for typical centroiding performance resulting from a simple weighted-average centroid equation. Here, the accuracy can reasonably be assumed to be 1/10-1/20 of a pixel, or 0.5 – 1 arcsec centroiding accuracy.

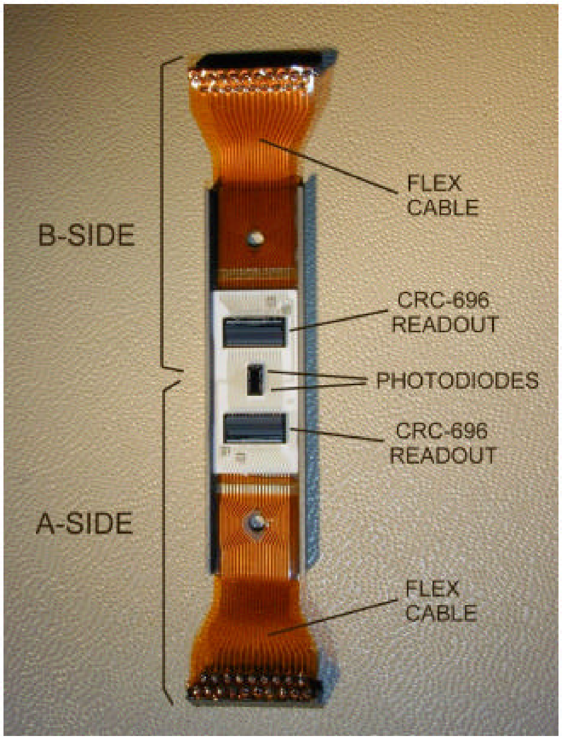


Figure 4: PCRS Focal Plane Array.

2.2 Cold Assembly

2.2.1 Mechanical Design

The Cold Assembly contains four 4x4-pixel silicon PIN detector arrays, along with supporting readout electronics, relay optics, and filters. Two of the arrays serve as the primary boresight alignment arrays, while the other two are used primarily for roll calibration updates. The PCRS is required to be fully electrically redundant, so the Cold Assembly contains two totally independent electrical halves, from the detectors to the readouts, ceramic fanout board traces, cables, and connectors. The Cold Assembly sits on the bottom of the Multiple Instrument Chamber, underneath the pickoff mirrors of the other science instruments. Since space limitations prevented the placement of the PCRS detectors in the SIRTF focal surface, relay optics were required to transfer the image down to the PCRS focal plane arrays.

The Cold Assembly's (CA) all-aluminum design of mirrors and housing allowed for easy alignment; diamond-turned mirrors produced by Speedring Systems of Englewood Cliffs, NJ were fabricated as an integral part of the housing itself. The lack of refractive elements means that the design is achromatic and very robust to thermal and mechanical shock. The CA consists of a top plate, out of which the secondary mirrors were directly cut, walls (called the spool), and a baseplate which has the primary mirrors directly carved into it. See Figure 2. The three pieces were pinned together for a precisely repeatable fit. As was required of all SIRTF science instruments parts extending

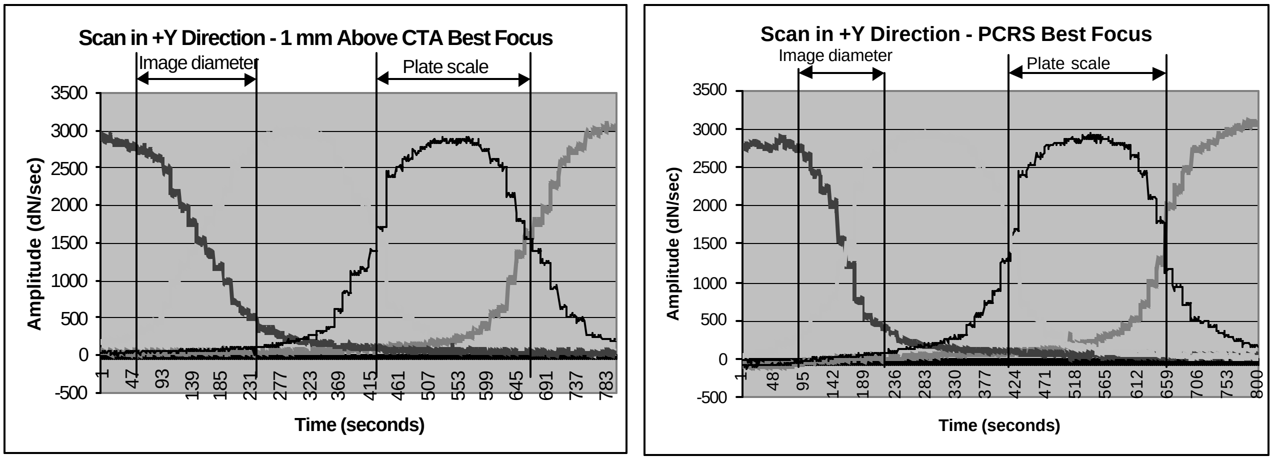


Figure 5a and 5b: A comparison of PCRS image diameters at two different focus positions, 1 mm above the SIRTF focal surface and at the PCRS best focus. The shrinking of the image diameter can be clearly seen by examining the steepness of the slopes.

into the focal plane, the exterior of the PCRS was first bead blasted, then anodized, and finally painted with Desoto black paint to blacken it sufficiently in the infrared.

To avoid thermal expansion coefficient mismatches between the silicon and ceramic Focal Plane Arrays and the aluminum housing, the FPAs were mounted to a molybdenum plate. The plate bolts to the PCRS baseplate via three stainless steel I beams, which form a kinematic mount capable of maintaining the detector positions over the entire cooldown from room temperature to 1.4 K.

2.2.2 Contamination

Like all the cold assemblies inside the Multiple Instrument Chamber, the PCRS is extremely contamination sensitive. The contamination requirements were driven by two forces: the need to avoid contaminating the other science instruments inside the MIC, and the need to keep particles off the PCRS optics and detectors. We were required to maintain Mil-Std 400A cleanliness levels on the Cold Assembly's exterior to be compatible with the MIC environment. However, the internal cleanliness requirement was set by the requirement to have no particles 25 µm or larger deposited on any of the pixels. With a pixel size of 250 µm and an accuracy requirement of 0.1 arcsec, which translates to 1/100 of a pixel, even one 25 µm particle on one of the inner four pixels can result in an unacceptably high centroid shift. Assembly was performed inside a class 1000 cleanroom, and we successfully met our internal and external cleanliness requirements.

2.2.3 Focal Plane Assemblies

The main challenge in the production the PCRS Focal Plane Assemblies (FPA) was to ensure their proper operation at the SIRTF instrument chamber temperature of 1.5 K. Both the silicon PIN photodiodes and the readout electronics had to be tested for performance at the low temperatures.

The silicon PIN photodiodes were manufactured by United Detector Technology of Hawthorne CA. These devices were fabricated from a custom mask set using the company's standard epitaxial technology. The photodiodes are arranged in a pair of 4x4 pixel arrays on a common substrate. The pixel size of 250x250 µm yields a pixel field of view of 10 arcsec after demagnification by the PCRS optics. The photodiode arrays have been anti-reflection coated for peak response at visual wavelengths. The pair of 4x4 arrays comprise the redundant halves of either the Roll or Central sensors. Hence, the PCRS has a total of four 16-element photodiode arrays.

Most conventional silicon amplifiers do not function properly below the freezeout temperature of ~20K. The devices exhibit a variety of anomalous behaviors including DC instability, excess noise, hysteresis, and non-linear amplification. Fortunately, there was a significant effort devoted to the development of low temperature silicon readouts for far-infrared detectors, and the PCRS was able to utilize this technology. The readouts used on the PCRS were the CRC-696 devices developed under NASA support at the Hughes Technology Center (now Raytheon Infrared Center of Excellence).[3] These devices operate well at the SIRTF focal plane temperatures, and were originally designed for the Ge:Ga far infrared focal plane arrays used on the Multiband Imaging Photometer for SIRTF (MIPS).

The CRC-696 is a 32-channel multiplexer with a Capacitive Transimpedance Amplifier (CTIA) for its unit cell. The CTIA is a charge sensitive amplifier where the feedback signal is sent to the input via a capacitor. Hence, the output voltage of the readout is proportional to the charge on the input node, and the photocurrent is derived by computing the rate of change of the output. Table 1 gives the basic characteristics of the CRC-696. Because there is a CRC-696 readout for each of the 16-element photodiode arrays, we only connect every other channel on the multiplexer.

Figure 4 shows the main components of the PCRS Focal Plane Assemblies. The A and B-side components are mounted on a common ceramic fanout board. Interconnections to the CRC-696 readouts are made via wire bonds, and there is a separate electrical connector with a flex cable for each side. The entire FPA is housed in a molybdenum carrier. The dimensions for each FPA are 10.4 mm x 62.6 mm.

2.2.4 Optical Design

The PCRS is mounted with the SIRTF science instruments inside the MIC and shares part of the SIRTF focal surface. It must therefore be compatible with the focus chosen for the Infrared Array Camera (IRAC), the Infrared Spectrograph (IRS), and the Multiband Imaging Photometer for SIRTF (MIPS). The SIRTF pointing control system is required to point to any location on the sky with an accuracy of 5 arcsec 1-σ radial. This means that we will land a star to within 5 arcsec of the PCRS array centers 67% of the time. We therefore sized the calibrated region of the PCRS, the sweetspot, to accommodate this range. In order to provide a suitably large target image for the SIRTF attitude control system, the PCRS was deliberately defocused by 4.40 mm relative to best focus as defined by the IRAC instrument. This expands the PCRS image from ~1.5 arcsec diameter at the PCRS best focus to ~6.5 arcsec diameter at the IRAC best focus. The other reason for deliberately defocusing the PCRS is that although the SIRTF telescope is diffraction limited at 3 μm, the PCRS must operate at 0.55 μm in order to use existing high precision star catalogs. At visible wavelengths, irregularities in the SIRTF optics scatter light and produce a PSF much larger than the diffraction limit. Thus, by deliberately defocusing the PCRS, we have smoothed out the extremely irregular point spread function from the telescope and PCRS alone. Figure 2 shows the model point spread functions resulting from the SIRTF telescope and PCRS with and without defocus. Changing the focus results in a linear growth in the PCRS' image diameter; 1 mm of defocus results in approximately 1 arcsec diameter change. The PCRS contains four redundant 4x4 arrays with 10 arcsec pixels. With only 16 pixels, the PCRS cannot adequately sample its point spread function by imaging alone. Hence, the image diameter must be measured by scanning a star across the array and seeing when the image crosses each pixel.

Since SIRTF's focal surface is shared by all three science instruments plus the PCRS, we needed to verify the optical performance (including confocality and alignment) of the instruments with the flight telescope. A test was performed at Ball Aerospace in which the whole CTA was placed inside a thermal vacuum chamber (the "Brutus" chamber). A full-aperture test mirror (the OSCAR flat) was suspended over the telescope, and beams originating from visible and infrared test sources collocated in the MIC were sent through the telescope, bounced off the OSCAR flat, and reflected back into the instruments, creating a double pass. We verified that the PCRS was at the proper focus relative to the science instruments during the Brutus test using the telescope in this double pass mode. This was done by stepping the image (generated by the visible test source located in the MIC) across the PCRS arrays using the OSCAR test flat. The sequence of pixel crossings were used to determine the image diameter. Figure 5a shows the results of a scan across four pixels in the SIRTF +Y direction with the secondary mirror focus position set to 1 mm above the SIRTF best focus. Time is plotted on the horizontal axis; the jagged steps represent images collected at each incremental step of the OSCAR test flat. We derive the plate scale by measuring the distance between pixel edges; the image diameter is determined by measuring the distance between 10% and 90% amplitude points on a given pixel (see Figure 5). We also measured the image diameter at the PCRS best focus location, 4.40 mm below the SIRTF focal surface. Figure 5b shows the results of a scan at the PCRS best focus. The image diameters measured at SIRTF best focus and at the PCRS best focus, 6.5 arcsec and 2.2 arcsec respectively, were consistent with the image sizes predicted by the double-pass optical model. The image size at the nominal SIRTF launch focus, 6.5 arcsec in diameter, falls within our required range of 6 – 8 arcsec. We therefore conclude that the PCRS optical system is compatible with the chosen launch focus setting.[4]

2.3 Warm Electronics

The Warm Electronics sends and receives imaging, setup, configuration, and built-in test commands and telemetry to and from the Cold Assembly. The WE consists of three cards: the primary and redundant sensor cards and the dual-sided power supply card, which contains both A and B sides. Each sensor card contains an FPGA, 16 bit A/D converters, and the RS422 hardware necessary to communicate with the spacecraft command and data handling unit (CDHU). The WE performs fairly minimal processing on the CA analog data stream; pixel voltages are collected synchronously with the spacecraft clock, digitized, and sent to the CDHU without further processing. All centroiding calculations are performed in the CDHU flight software. Housekeeping telemetry, including information on the detector bias, power supply voltages and currents, and temperatures are also monitored. The Warm Electronics is not cross-strapped to the Cold Assembly; the primary WE side can only power the primary Cold Assembly side. Synchronization with the spacecraft clock is required so that PCRS centroids can be accurately combined by the attitude observer with star tracker and gyro data.

2.4 PCRS Guide Star Catalog

In order to provide 0.14 arcsec centroiding accuracy, a source catalog with considerably lower positional error over the entire mission duration had to be created: the PCRS Guide Star Catalog. The only source catalog with sufficient precision was the ACT catalog, which has an average star positional accuracy of 0.025 arcsec. The ACT catalog is complete down to 11th magnitude. This catalog combined data from the Tycho Catalog with the U. S. Naval

Observatory's AC2000 catalog to yield extremely high precision proper motion measurements. To avoid buildup of gyroscopic drift errors, the pointing control system is required to slew no more than 30 arcmin between guide stars. This sets the mean separation between stars in the PCRS Guide Star Catalog and therefore the total catalog length. With only 16 pixels, the PCRS cannot distinguish between single and multiple stars. A close neighbor would result in a shifted centroid measurement. Therefore, a strict no-neighbors required was levied against potential catalog sources. This forced us to cross-reference to the Hubble Guide Star Catalog and various extragalactic object databases to remove potentially confusing close neighbors.

3. ORBITAL OPERATIONS

3.1 In-Orbit Checkout (IOC)

The PCRS has numerous calibration sequences that must be performed during the 60 day In-Orbit Checkout (IOC) phase immediately following launch. These include tests to verify focus, photometric response, radiation response, system noise performance, stray light performance, the calibration of the pixel response coefficients, spacecraft jitter, and centroiding accuracy.

Since the PCRS is a visible light sensor, it is not susceptible to changes in the telescope temperature. This makes it the optimal device for tracking the progress of the telescope cooldown after launch. We made use of this capability during the Brutus thermal vacuum test at the CTA level; this allowed us to track the location of the OSCAR test flat as the chamber was cooled from room temperature down to 5 K. Similarly, we plan to track the performance of the telescope on orbit as it cools from 292 K down to 5.5 K. The cooldown results in a major figure change in the telescope; by measuring the PCRS' image diameter every other day, we can track the changes in telescope focus.

We also used the PCRS to monitor the jitter of the OSCAR test flat during the Brutus testing of the CTA. With a sample rate of 10 Hz, we are sensitive to jitter frequencies of approximately half this rate. We measured the jitter by retroreflecting a single bright spot generated by the visible test source back into the PCRS, then holding it steady for several minutes. We determined the jitter amplitude by examining the standard deviation of the source brightness as a function of time in each pixel. In this way, we found that the OSCAR flat jittered no more than 0.04 arcsec radial at frequencies less than 5 Hz.

3.2 Nominal operations

Once the PCRS has completed its in-orbit checkout calibrations, we will begin normal operations. This entails performing the thrice-daily boresight alignment and roll calibrations, and peak-up operations as needed.

4. CONCLUSIONS

The PCRS was installed inside the SIRTF Cryo-Telescope Assembly in July, 2000 and has logged over 1000 hours of failure-free operation since then. We have verified at the instrument level that the PCRS meets all of its environmental requirements, including the 1.4 K operating temperature, random vibration, pyroshock, and EMI/EMC, necessary to survive launch and operations over SIRTF's anticipated lifetime. The CTA was integrated with the rest of the SIRTF spacecraft in June, 2002. Currently, the PCRS is undergoing testing as part of the recently integrated Observatory in preparation for a January, 2003 launch.

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