An Image Motion Compensation System for the Multi-Object Double Spectrograph

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ABSTRACT

We describe progress on a closed-loop image motion compensation system (IMCS) for the Multi-Object Double Spectrograph (MODS). The IMCS actively compensates for image motion in the focal plane within the instrument caused by temperature fluctuation, mechanism flexure, and large scale structural bending due to gravity. The system utilizes an infrared laser as a reference beam that shares a light path with the science beam and is detected by an infrared reference detector adjacent to the science detector. The reference detector is read out frequently and detects any image motion in the focal plane. The IMCS compensates for this motion during a science exposure by adjusting the tip and tilt angles of the collimator mirror. A working lab prototype meets specifications and is described.

1. INTRODUCTION

The IMCS controls image motion in the MODS spectrograph (Osmer et al 2000), which will be the primary optical spectrograph for the Large Binocular Telescope (LBT; see Hill & Salinari 2000). MODS is a Gregorian instrument that aims to have very high instrumental throughput and has relatively few optical surfaces. Consequently the instrument is large (~3 meters wide by ~4 meters long; ~2000 kg); this large size suggests that some sort of flexure compensation is required.

Rather than choose to implement an open-loop system (e.g., a flexure look-up table), we chose a closed-loop system that will compensate not only for flexure but also for image motion from any source, such as temperature fluctuations within the instrument or mechanical ticking. See Marshall et al 2003 (Paper 1) for a discussion of these issues. Note that the IMCS is not intended to compensate for rapid image motions such as those due to atmospheric disturbances (seeing); the LBT will be equipped with fully adaptive secondary mirrors that will perform this task.

The closed-loop IMCS has been fully prototyped in the lab. In this paper we describe the IMCS lab prototype as implemented and tested on an optics bench. This system is the test bed for the MODS IMCS, which will be deployed with the instrument at the LBT in early 2006.

2. SYSTEM DESIGN

The IMCS has been designed as a closed-loop compensator for image motion from any source encountered within MODS. The system has already been well defined, and most of the components already have been purchased or fabricated. Figure 1 shows a schematic drawing of the final system. Several of the component choices are more fully discussed in Paper 1.

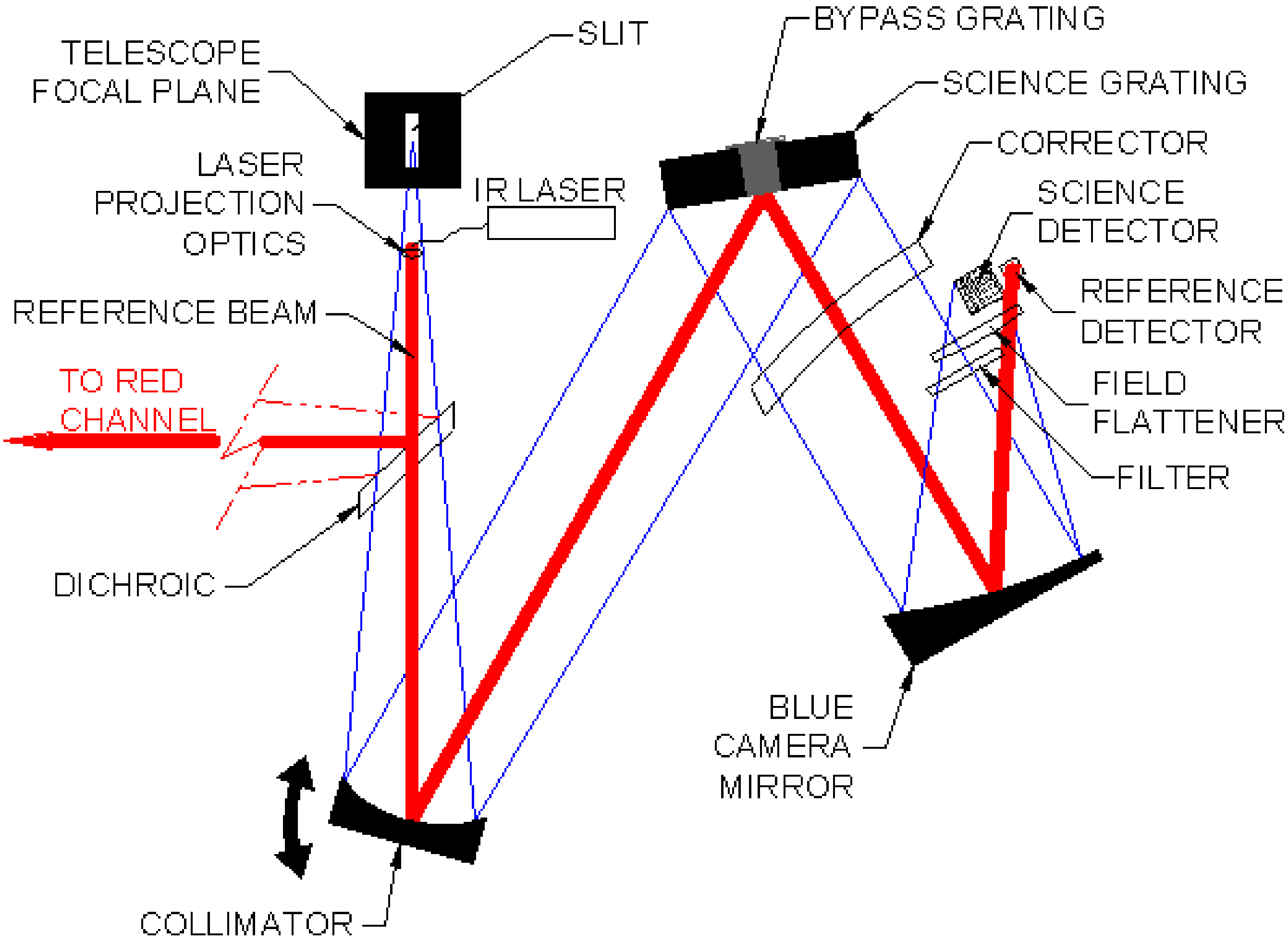

Figure 1: Schematic drawing of the MODS IMCS system optics and components. Note: figure is not to scale.

2.1. Specifications

The mission of the IMCS is straightforward: to control image motion in the detector plane to an acceptable amount over a reasonable exposure time. Due to the nature of the IMCS, it by definition will correct for all image motion, including flexure, temperature fluctuations, ticks in the structure, etc. We expect the magnitude of these sorts of image motions to be no more than 100 µm/hour during a typical science integration. We require the IMCS to control image motion over one hour to a tenth of a resolution element, or 6 µm (±1 standard deviation; ±1 σ) for a 0”.6 slit on the LBT. Ideally the IMCS will perform much better than this, and the system goal is to control image motion to ±1.5 µm over one hour (~0.1 pixel). The IMCS must not interfere with the science beam; we have avoided this by choosing an infrared laser to use as the reference beam. In order to meet these requirements, our design strategy is to require that the IMCS accurately track the motion of the science beam. This is accomplished by having the reference beam share the science beam path and as many optical components as possible.

2.2. Components

The IMCS lab prototype is as similar to the IMCS that will be deployed with MODS as possible. To that end, each component in the IMCS prototype is the actual part that will be used in the MODS instrument except where noted below. It is important to note that although the prototype IMCS is not the same size as the final version of the IMCS (it would not fit on our lab optics bench), it does preserve the angles, camera focal length, and final plate scale of the MODS IMCS. This will minimize changes between the prototype and the system as deployed with MODS. Figure 2 shows a photograph of the system as set up in the lab.

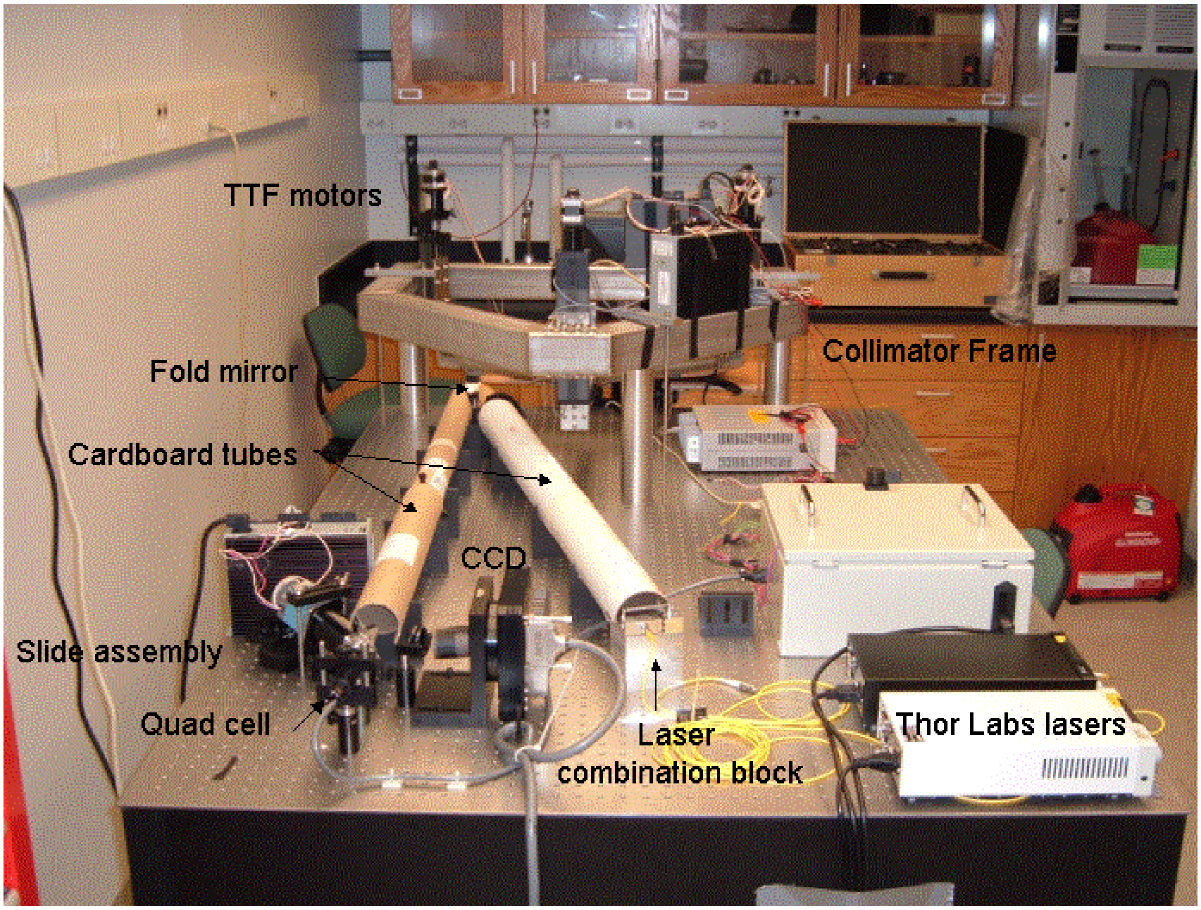

Figure 2: Photograph of prototype IMCS setup in the lab. Note that the prototype IMCS is significantly smaller than it will be when deployed in MODS. Instead of creating a full-size model, we have set up the prototype to preserve the angles and plate scales in MODS, creating an accurate representation of the system.

- Lasers

The IMCS uses two lasers, one optical (633 nm) and one infrared (1550 nm). For the final implementation of the IMCS we have selected commercially available Thor Labs lasers because of their modular design and ease of replacement in case of failures. Each laser unit consists of a box, including a power supply, which contains the laser diode. The laser is output through a fiber port on the front of the box. A fiber connects to the box and transfers the beam to the desired location. A laser "collimator" lens mounts to the fiber head to collimate the beam; we have modified this usage slightly, placing the lens slightly further from the fiber tip to produce not a collimated beam but rather an approximately f/40 beam, which is of the appropriate diameter to fill the IMCS prototype optics (the same technique will be used in the MODS instrument, but we will produce an f/100 beam, yielding a spot that fills the bypass grating). The 1550 nm infrared laser will be used to measure image motion; the 633 nm visible laser is for alignment purposes only and will be turned off whenever MODS is performing science observations.

- Laser combination block

The laser fibers mount to the combination block at right angles to each other. The laser combination block uses a dichroic beamsplitter to combine the two laser beams, producing a beam that is detectable by the IR quad cell and a CCD camera, as well as by eye. Again, this capability is for alignment purposes only, and the optical laser will be turned off separately from the IR laser during use to avoid contamination of the science beam with scattered visible laser light. The IR laser passes straight through the prism to minimize possible image motion due to possible movement of the prism. The combination block is the same unit that will be deployed in MODS. Figure 3 shows a photograph of the block mounted to the lab optics bench.

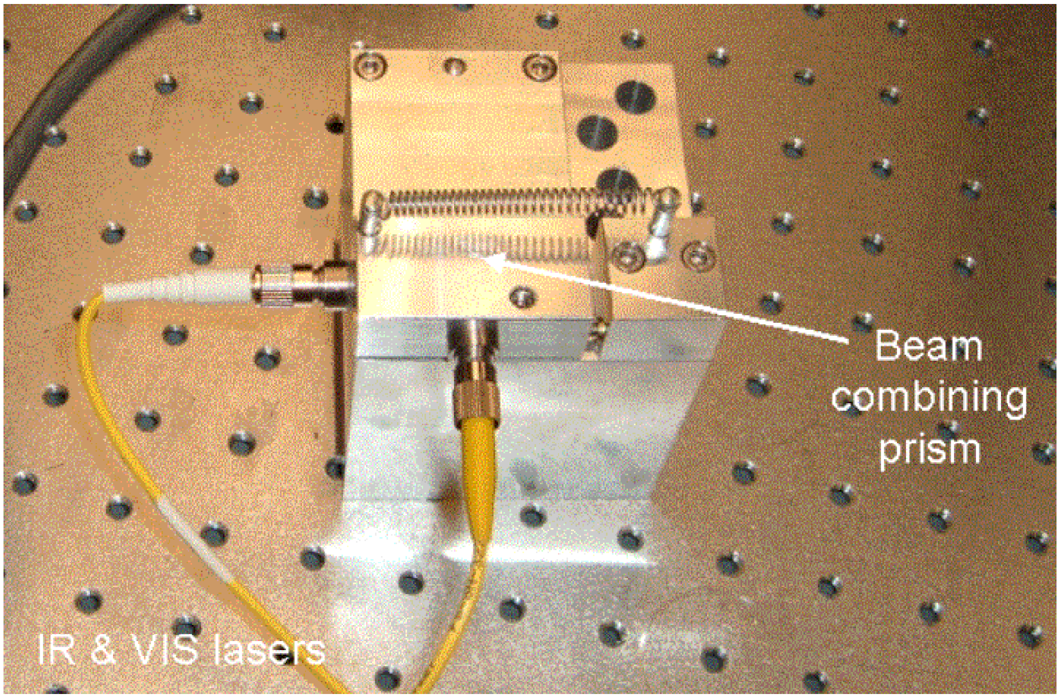

Figure 3: Photograph of the laser combination block mounted to the optics bench. The infrared and visible laser fibers are attached. The beam combining prism is located beneath the surface shown.

- Collimator lens

The collimator lens in the IMCS prototype produces a collimated laser beam. This lens in the prototype IMCS takes the place of the collimator mirror in MODS.

- Fold prism/flat mirror

The collimated beam is reflected vertically by a 45-degree fold mirror onto a flat mirror mounted on the bottom of the collimator cell. The angled mirror is oriented such that it redirects the reflected beam toward the detectors. This arrangement allows for two-dimensional correction of the reference beam by directing the laser beam toward the collimator cell at right angles.

- TTF motors/collimator structure

The flat mirror is mounted to the underside of the MODS collimator cell: this is the actual cell that will be used in the MODS instrument to support the collimator mirrors, although it will be used in a different orientation. The steel cell incorporates three flexures each connected to stepper motor-driven linear stages, allowing for three axes (tip, tilt, and focus) of motion. Note that in MODS this collimator lens/fold mirror combination is replaced by the instrument's collimator mirror, which is mounted to the collimator cell and is moved by the TTF motors to compensate for image motion. Refer to Paper 1 for detailed performance data on the TTF actuators; see figure 4 for a photograph of the orientation of this structure in the lab prototype.

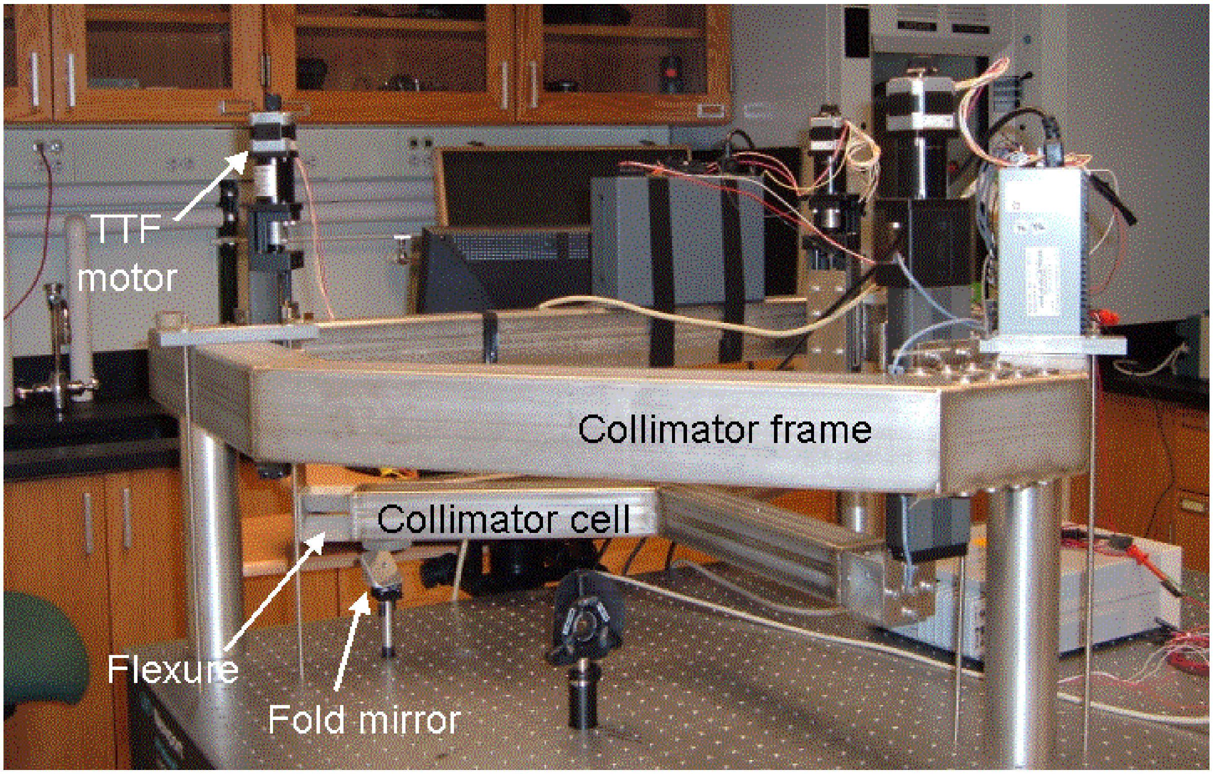

Figure 4: Photograph of the collimator structure showing the TTF motors, the collimator frame and cell with flexures, and the fold mirror. The collimator lens is mounted to the optics bench beneath the collimator cell.

- Camera lens

The camera lens focuses the collimated beam onto the detectors. Its focal length is identical to that of the MODS camera. In MODS, this simple lens is replaced by the Maksutov-Schmidt camera (Byard et al. 2000).

- Dichroic prism

Another dichroic (identical to that used in the laser combination block) divides the IR and VIS laser light back into their respective beams, passing them to the IR quad cell and to a CCD camera. This prism will not be present in MODS.

- Neutral density filters

To control beam intensity at the quad cell and CCD, absorptive neutral density filters are inserted into the beam directly in front of the detectors. These will not be present in the final version of the IMCS, where the IR laser power will be adjusted to give the optimal signal level for the quad cell. The MODS camera includes a filter wheel with bypass holes drilled adjacent to each filter position through which the infrared IMCS reference beam will pass.

- Infrared quad cell

An IR germanium photodiode quad cell will be the IMCS reference detector deployed with the first implementation of the IMCS in MODS. A larger infrared detector is a possible upgrade. See Paper 1 for a description of the quad cell selected, and figure 5 for a picture of the setup of the detectors in the lab.

- CCD camera

A CCD camera is introduced into the prototype IMCS as a cross-check on the image motion detected in the quad cell. The CCD was used in the lab to confirm predicted calibrations of the system, as well as for alignment and inspection purposes. There will be no CCD associated with the MODS IMCS.

- A/D converters

Twelve-bit A/D converters read the output of the quad cell and relay the signals to the motor control software.

- Motor control software

The motor control program reads the signals from the quad cell, calculates the position of the reference beam on the quad cell, and computes the tip-tilt offset moves required to re-center the reference beam on the quad cell. It then sends this motion command to the TTF motors to null the offset, thus actively closing the loop. In the final MODS implementation a more sophisticated C++ program will replace the simple BASIC program currently running in the lab. The prototype IMCS samples the quad cell voltages and moves the motors every 2 seconds. This is much faster than is required for flexure compensation, and the final IMCS will probably be run at a lower bandwidth. The bandwidth currently in use suffices for system tests; however, it is too slow to remove rapid image motions such as those caused by air currents in the room (seeing).

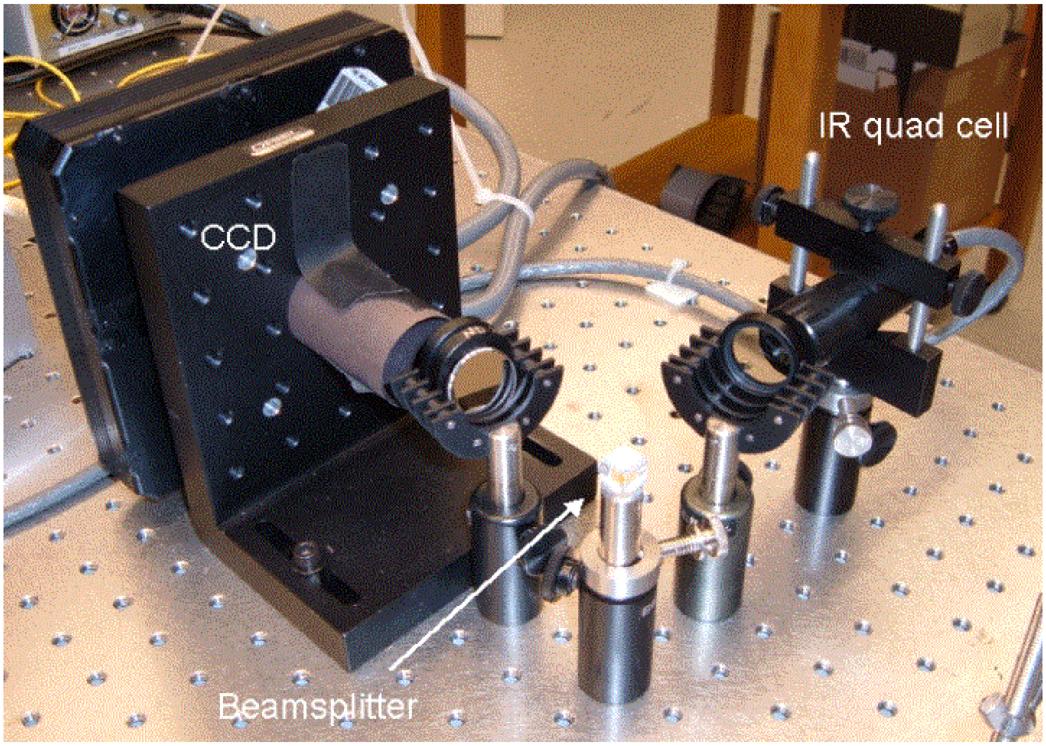

Figure 5: Photograph showing the beamsplitter, IR quad cell, and CCD detector, both with ND filters. The CCD is included in the prototype IMCS for inspection purposes only, and will not be present in MODS.

3. SYSTEM TESTS

We have set up the prototype IMCS on an optics table in an interior lab to avoid light contamination by outside sources. A thermostat with a cycle time of about 30 minutes controls the temperature in the lab in which the tests were run. The optics bench to which the lab IMCS was mounted suffered noticeable temperature effects due to this ~ 2 degrees C temperature variation in the room. In an effort to control this "room seeing" we placed cardboard tubes on the lab bench, through which the reference beam passed. This helped to control the problem to some degree but in the end all of the lab tests have a small unavoidable temperature effect versus time. Fortunately, this relatively small-scale disturbance provided a good test of IMCS performance.

3.1. Quad Cell Electronic Noise and Stability

It is important that each individual channel of the quad cell detector be stable over time. Any instability will be counted as noise in the error budget. We have tested the quad cell stability, looking at a fluorescent light source through a diffuser. Figure 6 shows the data from this experiment. Each channel is stable over 2 hours to ~0.001 mV, or an equivalent image motion of ~0.2 μm. It should be noted that although the quad cell output is a voltage we have converted these voltages throughout this paper into equivalent microns of image motion. The spot locations are measured by the quad cell, and are calculated from the output voltages of the quad cell: dx is the sum of the two left quadrants minus the two right quadrants divided by the sum of all four quadrants, dy is calculated similarly with the top two and bottom two quadrants.

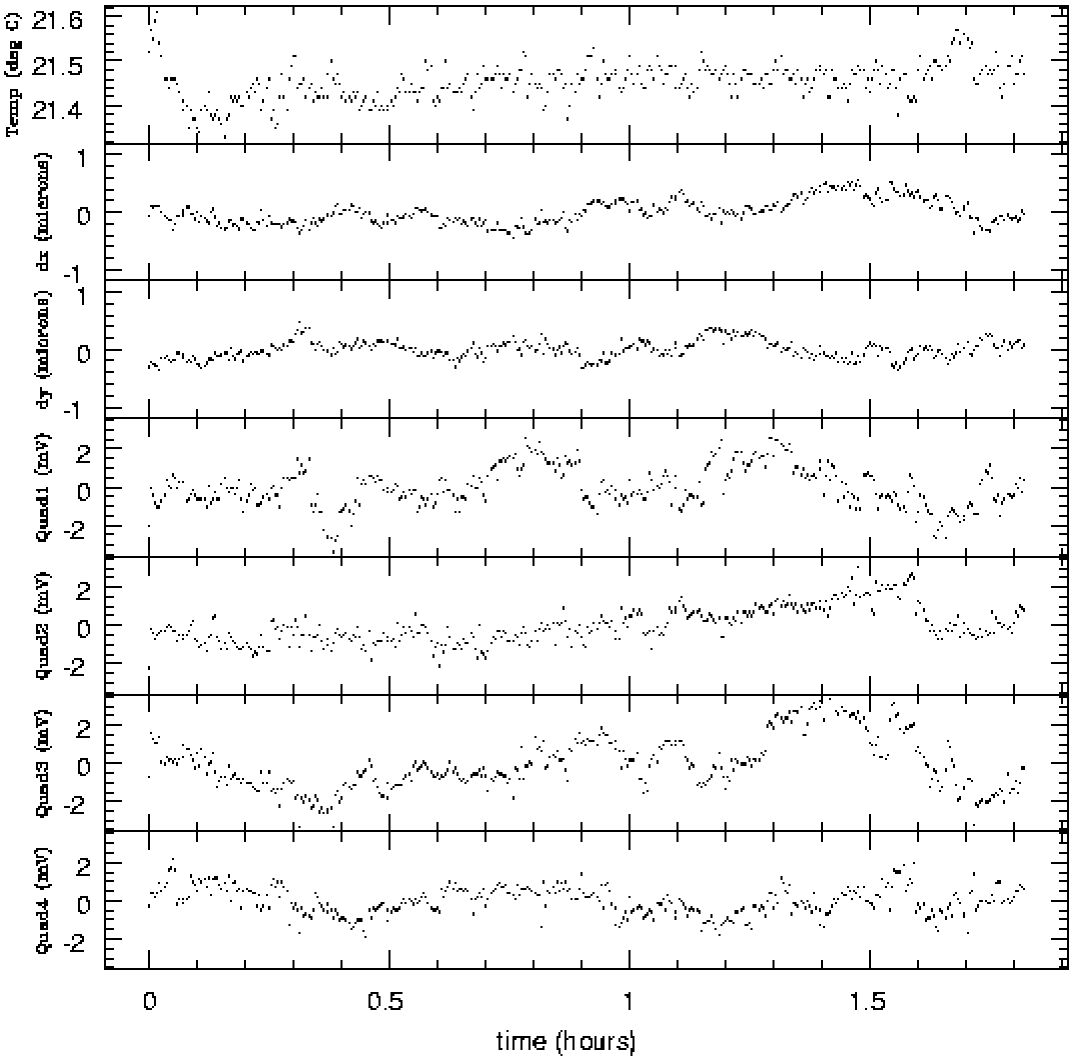

Figure 6: Output of each quad cell channel voltage, as well as the equivalent horizontal (dx) and vertical (dy) motions. The quad cell is aimed at a fluorescent light source and a diffuser has been placed in front of all four quadrants. Some of the noise in the data may be due to instability of the light source.

3.2. Small-scale Image Motion Compensation

The IMCS lab prototype compensates for image motion in two dimensions. One axis of motion is simply obtained by attaching a TTF motor to the motor controller that moves the collimator cell perpendicular to the tabletop (y-axis). The second axis of motion (x-axis) is achieved by attaching the two remaining TTF motors to one motor controller, inverting the sign of one motor to produce negative motion relative to the first. In the MODS instrument, the three axes will be controlled independently with more sophisticated software so as to provide collimator mirror focus in addition to tip and tilt. Since focus is not an issue in the prototype IMCS this control mode is acceptable.

In the tests discussed below the prototype IMCS was required to correct for varying scales of two-dimensional image motion. The tests were run with the disturbance turned on for the duration of the experiment; the IMCS was only turned on after ~2 hours. This allows the test data to show the magnitude of the disturbance as well as the degree to which the IMCS was able to correct for it.

We first demonstrate that the prototype IMCS functions for small disturbances. For this test, we simply allow the room temperature to vary as controlled by the thermostat in the lab. This produces image motions of order 25 µm. In figure 7 we show the room temperature (as measured by a thermistor placed on the optics bench), horizontal infrared reference spot location (dx) and vertical spot location (dy).

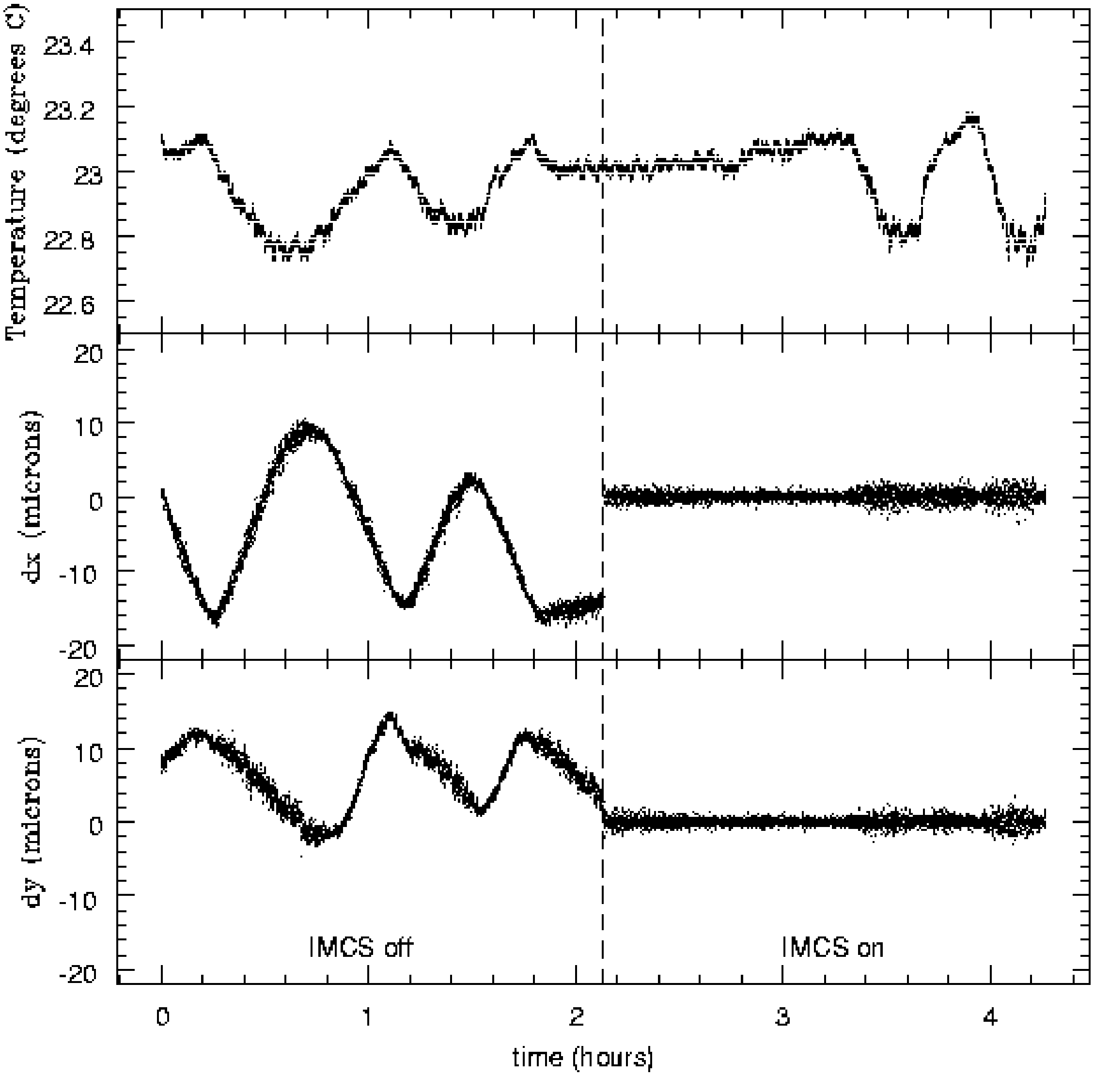

Figure 7: IMCS prototype performance for small-scale image motion due to variations in room temperature. The test was run first with the IMCS off to demonstrate the magnitude of the disturbance. The IMCS was then turned on, compensating for the image motion. The dashed lines separate these two regions.

3.3. Large-scale Image Motion Compensation

To obtain disturbances of the order that we expect in MODS when it is on the telescope we introduced an additional disturbance in the form of a microscope slide rotating slowly in the beam. As the slide moves it translates the laser beam image on the quad cell, accurately simulating flexure in the instrument in both magnitude and rate. The slide produces ~130 μm of image motion in a sawtooth pattern with a time period of ~1 hour. The slide is oriented at a 45-degree angle to the tabletop producing image motion in both the x- and y-axes. Figure 8 shows the results of these tests.

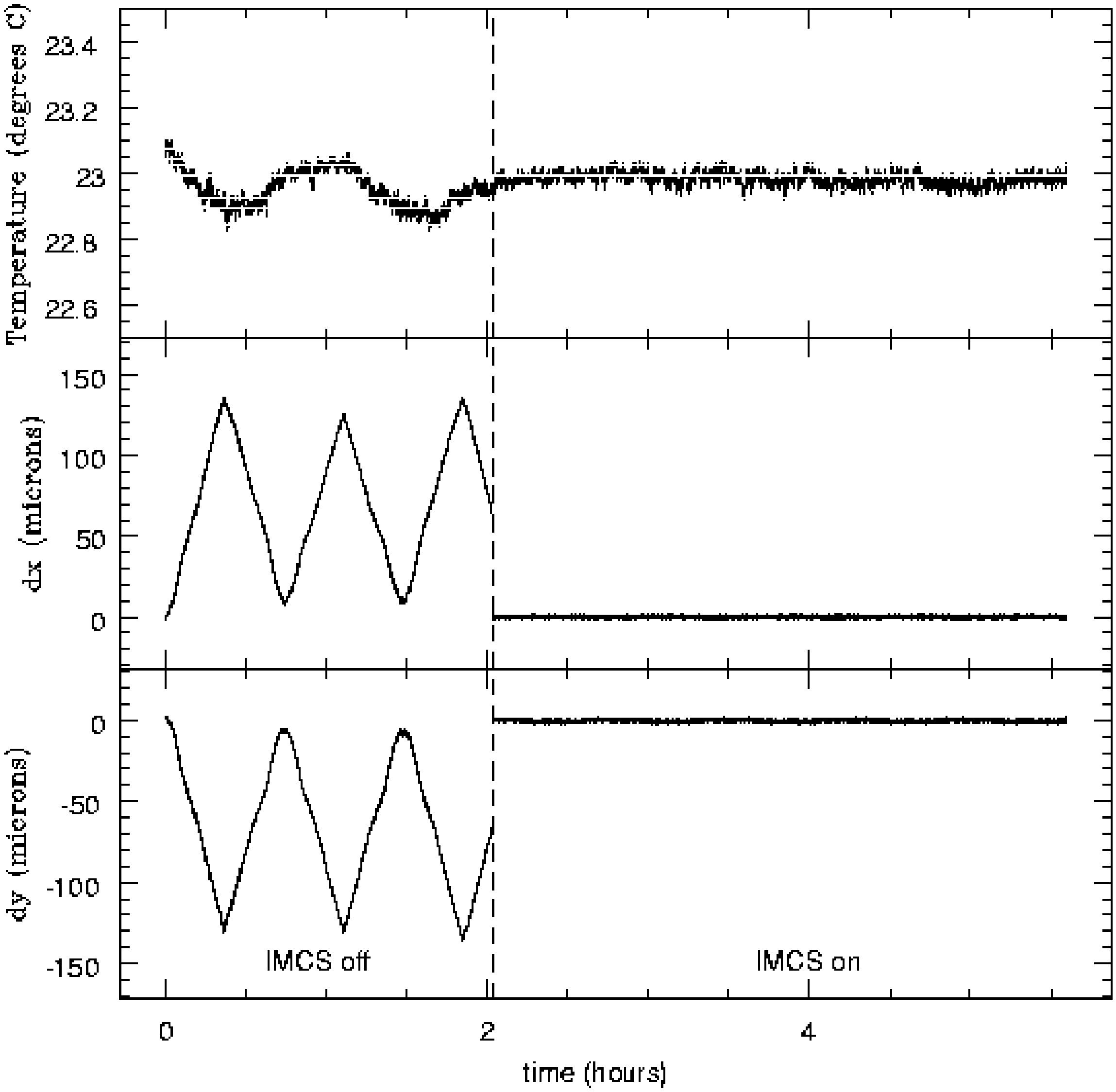

Figure 8: IMCS prototype performance for small- and large-scale image motions due to both room temperature variation and beam displacement by a rotating microscope slide. The reference beam displacement by the rotating slide simulates the expected MODS instrument flexures in both magnitude and rate.

4. RESULTS

The prototype IMCS is currently exceeding the specifications given above. The IMCS must correct for both small- and large-scale image motions. In the small-scale tests (with disturbances given by room temperature variations) the IMCS has compensated for all of the ~25 µm of image motion caused by the changing room temperature. Specifically, in the region 2.2 to 3.2 hours after the test began the IMCS held the laser spot at a constant location to ±0.45 µm (±1 σ) in both axes (x and y). During this time the temperature in the room (for reasons unknown) varied by only ~0.1 degrees/hour. After this time the room temperature was varying by ~1 degree/hour and the spot location was constant to ±0.81 µm in the horizontal direction and ±0.70 µm in the vertical. The reason for this increase is being investigated, but we expect the change was due to short-timescale fluctuations in the image position (seeing) from air currents in the room generated by the HVAC system.

It is important that the zero point of the image correction not drift over the expected timescales of motion compensation. Once the IMCS was turned on, the slope seen in the data in the horizontal direction was ~0.014 µm/hour; in the vertical direction the slope was ~0.0005 µm/hour. This very small slope in both directions is negligible.

The IMCS also corrects for large-scale motions. When the microscope slide was introduced into the system, producing image motions 5 times as large as the room temperature-induced disturbances, the IMCS held the laser spot at a constant location to ±0.52 µm horizontally and ±0.59 µm vertically. Though the slide was rotating for the duration of the experiment, there was little temperature variation in the room during this time. Consequently, the effect of room seeing was minimized in this test while the IMCS was turned on. With the rotating slide in the beam, the slope seen in the data in the horizontal direction is ~0.0081 µm/hour; in the vertical direction the slope was ~-0.025 µm/hour. Again, these small slopes are negligible.

The current lab tests indicate that the IMCS works well. The system can null image motions that approximate what we expect in MODS (i.e., ~100 µm/hour) to within <1 µm. This is well within our goal of 0.1 pixel stability and suggests that the system is ready for installation into the spectrograph.

5. DEPLOYMENT SCHEDULE

The IMCS will be installed in MODS as the instrument is assembled in late 2004 and 2005. The system will undergo an extensive series of tests with the MODS structure and optics; performance will be demonstrated under conditions that simulate real observing situations. The system will be integrated into the MODS control system and observing setup and exposure protocols will be determined. We expect to deploy MODS to the LBT and begin using the instrument for science operations by January 2006.

6. ACKNOWLEDGEMENTS

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