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Characterization of FLITECAM: the first light camera for SOFIA

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ABSTRACT

Preliminary test results are reported for FLITECAM, the First Light Camera for SOFIA. This instrument is designed to perform imaging from 1 to 5 μm over the entire 8 arcmin field of view of SOFIA with 0.47arcsec pixels. The detector is a 1024 x 1024 InSb array, and large refractive optics are used for collimation and re-imaging. FLITECAM also has a pupil-viewing mode optimized for 3.5 μm and can accommodate grisms for slit spectroscopy. The instrument has passed Critical Airworthiness Design Review and has received the first part of its certificate of conformity. Ground-based tests of the finished instrument are planned for later in 2002 at the Lick Observatory 3-m Shane Telescope to verify that the point spread function meets its required FWHM of 1 arcsec over the full field and wavelength range. FLITECAM will be used to test the image quality and background of the SOFIA telescope, as well as for science applications.

Keywords: infrared, cryogenic, airborne astronomy, imaging, SOFIA

1. INTRODUCTION

FLITECAM is a general purpose 1 to 5.5 μm camera (I. McLean, P.I.) for SOFIA (the Stratospheric Observatory for Infrared Astronomy) with imaging, spectroscopy, and pupil viewing modes, being developed at UCLA.[1,2,3] FLITECAM has the capability to image the entire 8 arcmin SOFIA field of view. This wide field of view is also particularly useful for a broad range of scientific programs. The imaging detector in FLITECAM is an ALADDIN indium antimonide (InSb) array of 1024 x 1024 pixels fabricated by Raytheon Infrared Operations, Goleta, CA. Imaging from 1 – 5.5 μm includes standard J, H, K, K', L, L', M filters, as well as a limited set of narrow band filters. The performance of the camera is expected to be seeing-limited from 1 –3 μm and diffraction-limited from about 3 – 5.5 μm. With the addition of grisms, FLITECAM will perform low resolution spectroscopy with typical resolving powers (2 pixels) of R = 2000. A special feature of FLITECAM is that it can be co-mounted for simultaneous operation with HIPO (High-speed Imaging Photometer for Occultations), which will enable both infrared and optical photometry of occultation events. In

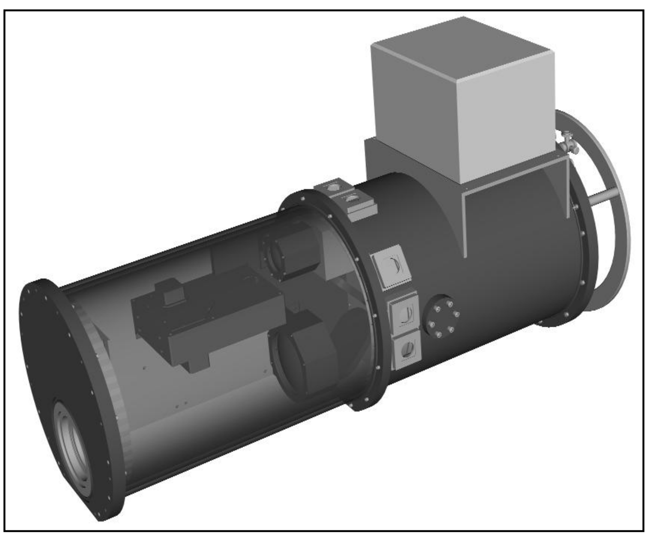

Figure 1: A CAD view of the FLITECAM cryostat.

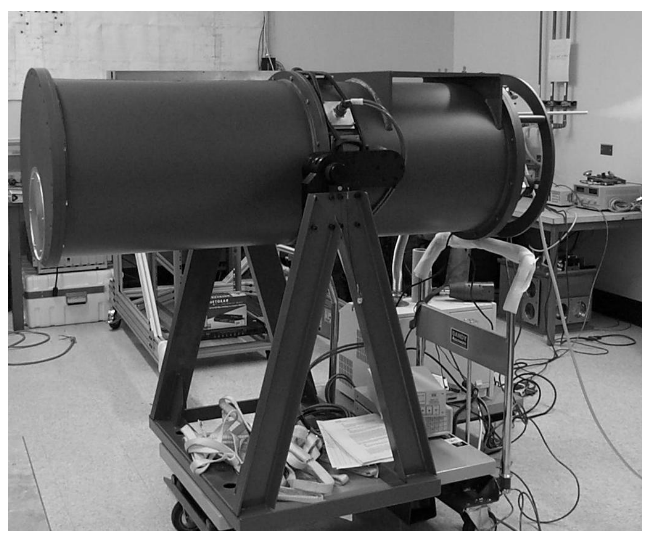

Figure 2: The delivered FLITECAM cryostat at UCLA.

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its pupil-viewing mode, FLITECAM will image small (~3 mm diameter) black spots on the SOFIA telescope primary mirror. As a facility instrument for SOFIA, FLITECAM is required to meet Federal Aviation Agency (FAA) flight qualification standards. FLITECAM will be tested on the 3-m Shane telescope at Lick Observatory prior to scheduled delivery to SOFIA in early 2004. This paper summarizes the status of the instrument prior to deployment.

Characteristic	**Value**
Wavelength range	1 to 5.5 μm; L band for pupil viewing
Filters	J, H, K, K', L, L', M, plus narrow band
Spectral resolution	1000 - 2000
Spatial resolution	0.47" per pixel
Detector type	InSb Raytheon ALADDIN III
Detector format	1024x1024
Field of view on SOFIA	8 arcmin diameter
Read noise	~40 electrons
Well depth	~100,000 electrons
Dark current	≤ 1 electron/sec
Highest time resolution	~1.6 msec per frame for 32x32 subarray
Instrument efficiency	~40% (not including QE)
Detector quantum efficiency	~80%

Table 1: FLITECAM general characteristics.

Table 1 shows the general instrument characteristics of FLITECAM. As illustrated in Figures 1 and 2, the instrument consists of an optical bench mounted inside a 60-in. long x 19-in. diameter cylindrical liquid helium/liquid nitrogen cryostat. A combination of refractive elements and fold mirrors relays the beam to the InSb detector. The instrument optics must be cooled to 77 K, and the InSb detector temperature is optimized for operation over the 30 - 35 K range.

Figure 3 shows the predicted broadband sensitivities for the instrument on the SOFIA telescope. At an altitude of 41,000 feet, SOFIA will fly above significant quantities of atmospheric water vapor. With its large field of view, FLITECAM will be especially useful for surveys of star forming regions.

2. INSTRUMENT DESIGN

2.1 Opto-mechanical design and performance

In imaging mode, the FLITECAM optical train consists of an entrance aperture, a collimator triplet, four fold mirrors, a double filter wheel, and an F/5 re-imaging camera. Three additional lenses are moved into the optical path (one in the filter wheel and two on a special slide mechanism) to enable the pupil viewing mode.

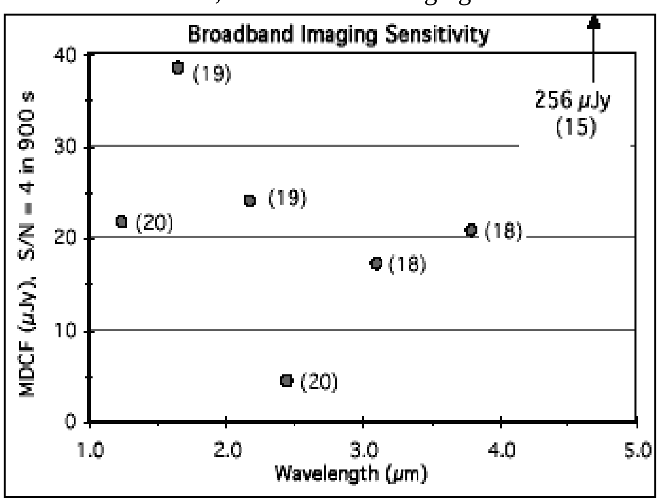

Figure 3: Predicted FLITECAM broadband sensitivities as a function of wavelength.

One wheel of the dual filter wheel module contains FLITECAM's filters; the other wheel will contain grisms and the first additional pupil viewing lens. Neither the grism nor the pupil viewing mode has been implemented yet, but both will be available for first flights.

FLITECAM's four fold mirrors are mounted to a mirror subassembly plate, which in turn bolts to the optical bench. The housing for the collimator triplet bolts directly to the optical bench and is located by referencing precision-machined surfaces on the mirror subassembly plate. The F/5 imager bolts to the mirror sub-plate and is similarly referenced to various edges on it. The goal was to simplify the optical alignment procedure by making use of machinable tolerances whenever possible. The lenses (including both the collimator and F/5 lenses) are held by a system of spring-loaded “fingers” that contact the lenses tangentially around their perimeters; they are also axially spring loaded against reference surfaces machined into the fronts of the holders. The groups of lenses in their holders are then slip-fitted into overall housings for both the collimator and F/5 imager respectively. Since the lenses are crystalline, care was taken to avoid exerting pressure on any crystal boundaries that had been marked by the lens vendor. See Figures 4 and 5 for the mechanical and optical layout.

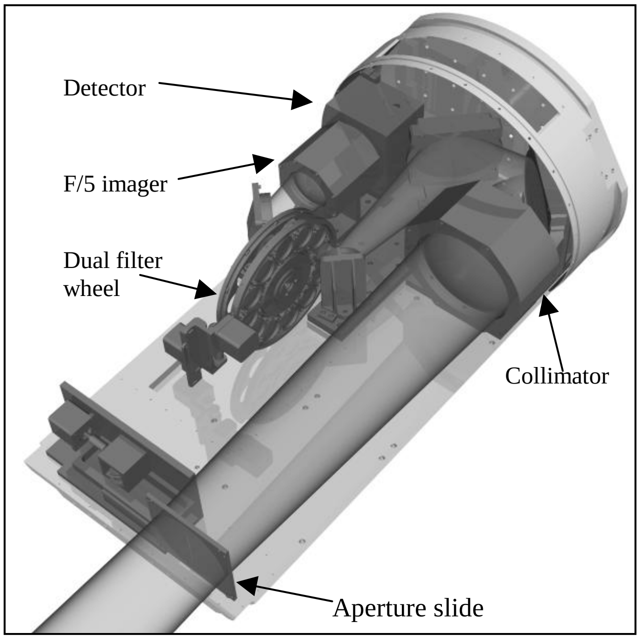

Figure 4: Interior view of the optical bench, depicting the optical train.

The decenter and tilts of the lenses are controlled by the mechanical tolerancing set by the mount machining. An analysis of the overall FLITECAM optical tolerances was made using Zemax. Table 2 shows typical tilt and decenter tolerances of FLITECAM’s optics; most are forgiving except for the ±0.09 mm decenter tolerance of the first two elements of the F/5 imager with respect to each other. However, image quality testing has shown that the precision machining of the optical mounts met this requirement.

The only exception to the use of mechanical alignment was the FLITECAM fold mirrors. The fold mirrors are all oriented at 45° to the beam path. The mirror subassembly plate was fabricated with multiple parallel surfaces, all machined to be precisely parallel to the input optical beam. To align the mirrors, a return flat was placed against the parallel mirror plate surfaces perpendicular to the beam in front of each mirror in sequence. An autocollimator was used to measure the return of a target fixture off each mirror and the return flat; each mirror was adjusted to return the target back on itself. The total beam misalignment after passage through all four mirrors was less than 5 arcmin in both directions.

Element	**Tilt (about X and Y, per axis)**	**Decenter (X and Y, per axis) (mm)**
Mirror 1	±8.4 arcmin	> ±2
Mirror 2	±11.4 arcmin	> ±2
Mirror 3	±27.6 arcmin	> ±2
Mirror 4	±1.3 °	> ±2
Collimator Lens 1	±1.1 °	> ±2
Collimator Lens 2	±1.2 °	±0.8
Collimator Lens 3	±1.5 °	> ±2
F/5 Lens 1	±16.8 arcmin	±0.09
F/5 Lens 2	±6.6 arcmin	±0.10
F/5 Lens 3	±42.0 arcmin	±0.65
F/5 Lens 4	±32.4 arcmin	±0.85
F/5 Lens 5	±1.5 °	±1.85

Table 2 : Tilt and decenter tolerances on FLITECAM optical elements. The most sensitive tolerances in the system are the tilts and decenters on the first two F/5 lenses.

Since each cryogenic cycle takes many days, it was desirable to perform the initial image quality testing with the instrument at room temperature. The focal shift required was calculated between room temperature and 77 K. Best focus was set warm, then the detector was shifted to its expected cold location. Room temperature testing allowed us to make real-time changes to the detector focus. A bare multiplexer that had not been bonded to a detector was used to take pictures at room temperature. Figure 6 shows a best-focus image of a warm test target held in a metal frame at the warm

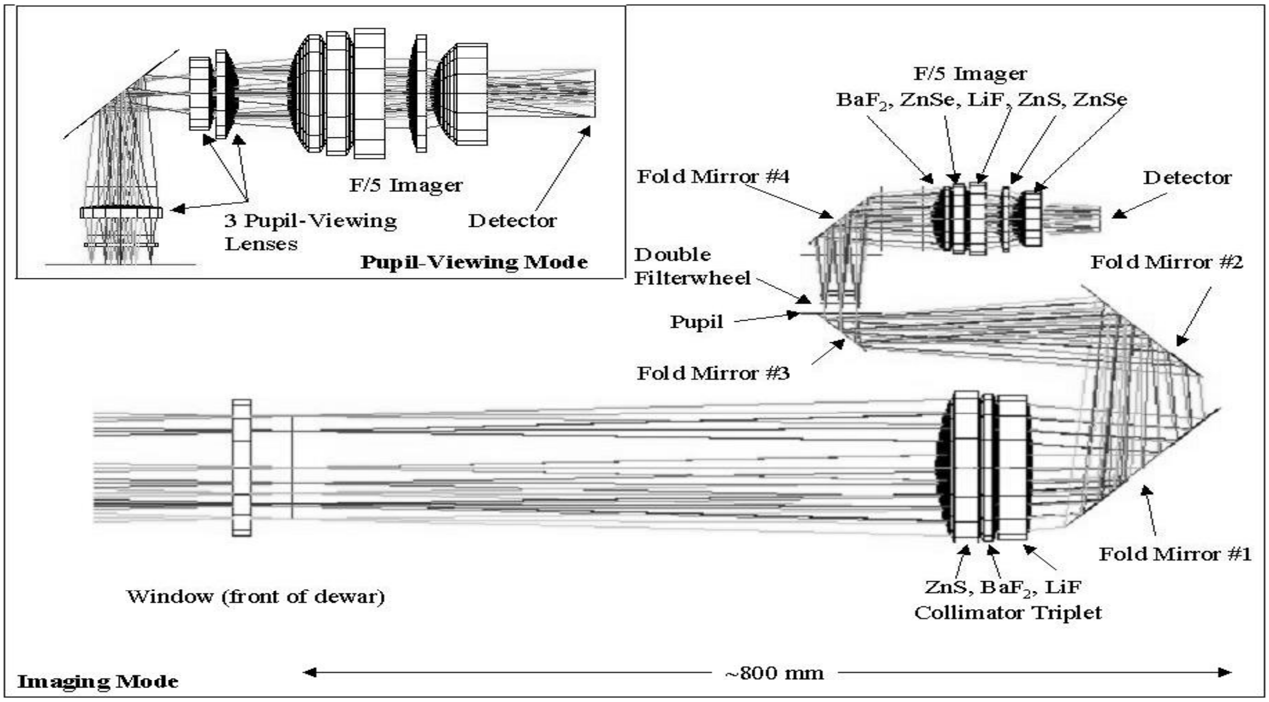

Figure 5: FLITECAM's optical train, depicting both imaging and pupil viewing modes.

SOFIA focal plane location inside FLITECAM. Image quality testing showed that the best warm focus location agreed with the model to the depth of focus at the detector. Figure 7 shows the multiwavelength point spread function (PSF) at best cold focus in several different field positions. The overall performance meets the specifications for SOFIA image quality across the full 8 arcmin field of view.

2.1.1 Thermo-optical performance

FLITECAM was originally intended to use a 512x512 InSb array. However, between PDR and CDR, the decision was made to upgrade to the 1024x1024 array to enable imaging of the entire 8 arcmin SOFIA field of view. However, this field of view requirement drove the collimator lenses to ~165 mm in diameter. The collimator triplet consists of ZnS, BaF_2, and LiF lenses, all of which are extremely sensitive to thermal and mechanical shock and take many months to procure. Indeed, calculations show that the LiF lens can only tolerate a gradient of 7 K across it before exceeding the material's rupture pressure. Using a thin plate approximation, LiF turns out to be roughly four times more susceptible to thermal shock than BaF_2 owing to its large thermal expansion coefficient and relatively low rupture pressure: it will literally pull itself apart as it cools. The basic difference between the behavior of these large lenses and smaller lenses is that radiative cooling becomes a significant effect due to the lens' large surface area. Our optics vendor, Optical Solutions, Inc. (OSI) of Charlestown, NH, recommended a minimum cooldown time of 15 hours to avoid thermal shock to the lenses. Initial cooldown calculations and tests with FLITECAM indicated that the collimator would reach 77 K in only a few hours, resulting in unacceptably rapid thermal transients. This issue was resolved by increasing the thermal isolation of the optical bench and cold shield from the liquid nitrogen bath (see section 2.2 below). This reduces the thermal gradient across the lenses while still allowing us to reach the desired background temperature.

To ensure the safety of the lenses with the new thermal design, a dummy collimator was constructed to simulate the thermomechanical performance of the three large lenses during cryocycling. OSI graciously donated a spare LiF lens that was intended for our collimator but was damaged slightly, rendering it unusable. The spare lens has the same shape and figure as the real lens but was never polished. We used two additional glass blanks of similar size and shape to the other two large lenses to constitute the dummy collimator, along with a duplicate housing. Thermometers were epoxied to the front center, back center, and front edge of the spare LiF lens. Additional temperature sensors were placed on the collimator housing and across the optical baseplate. Four cryogenic cycles were performed using the dummy collimator

Figure 6: A test pattern imaged with FLITECAM using a bare ALADDIN multiplexer at room temperature.

to characterize the gradients that developed across the lens at different cooldown/warmup rates. We found that the lens successfully survived rates up to 13 K/hr while developing gradients of 1.5 K from center-to-center and edge-to-center. Figure 8 shows the temperature gradients across the lens that developed as a function of temperature. We will continue characterizing the relationship between temperature transient rates and temperature gradients using the dummy collimator. Eventually, we will test it to destruction under controlled conditions to establish the maximum safe cooldown/warmup rate and temperature gradient for a LiF lens of this size.

2.2 Cryostat design

In operation, the cryostat can only be refilled with cryogens immediately prior to or after observing flights. Per FAA requirements, the cryostat is equipped with seven psi burst disks. See Figure 3. Following completion of the 8110-3 FAA design approval in September, 2001, fabrication of the cryostat began at Precision Cryogenics, Inc. of Indianapolis, IN. The FAA witnessed the cryostat's proof-pressure test in March, 2002; we received our 8130-3 Authorized Release Certificate, after which the dewar was delivered to UCLA. The detector head is thermally connected to the 4 K helium tank via a thermal bridge. To maintain its desired 35 K

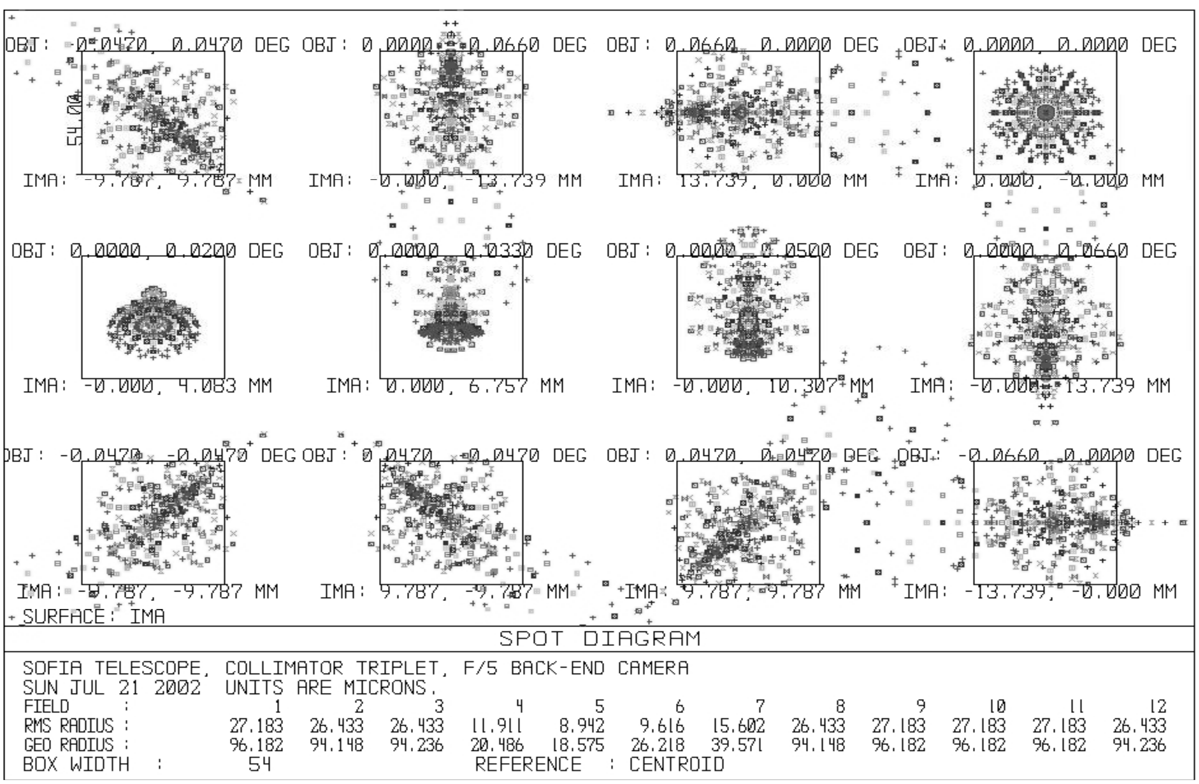

Figure 7: FLITECAM spot diagram for 1- 5.5 µm at various field positions, 77 K. The box size is 2x2 pixels.

temperature, we use a Lakeshore 330 temperature controller.

To control the rate of cooldown, the optical bench and cold shield were carefully isolated thermally from the nitrogen sink using thin G10 shims. This successfully slowed the cooldown rate of the large collimator lenses to ~7 K per hour, while still achieving a baseplate temperature of 95 K. We need to reach a baseplate temperature of ~95 K in order to ensure acceptable thermal background performance.

2.3 Detector Assembly

The detector head assembly was purchased from Mauna Kea Infrared (MKIR) along with all the detector electronics. The head and a short baffle tube are all held at 35K and mounted inside a 77 K cold shield.

2.4 FAA Certification

FLITECAM is a facility class instrument intended for the SOFIA airborne observatory managed by USRA (Universities Space Research Association) for NASA/DLR. In contrast to previous airborne astronomical observatories such as the Kuiper C-141 platform, SOFIA is classified as a civilian aircraft. Therefore, all of its subsystems, including instrumentation packages such as FLITECAM, must comply with the relevant FAA safety requirements, in this case FAR (Federal Aviation Regulation) 25. The 747 aircraft modifications and telescope installation are being undertaken by L-3 Systems (Waco, TX). The plethora of regulatory agencies places constraints on the overall instrument design not normally encountered in either ground or space based instrumentation. The overall design, down to the detailed drawing level, must be approved by the FAA DERs (Designated Engineering Representatives) prior to fabrication. Each major structure must be analyzed mechanically and shown to be safe under emergency flight operating conditions. Rigorous manufacturing procedures must be implemented to ensure that only certified materials and fasteners are used. A full production documentation path is followed to guarantee traceability of each part used. Pressure vessels such as cryogen containers must be tested (and witnessed) according to FAA approved procedures. The entire system is periodically inspected during the manufacturing process to ensure conformity with FAA/NASA safety standards.

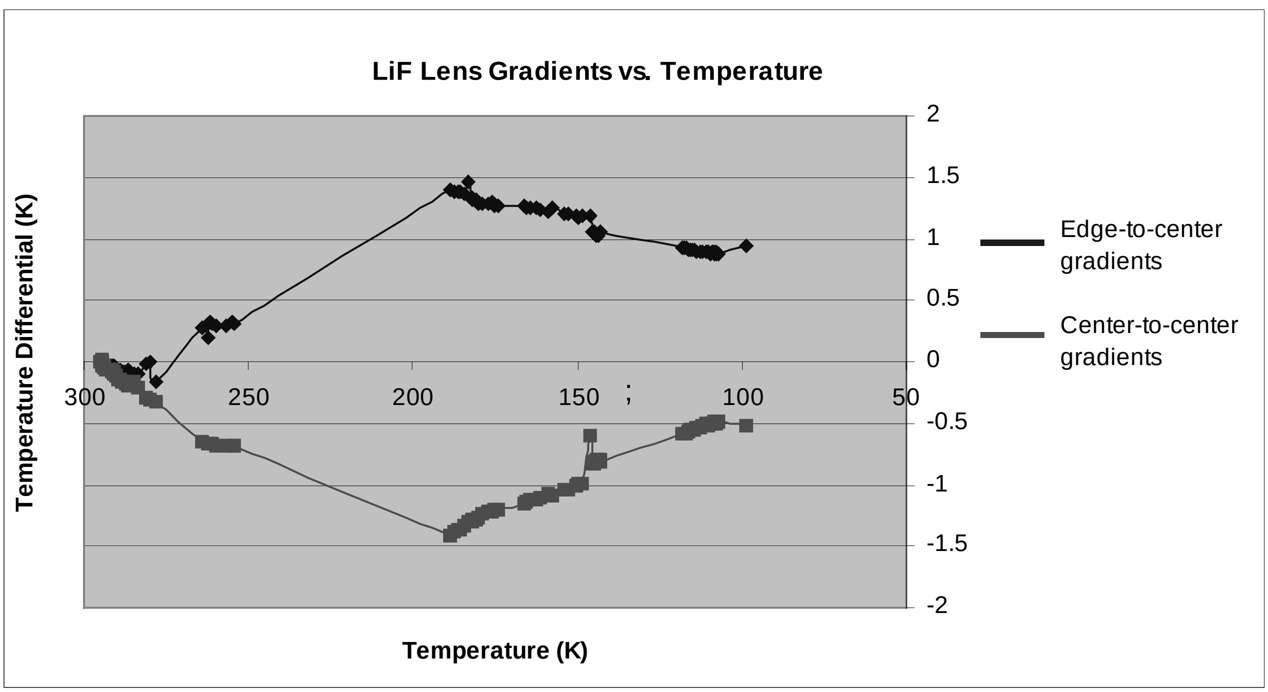

Figure 8: Temperature gradients (edge-to-center and center-to-center) developed across the LiF lens versus temperature. This particular cooldown was performed with a maximum rate of 7 K/hr on the lenses.

2.5 Software

The FLITECAM Instrument Control Software System (FICSS) is based on a set of highly distributed software objects that communicate via CORBA . The primary user interface, which allows monitoring and control of all the instrument's subsystems, is the FLITECAM Instrument Controller. The FLITECAM Instrument Controller communicates with the pressure-temperature (PT) server for housekeeping data, the mechanism server for the control of opto-mechanical components and the MKIR software for control of the detector electronics. The PT server maintains continuous monitoring of all the housekeeping instruments including temperature sensors and controller, vacuum gauge, helium level sensor), and power controller. The mechanism server is responsible for the manipulation of the dual filter wheel module, a pupil lens slide mechanism, and an aperture slide mechanism. The MKIR software is responsible for real-time control of the DSPs that control the Aladdin-III detector electronics. The servers use RS-232 communication to communicate with housekeeping instruments and motor controllers. The RS-232 communication is accomplished creating CORBA objects that give access to a remote systems serial communication ports. Each CORBA object runs as a separate process within a SerialServer. Since hardware communication with individual instruments is encapsulated within separate processes, this design increases the systems fault tolerance considerable. The MKIR electronics and the SOFIA telescope are controlled by TCP/IP socket communications from the FLITECAM Instrument Controller.

The use of CORBA and TCP/IP for all command/control interactions results in a system that inherently allows remote control from anywhere on a local or wide area network. The use of Java and open source libraries has also resulted in a system that is platform independent and highly distributable. All of the FICSS programs can run on any platform with the exception of the MKIR detector control electronics. Any of the programs within the FICSS to be started remotely. The entire FICSS can be started with a single command on any of the computers within the network.

When delivered to SOFIA, FLITECAM will operate by submission of Astronomical Observation Requests (AORs) to the FICSS. AOR's may be prepared using Astronomical Observation Templates (AOT's) built into the FLITECAM Instrument Controller and with a version of SPOT (SIRTF Planning and Observation Tool) that has been modified for use with SOFIA. The modified version of SPOT used by FLITECAM will be the primary tool for observation planning during deployment at the Lick Observatory and during initial testing and operation of SOFIA.

All of the FICSS is written in Java and was developed using Borland's JBuilder Enterprise Edition development environment. Communication between software processes (e.g. FLITECAM Instrument Controller and the servers) is by CORBA using Inprise VisiBroker Object Request Broker. Many of the Java components within FICSS were incorporated directly from SPOT, SEA (Science Expert Assistant – Goddard Space Flight Center and HST), Gemini, and the JSky Java archive.

2.6 Electronics

FLITECAM uses controller electronics purchased from Mauna Kea Infrared (MKIR) Systems of Hilo, HI. The MKIR electronics digitize the signals from the detector, supply the voltages and currents necessary to run the cold electronics, and communicate with the main FLITECAM computer system. In addition, the MKIR electronics contain DSPs that coadd individual frames to reduce disk storage space.

3. CONCLUSIONS

Since FLITECAM is not due to be delivered to SOFIA until 2004, FLITECAM will be commissioned at the 3 m Shane Telescope at Lick Observatory. Three initial engineering and observing runs have been scheduled for the fall semester of 2002. The Shane Telescope was selected because its F/17 optics are compatible with the F/19.6 SOFIA optical system for which FLITECAM was designed. By re-sizing the Lyot stop at the pupil image we will have only a 5-6% light loss on the 3-m telescope and we will achieve essentially the same pixel size and field of view as on SOFIA. We will use these observing runs to assess FLITECAM's imaging performance; later runs will verify grism and pupil viewing modes. The runs at Lick will help us assess instrument balance, handling logistics, mounting and cooling; on-telescope hold time performance; cable paths; software interfaces; image quality (including plate scale, field and flat field distortions); and noise performance. Given our current progress, FLITECAM will be commissioned well in advance of the March, 2004 delivery to SOFIA.

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