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

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ABSTRACT

We discuss the performance of the Image Motion Compensation System (IMCS) for the Multi-Object Double Spectrograph (MODS). The system performs closed-loop image motion compensation, actively correcting for image motion in the spectrograph's focal plane caused by large scale structural bending due to gravity as well as other effects such as temperature fluctuation and mechanism flexure within the instrument. Not only does the system control instrumental flexure to within the specifications (0.1 pixels on the science CCD, or 1.5 μm), but it also has proven to be an excellent diagnostic tool for assembling and testing the spectrograph. We describe both the final performance of the system as deployed in the spectrograph as well as the instrumental tests made possible by the IMCS.

Keywords: flexure compensation, optical spectrographs, large telescope instrumentation

1. INTRODUCTION

The IMCS is an innovative closed-loop flexure compensation system for the MODS spectrograph (Osmer et al. 2000), the workhorse optical spectrograph at the Gregorian focus of the Large Binocular Telescope (LBT; see Hill & Salinari 2000). The IMCS actively compensates for image motion in the instrument focal plane caused by temperature fluctuation, mechanism flexure, and large scale structural bending due to gravity. The IMCS has been designed (Marshall et al. 2003; Paper I) and fully prototyped in the lab (Marshall et al 2004; Paper II), and is now installed in the MODS instrument. Figure 1 shows a photograph of the first MODS instrument (MODS1) mounted on its handling cart in its current assembly location. See Pogge et al. (2006) for an update on the status of the MODS instrument.

As discussed in detail in Papers I & II, the IMCS 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 at 10 Hz 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 at 1 Hz.

In this paper we describe the on-instrument performance of the IMCS, in particular the specific operational modes, the final system parameters, and the final measured system performance of the IMCS. We also discuss the fortuitous usage of the IMCS as a diagnostic tool to measure other instrument parameters and performance metrics. Note that the tests presented in this paper have been done on the blue channel of MODS1; we expect similar results for the red channel.

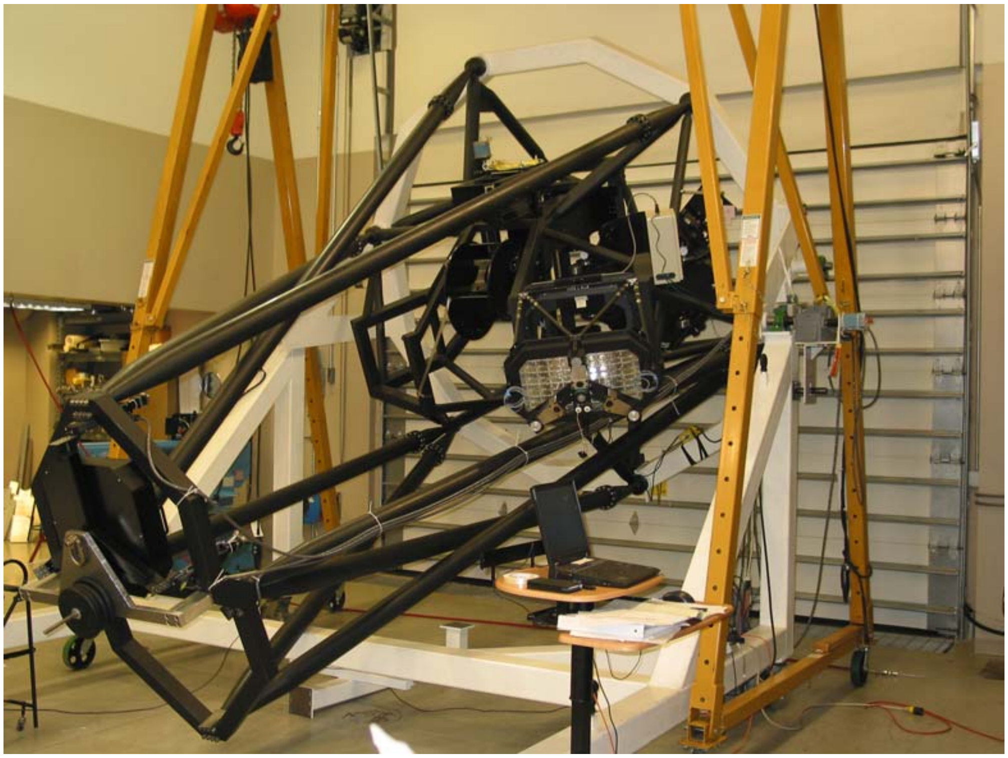

Figure 1. Photograph of the MODS1 instrument on its handling cart in the OSU Astronomy Department instrument assembly area. The photograph shows the entire MODS structure with all of the blue channel optics and mechanisms installed. The instrument is rotated on the axis of its handling cart, and as pictured is pointed about 20º above the horizon.

2. SYSTEM ALIGNMENT AND OPERATION

The detailed lightpath of the IMCS is more fully described in Paper I and is outlined in brief here. A design requirement of the IMCS is that the IMCS lightpath traces the science lightpath and uses the science optics wherever possible. The infrared reference laser beam is inserted into the optics at the telescope focal plane, adjacent to the slit mask mechanism. It reflects off the collimator mirror to the bypass grating, which is mounted in the shadow of the telescope secondary mirror in the center of the science grating or imaging flat. The reference beam then passes through the camera corrector and reflects off of the camera primary mirror. The bypass grating is oriented so as to direct the reference beam through the bypass filter, which is located adjacent to the science filter and transmits only infrared light. The reference beam is detected by the reference detector, an infrared-sensitive germanium quad cell detector mounted adjacent to the science detector on a common mounting plate.

The IMCS will be operated at the telescope in an on/off mode, with virtually no input from the observer. The IMCS is automatically aligned at the beginning of each night so that a laser spot is detected by and centered on the quad cell detector. Before beginning an observation the observer will turn on the IMCS, the IMCS will open the shutter, center a spot on the quad cell detector, close the shutter, and will signal the observer that the system is ready to start the observation. The observer will start the observation and the IMCS will "guide" on the spot during the entire observation. At the end of the observation the shutter will close and the IMCS will remain idle until the observer begins the next observation.

The bypass grating produces a line of spots in the plane of the reference detector (see Section 3.2). The IMCS operates by centering one of these spots on the quad cell, and "guides" on this spot for the duration of the observation. The spots are spaced at 5mm intervals; a consequence of this is that only quantized grating settings are allowed, i.e., that the central wavelength on the science detector can be adjusted in intervals of 5 mm (which translates to 333 unbinned pixels on the science detector). This affects the science observations in that the observer does not have complete freedom over what wavelength lies at the center of the detector. This feature affects observations at various resolutions in different ways: since MODS fully illuminates a detector as long as 123mm (8K x 15 μm pixels), resolutions lower than R~3000 are not affected. Higher resolutions, up to the MODS maximum of R~15000, will be affected. The grating is adjustable in 333 pixel increments, or by about 4% of the wavelength coverage of the detector. First light MODS observations will be done with a R~2000 grating, so this will not be a consideration initially.

3. MEASURED IMCS SYSTEM PARAMETERS

In the on-instrument version of the IMCS we have measured the final IMCS system parameters and present here those that have not been discussed previously in the lab results of Papers I & II.

3.1 Laser Power and Beam Profile

The IMCS laser will be operated at 1.5 mW, providing more than enough power in the laser spots at the reference detector. Figure 2 shows the beam profile of the IMCS laser, measured in the plane of the MODS science grating.

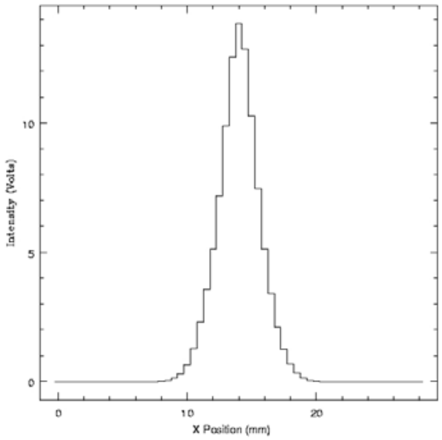

Figure 2. Measured beam profile of the IMCS infrared laser beam measured at the bypass grating.

The *f*/500 beam produced by the laser combination block optics produces a ~6.5 mm spot (D80) at the bypass grating.

3.2 Bypass Grating

The bypass grating is a 12.5 mm diameter diffractive optic that is designed to produce 27 orders (13 orders on either side of zeroth order) of nearly equal intensity from the 1550 nm laser. The grating was designed by and purchased from Holo Or Ltd. (http://www.holoor.co.il/), a company that specializes in holographic gratings. Figure 3 shows the measured peak intensity of the 27 orders. The 6.5 mm beam diameter of the infrared laser sufficiently fills the 12.5 mm bypass grating; i.e., the bypass grating need not be fully filled by the laser to function as designed.

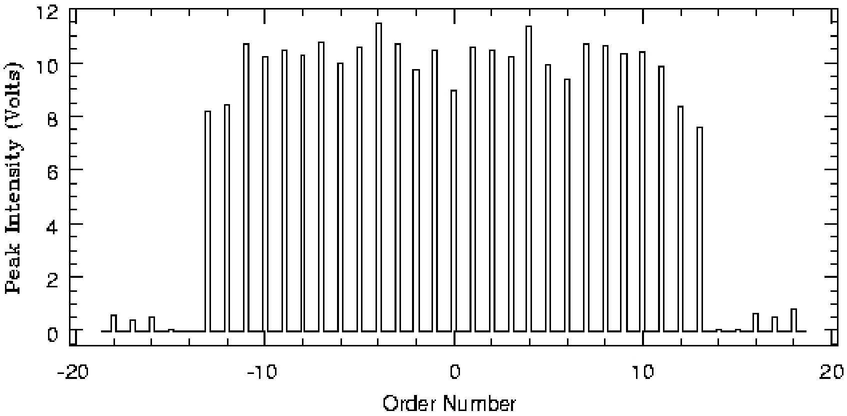

Figure 3. Peak intensity vs. order number for the bypass grating. Nearly all of the power is distributed in orders –13 through +13, with very little light contamination between orders.

The bypass grating is positioned in the center of the science grating, which coincides with the shadow of the telescope secondary mirror. A hole has been drilled in the center of each MODS science grating and the imaging flat. The bypass grating is mounted in this hole with adjustable tip and tilt with respect to the surface of the science grating. This allows the bypass grating to direct the IMCS beam onto the IMCS detector (adjacent to the science detector) while the science beam is centered on the science detector.

3.3 Laser Spot Size

The proportional gain of the on-instrument IMCS control loop is determined by the final reference spot size on the reference quad cell. The measured spot diameter on the 5mm quad cell detector is 0.25 mm (D80). The position sensitivity is proportional to the spot size on the detector.

4. IMCS ON-INSTRUMENT PERFORMANCE

4.1 Performance: IMCS Spot Position vs. Time

The IMCS specification for operation is to hold the science spectrum steady to 0.1 pixel (1.5 μm) over the typical science integration time of about one hour. In Paper II, we demonstrate that the lab IMCS (using nearly identical components to the on-instrument IMCS, but installed on an optical bench rather than in the instrument) met this goal: the lab IMCS held simulated image motion steady to < ±1.0 μm (±1 σ). The on-instrument IMCS system performs as well as the lab IMCS, most likely due to reduced "seeing" effects in the on-instrument system as compared to the lab IMCS setup.

The tests of the on-instrument IMCS are run on the MODS handling cart, a fixture that holds the MODS instrument parallel to the floor (horizon-pointing), and allows for instrument rotation from –20˚ to +73˚ (i.e., from pointing 20˚ above the horizon to nearly upside-down). This setup allows for tests of the on-instrument IMCS performance, but does introduce some noise. The primary source of noise is introduced by the motor used to rotate the instrument on the cart: as the instrument is rotated to the downward-looking direction, the system becomes more unbalanced and more strain is placed on the motor. This causes a noticeable increase in the noise pattern of the data, apparent in the last third of the data shown in Figure 4. This will not be a problem once the instrument is on the telescope.

Figure 4 shows a typical on-instrument IMCS test run. During this test the instrument was rotated from –20˚ to +70˚. This figure plots 10 points per second with corrections made every 1 second based on the average of the previous 10 points.

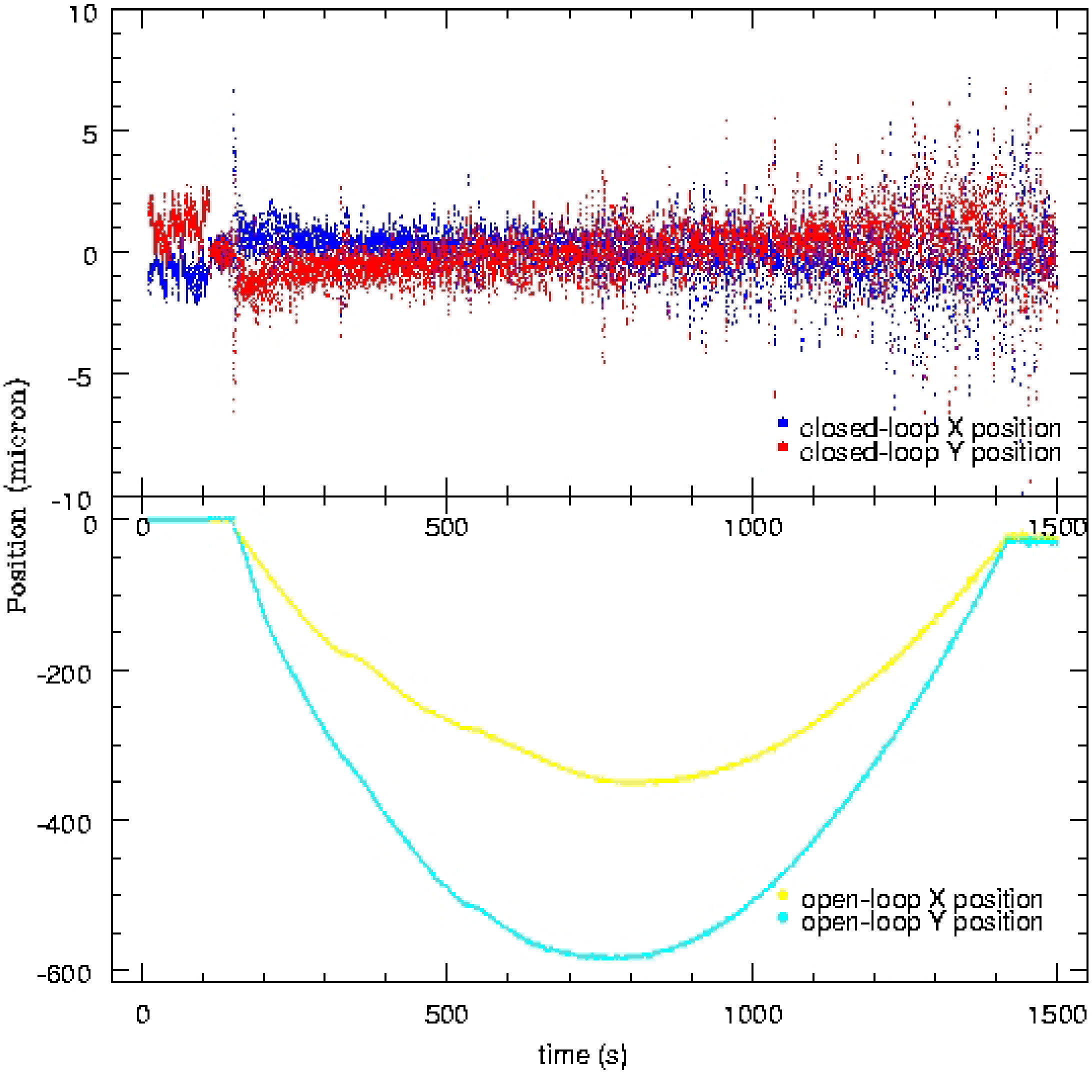

Figure 4. IMCS rotation test, showing the instrument moving from –20 to +70 degrees (nearly horizon-pointing to nearly upside-down) in about 20 minutes. The top panel shows the measured spot position on the quad cell; the lower panel shows the spot position if the system were run in open-loop mode. The closed-loop on-instrument IMCS controls image motion to about 1.2 µm, or less than 0.1 pixel on the science detector.

A consequence of the way we compute the commands to send to the collimator actuators is seen in the closed-loop X and Y positions shown in the top panel of Figure 4. The linear nature of the residual, of opposite sign in X and Y, is directly related to the derivative of the X or Y motion of the spot, which is proportional to the speed at which the instrument is rotated. The test presented in Figure 4 is run at 17 times the sidereal rate, so the slope here is 17 times that expected in normal use. When the instrument is rotated at the sidereal rate, this effect is negligible.

Figure 5 shows the “seeing disk” of the IMCS test run presented in Figure 4, again plotting 10 points per second with corrections made every 1 second. The size of the box is the size of one MODS 2x2 binned pixel (30 μm). Noticeable outliers are observed, but are corrected for within one correction cycle (1 Hz). The RMS error of these data is 1.1 μm in the X direction and 1.3 μm in the Y direction. The system is currently performing within specifications in the lab.

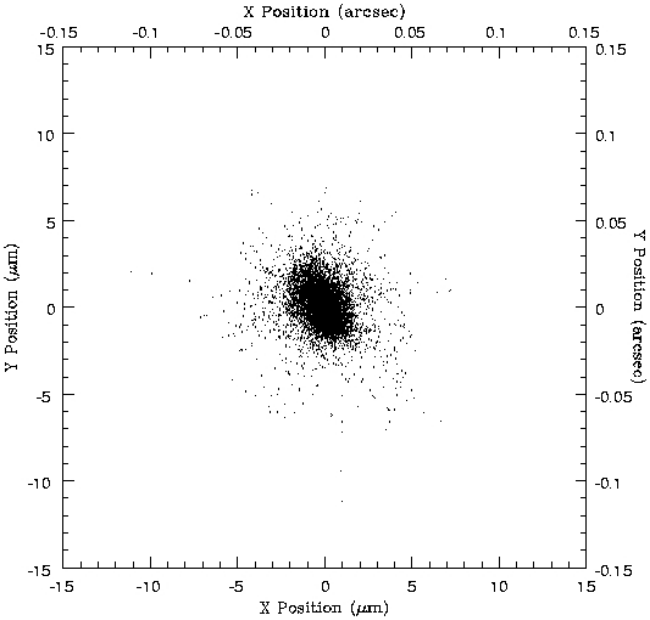

Figure 5. The “seeing disk” of the IMCS test presented in Figure 4. The RMS error of these points is 1.1 μm in X and 1.3 μm in Y. Note the slight diagonal elongation of the disk, due to the slope errors discussed above.

The IMCS system installed on the MODS instrument performs to within the specifications. Specifically, it controls image motion to about 1.2 μm (±1 σ) over the equivalent of six hours of tracking at the sidereal rate. This result includes all of the sources of error unique to the system as mounted on its cart in the lab. Even though MODS instrument flexure is larger than expected (i.e., ~300 μm/hour when rotated at the sidereal rate, rather than ~100 μm/hour; see Paper II), the system still meets the performance specifications.

4.2 Differential Image Motion

The largest source of error in a closed-loop image motion nulling system such as the on-instrument IMCS is differential image motion between the science beam and the reference beam. Differential image motion may be introduced at any point at which the two beams contact separate surfaces in one plane; however, in the MODS instrument this happens relatively infrequently. Differential image motion might be introduced in the focal plane by motion of the reference beam launch point with respect to the incoming science light. We have addressed this concern by creating a very stable laser mount with a close structural connection to the instrument and have epoxied the laser fiber into the combination block to eliminate reference beam motion with respect to the launch optics. The grating assembly might introduce differential motion between the science grating and the bypass grating. The bypass grating has been kinematically referenced to the science grating to minimize this motion. Finally, differential motion is eliminated in the detector plane by mounting both the science and the quad cell detectors to a common mounting plate and placing them both in a temperature-controlled environment. Consequently, we expect negligible differential image motion between the science beam and the reference beam inside the instrument.

5. THE IMCS AS A DIAGNOSTIC TOOL

An important benefit of the IMCS is its utility in testing many aspects of instrument performance, including elements that are not specifically part of the IMCS itself. Because the IMCS uses the entire lightpath of the MODS instrument, it may be used in open-loop mode (i.e., with the IMCS correction routine turned off) as a diagnostic tool to test the stability of every optical element and associated optical mounts and mechanisms in the instrument. Furthermore, the IMCS interface and data-logging system provides a simpler interface than the science CCD, especially for quick engineering tests.

The IMCS, run in open-loop mode, may be used for any number of diagnostic instrument tests within the MODS instrument. In particular, the open-loop IMCS may be used to test the repeatability of the dichroic select mechanism, and the collimator TTF actuator performance. It will also be used to test the grating select turret repeatability, to look for hysteresis in the grating tilt mechanism, and to measure image motion caused by the camera focus mechanism. The IMCS will be able to measure the long-term stability of MODS, both in the lab and at the telescope. Perhaps most importantly, the open-loop IMCS is an excellent tool to measure the instrumental “seeing”, or the internal air stability within the MODS instrument (with the dark slide closed). This will be an ideal tool when determining, for example, whether a new electrical component has any thermal effect on the internal environment of the instrument.

To give one example, we have used the open-loop IMCS to measure the repeatability of positioning the grating select mechanism. By moving the imaging flat in the grating turret into and out of the beam repeatedly, we determine that the grating select mechanism is repositionable with a random error of about 50 μm. More importantly, we show that the IMCS is a very useful tool to accurately measure the performance of almost any MODS instrument mechanism in the lab.

6. SUMMARY

The IMCS has been installed in the MODS instrument and performs to within specifications. It controls image motion to about 1.2 μm, or about as well as the lab version of the IMCS. We expect even better performance once the MODS instrument is mounted on the LBT telescope. A complete MODS1 will be installed on the LBT in late 2007; MODS2 should follow shortly thereafter.

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