MODS

Instrument Calibration Protocol

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Contents

1 Introduction

1.1 Scope

This document describes the calibration protocol for the Multi-Object Double Spectrograph (MODS), and establishes the requirements for the instrument's onboard calibration system.

1.2 Reference Documents

1. *MODS: A Multi-Object Double Spectrograph for the LBT*, Preliminary Design Review Document, 2001 June 11.
2. *Definition of the Flexible Image Transport System (FITS)*, NOST 100-2.0, NASA/Science Office of Standards & Technology, 1999 March 29

1.3 List of Abbreviations and Acronyms

FITS	Flexible Image Transport System
GUI	Graphical User Interface
ICRS	International Celestial Reference System
IRAF	Image Reduction & Analysis Facility (NOAO data reduction package)
KPNO	Kitt Peak National Observatory
LBT	Large Binocular Telescope
LBTO	Large Binocular Telescope Observatory
LED	Light-Emitting Diode
MODS	Multi-Object Double Spectrograph
MOS	Multi-Object Spectroscopy
OSU	The Ohio State University
OT	Overscan & Trim
OTZ	Overscan, Trim, & Zero
OTZF	Overscan, Trim, Zero & Flat-Field
RMS	Root-Mean Square
WCS	World Coordinate System

2 MODS Calibration Requirements

The MODS calibration system and calibration procedures must provide for the following:

1. A spatially uniform and bright source of illumination for the instrument, with optics that mimic as closely as practical the entrance pupil of the LBT Telescope. This is accomplished with an integrating sphere, lamp sources, and projection optics.
2. Flat Field calibration of the science CCD arrays in both imaging and spectroscopic modes using artificial light sources and the twilight sky. The flat-field lamp source must provide a clean, spectrally pure continuous spectrum free of emission or absorption features. We have adopted high-intensity quartz-halide lamps for MODS.
3. Wavelength calibration of the spectroscopic modes using internal wavelength reference lamps. These lamps must provide:
    a. Sufficient unblended bright lines to provide good wavelength calibration in the "low" (R≈1800) resolution modes.
    b. Sufficient emission line density to provide good wavelength calibration in the "medium" (R≈8000) resolution modes

    The current system employs five (5) wavelength calibration sources: Neon, Argon, Mercury, Xenon, and Krypton lamps of the "Pen-Ray" design mounted in the integrating sphere. They may be illuminated individually or in groups.
4. The calibration system must be able to operate in any instrument orientation, not just zenith-pointing. It must also be able to deploy rapidly to reduce operational overheads, particularly when "point" calibrations (wavelength or flat-field) are acquired at the same instrument orientation as a science target (e.g., target-by-target wavelength lamp snapshots used to support precision radial velocity work).
5. The calibration system must not spill light into the LBT environment, so that it may be operated at night without interfering with other instruments or LBT telescope systems.
6. The calibration system must be able to operate during the daytime hours for extensive pre-observing calibrations.
7. Provision for geometric and astrometric calibration to support slit mask generation.
8. Simple user interfaces to all calibration procedures easy. For major supported modes of the instrument, standard "built-in" calibration setups will be provided as part of the observing interface. These standard modes shall be well-characterized, and allow users to confidently acquire basic calibration data. Because the data are acquired in a standard way, they become part of the operational database of the instrument, making them useful for tracking instrument health and performance.

The following sections describe the current MODS calibration system (§3), then the basic calibration procedures common to all modes (§4), calibration specific to imaging (§5) and spectroscopic (§6) modes, and procedures for photometric (§7) and astrometric (§8) calibration.

3 MODS Calibration System

The MODS calibration system is composed of the following components

- A calibration "tower" mounted on a linear stage just behind the instrument's entrance dark slide (Figure 3-1). It has two positions: stowed to one side where it does not obstruct the telescope beam, and a "calibration" position were it replicates the incoming telescope beam. The top of the tower contains a flat mirror to view the integrating sphere located off to the other side of the MODS upper structure, and a pupil lens at the bottom (just above the slit plane) that re-images the pupil mask at the exit port of the integrating sphere onto the grating, mimicking the pupil of the telescope.
- A 30-cm diameter integrating sphere located on MODS upper structure diametrically opposite the calibration tower's stowed position. A baffle extends from the exit port of the integrating sphere to where it will mate with the calibration tower when the latter is in its "in-beam" position (Figure 3-2). The integrating sphere has 8 lamp ports located at 45° intervals around its diameter, and a 10-cm diameter exit aperture covered with a pupil mask.
- Five (5) pen-ray type spectral calibration lamps (Ne, Ar, Hg, Kr, & Xe) with a remotely-operated power supply. The lamps may be powered on individually or in multiples.
- Three (3) quartz-halide continuum lamps occupy 3 of the 8 lamp ports, and are controlled with an external power system that can turn them on in any combination (singly or all at once). These provide enough UV output when all 3 are illuminated at full power for spectroscopic flat-field calibration in the $R\approx8000$ blue channel mode.

Design drawings of the MODS Calibration system are shown in Figure 3-1 and Figure 3-2.

3.1 Calibration Procedures

The usual steps in acquiring calibration data with MODS are as follows:

For calibrations using the white-light or spectral lamp sources...

1. Close the instrument dark slide.
2. Translate the calibration tower into its "in-beam" position
3. Turn on power to the desired calibration lamps (white-light or spectral)
4. Acquire calibration data
5. Turn off the lamp power
6. Stow the calibration tower
7. If observing, the instrument dark slide may be opened at this time.

Calibrations may, in principle, be obtained with MODS in any orientation, or at any time.

During calibration observations with any of the lamp sources, the MODS dark slide must be closed, both to reject stray light from outside the instrument, and to keep stray calibration light from escaping back into the observatory environment. Software interlocks will be used to prevent the operator from turning on the calibration lamps when the dark slide is open and/or the calibration tower is in its "Stowed" position. These interlocks may be overridden in engineering modes (via a set of EXEC: type executive override directives), but such overrides are not enabled in the standard observing interface.

For "dark" calibrations like zero ("2D bias") and dark frames, the procedure is to close the instrument dark slide before acquiring observations. The observing interface will issue warnings if images of type "bias" or "dark" are requested while the dark slide is open, but there will be no software interlocks active as sometimes taking data in these configurations is required (e.g., to assess the impact of straylight from the observatory environment).

To assist in obtaining calibration data in an efficient fashion, the observing software will provide calibration "macro" scripts and/or GUI "wizards" to implement practices established during instrument commissioning.

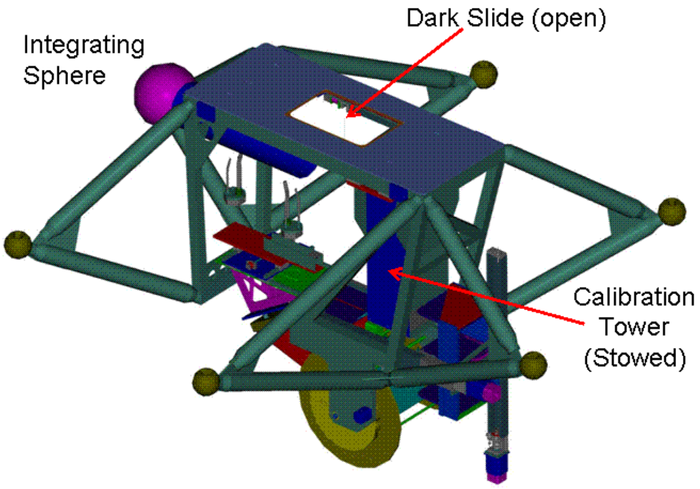

Figure 3-1: MODS Calibration System shown in relation to the upper structure of MODS in its stowed position.

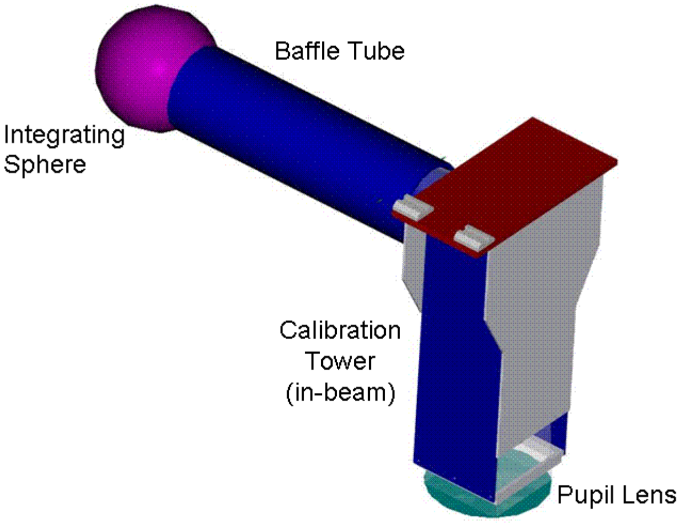

Figure 3-2: Calibration Tower and Integrating Sphere, in the "in-beam" position.

4 Generic Calibrations

All 2D images acquired by MODS in spectral and direct imaging modes will require basic Overscan. Trim, and Zero (OTZ) processing:

- **O**verscan subtraction of the DC bias level associated with each readout amplifier.
- **T**rim the overscan sections from the data sections of the raw image.
- **Z**ero (2D Bias) subtraction to remove any residual bias after DC bias subtraction using the overscan columns.

These steps are common to all basic CCD image calibration. OTZ processing precedes all other processing steps for both calibration and science images. The requirements for each of these calibrations are described below.

Because this calibration steps are generic to all CCD images, a provision for mountain-top preprocessing will be considered, although in general most astronomers will wish to perform OTZ calibration on individual images using their own data-reduction programs.

4.1 Overscan Subtraction

Each raw CCD image from MODS will include an overscan strip on the image for subtracting the DC bias signal from each amplifier of each MODS detector. Device (pixel) coordinates of the overscan sections for each amplifier of each CCD will be stored in the FITS headers as the `BIASSECn` keywords, where “n” is the readout amplifier number.

The DC bias level for each row of the CCD is measured by computing the average of the pixels for that row in the overscan region, and then fitting a low-order polynomial to the DC level as a function of detector row number. The best-fit DC bias level is then subtracted from each row to remove the DC bias level imposed at readout time.

4.2 Trimming

After subtracting the DC bias, the image is trimmed to remove the now extraneous overscan regions. Device (pixel) coordinates of the data seconds of each amplifier for each CCD are stored in the FITS header as the `DATASECn` keywords, where “n” is the readout amplifier number.

The resulting overscan subtracted and trimmed image is usually written into a different image file so as to preserve the raw CCD image should reprocessing be required.

4.3 Zero (Bias) Calibration

After removing the DC bias level imposed at readout, there is sometimes residual 2D structure in the image added at readout. This includes such artifacts as amplifier gain variations, fixed pattern noise, etc. Because it is an artifact of the readout process, it is an additive correction and must be applied immediately after removing the DC bias.

A set of “zero images” is required to measure and subtract this 2D residual bias for each detector. A zero image is one in which the CCD is erased then immediately readout. If there were no 2D bias pattern in the detector, the zero image pixels would contain only DC bias and readout noise. If 2D bias is present in CCDs it is usually persistent and can be subtracted from the raw images using a suitably created zero calibration image. Unstable 2D bias structure is often a harbinger of detector electronics problems, so zero frames should be taken regularly even in the event they are not required as diagnostics of the CCD electronics.

A master zero calibration image for a given data set is usually created by combining many (usually 8-10) individual zero images. The averaging process reduces the effect of readout noise and yields a high-quality zero image that will not add noise to science or calibration images. In order to provide a check on the detector's bias stability, stacks of zero images should be acquired at the start and end of each night and compared as part of the regular engineering health monitoring of the instrument.

The MODS data-acquisition system will provide a standard set of procedures (macros and/or GUI wizards) for acquiring beginning and ending zero calibration images. Post-processing software to combine the zero images will also be provided as part of a mountain calibration pipeline system, and as part of the mountain engineering software.

5 Direct Imaging Mode

5.1 Flat Field Calibration

The large collecting area of the individual LBT primary mirrors makes twilight sky flats the most practical option for direct imaging. The basic procedure will be to park the telescope and allow the sky to drift while flats are being acquired. Software will use a lookup table created during commissioning and a sky-flat model (e.g., Tyson & Gal 1993, AJ, 105, 1206) built into the MODS data acquisition system to provide reasonable automation of the procedure. There is also future capacity for introducing low-intensity LED-based illumination in the calibration system integrating sphere, but this is not part of the baseline instrument.

For projects requiring flat fields that are color-matched to the night sky, the observer can use a dithering pattern like with IR imaging to eliminate star and galaxy images and form a "superflat" of the night-sky. Adequate results may be obtained from 4 images with good S/N in the sky dithering by ≥5″ between images. The data-taking system will provide commands for automated acquisition of dithered images, using either built-in dithering patterns with adjustable scale or user-provided dithering tables. Access to these patterns will either be via facility "macro" scripts or wizard GUIs.

Methods for combining sky flats vary depending upon the science goals of the project and the habits of the investigator. No automated pre-reduction pipeline for flat fielding will be provided except OTZ processing of raw flat fields on the mountain. IRAF parameter files to facility image combination on the mountain (or at home) will also be created as part of the commissioning activities.

5.2 Direct Imaging Calibration & Reduction Protocol

The basic calibration data required for direct imaging is as follows:

1. Zero images for 2D bias correction, independent of filter.
2. Twilight Sky flats for each filter used.

The reduction procedure is:

1. OT (Overscan & Trim) process the zero images and combine into a master zero image.

2. OTZ process the twilight sky flats and combine into a normalized sky flat for each filter. Combination would likely be a median of the ensemble to eliminate star tracks on the individual images.
3. OTZF (Overscan, Trim, Zero, and Flat-Field) process the individual object images. The procedures for combining a set of multiple images of the same object in the same filter are left to the discretion of the observer.

Dark correction is not likely to be required for the MODS science CCDs, but the data-taking system will provide the means to collect dark images if that is felt to be necessary for some observations. Dark subtraction comes after Zero subtraction but before flat-field division for normal images. Individual dark images must be OTZ processed to create the reference Dark image.

6 Spectroscopic Mode

6.1 Generic Calibrations

Spectral object and calibration images will require the same OTZ pipeline calibration data described in Section 1.

6.2 Flat-Field Calibration

There are two basic components of flat-field calibration for spectral data:

1. "White Light" spectral flats to remove pixel-to-pixel gain variations as a function of wavelength in the CCDs. The white-light source is a set of 3 quartz-halide lamps packaged in the integrating sphere along with the wavelength calibration lamps, and use the same projection optics to provide correct pupil matching, but need not be spatially uniform on large scales.
2. An illumination correction image composed of a spectrum of the twilight sky (a spectrum of scattered sunlight). The spectral information is collapsed to extract the pattern of illumination along the slit to correct for the non-uniform illumination of the brighter, spectrally clean white-light spectral flats.

White-light flats will be acquired using the onboard calibration system. The light source will be a high-intensity quartz-halogen lamps shining into the same integrating sphere used by the wavelength calibration lamps.

The requirements for the white-light source are that it should have no spectral line or band features, and be bright to keep integration times short. Since aluminum has a strong absorption band in the near-IR, we should consider two different lamp reflector systems: silver for red and aluminum for blue flats. Blue filters (in practice red-blocking filters) installed in the instrument filter wheel for the blue channel can be used to help boost the relative blue light signal for extremely blue flats.

Illumination correction images are formed from spectra of the twilight sky that have been OTZF processed using flat fields derived from observing the calibration system's white-light source. The twilight sky uniformly illuminates the slit (or slitlets in an MOS mask) along the spatial axis, but the spectral axis records a reflected solar spectrum filled with absorption lines. By collapsing the twilight flats along the spectral axis and building up signal along the spatial axis, these data are used to correct for the non-uniform illumination of the slit by the white-light flats. This allows us to substantially relax the uniformity requirements for the white-light projection system. The use of a combination of bright but ultimately non-uniform white-light flats with twilight sky spectral flats is a standard observing procedure: all facility spectrometers require some degree of illumination correction as part of the calibration. Even those that take heroic efforts with integrating sphere projectors usually need additional twilight sky illumination correction data for high-precision work with long slits.

6.3 Wavelength Calibration (General)

The same integrating sphere and projector used for white-light flats can be used for spectral line comparison lamps. There is no requirement that the illumination of the slit be uniform, but there does need to be enough light across the focal plane to achieve similar (factor of 2 or so) signal across the field of view for both long-slit and multi-object modes. Signal-to-Noise requirements for spectral calibration lamps are not as severe as for flat fields (where fraction of a percent flat fielding precision is required), but wavelength calibrations should not be unnecessarily time consuming. Initial design calculations suggest that exposures should be at most a few 10s of seconds for the faintest lamps, but this will be determined as part of the commissioning activities and corrected if problems of excessive calibration times emerge.

Current Lamps to be used in the MODS integrating sphere:

1. Neon (λ>600nm)
2. Argon (λ>500nm, but some blue lines)
3. Mercury (λ<500nm)
4. Krypton (λ<600nm)
5. Xenon (λ<600nm, especially in UV)

If future high-resolution modes ($R \approx 15000$) are implemented, we would need additional ThAr or CuAr lamps to provide enough lines across the tiny free spectral ranges of individual spectral orders.

Lamps can be turned on individually or in groups to mix lines as necessary. Since some lamps will prove intrinsically brighter than others this is not always practical, but should be allowed for in the design.

If very precise wavelength calibration associated with an object is required (e.g., a radial velocity program studying bright stars were one cannot expect night-sky emission of sufficient brightness in short exposures to provide a precise wavelength zero-point correction), the lamps may be observed at any telescope position angle, and they should be bright enough so as to not impose unnecessary observing overhead.

In general, the bright comparison-lamp images are used to measure the linear and high-order terms of the wavelength solution, while “flexure” of the spectrograph introduces a zero-point shift without changing the linear or high-order wavelength coefficients. Use of night-sky lines to correct an remaining zero-point offset of a wavelength-calibrated spectrum is a standard technique.

6.4 Long-Slit Mode

The basic calibration protocol for long-slit spectra is as follows:

1. Zero images for 2D bias correction

2. White-light flats at the spectral setting to be used for science targets
3. Twilight Sky spectral flats to provide the slit illumination correction at the spectral setting to be used with the science targets
4. Calibration lamp spectra as required for the wavelength region of interest.

The reduction procedure is:

1. OT process the zero images and combine into a master Zero image.
2. OTZ process the white-light flats and combine into a normalized white-light flat.
3. OTZ process the twilight sky spectral flats and combine in a raw twilight flat.
4. Divide the grand twilight flat by the normalized white-light flat, and then sum over wavelengths to get a 1-D cut giving the slit illumination pattern. This may be done in wavelength segments if there is any wavelength-dependence to the illumination (this is an option, for example, in IRAF, best practices will be determined during MODS commissioning).
5. Apply the slit illumination correction image to the normalized white-light flat. This creates the normalized, corrected flat field to be used with all subsequent object and calibration-star spectra.
6. OTZ process the calibration lamp spectra. Flat fielding and slit correction rarely accomplish gains (the line search/measurement algorithms use logarithmic spectra extracted following standard star spectral tracks).

After this processing, object and standard star spectra are OTZF processed using the normalized, corrected flat field. All subsequent reductions to 1-D or 2D wavelength and flux-calibrated spectra proceed following standard practices.

6.5 Multi-Object Mode

The basic protocol for what calibrations to take in MOS mode is the same as in long-slit mode. The reductions are the same as long-slit mode, except that you now have N slits scattered about the spectral image instead of one that require separate treatment. A second difference is how the twilight spectral flats are used. The twilight sky spectral flats are used in two ways in MOS reductions:

1. Provides the illumination correction function along each slitlet, like in long-slit mode.
2. The twilight sky spectrum is extracted from each slitlet and then compared within a common wavelength region to compute a “gray shift” for each slitlet that is used to scale observations of standard stars acquired in only one or so of the slitlets.

Each MOS mask used on a given night will require separate flat-field, twilight, and wavelength calibrations.

7 Photometric Calibration

In general, individual investigators will be responsible for determining how best to photometrically calibrate their MODS data. However, a regular LBTO program of taking basic standard star data in imaging and spectroscopic mode on 3-6 month timescales will allow us to monitor the health of the instrument, particularly detectors and filters. Significant changes in photometric zero-points or color terms are excellent diagnostics of changes in the instrument.

For imaging observations with the SDSS ugriz filters used in MODS, observations of SDSS standard star fields taken on clear, photometric nights and reduced using standard procedures (e.g., the IRAF photcal task) will accomplish this. It is expected that the LBTO instrument scientist for MODS will make these observations using DD time, and report the results both to LBTO and the MODS team at OSU for evaluation and posting for the community. These data are also useful for keeping exposure-time calculators accurate.

Spectrophotometric performance can be monitored using observations of selected KPNO standard stars (e.g., the traditional IIDS standards). Such observations would similarly be taken on a 3-6 month timescale by the LBTO instrument scientist for MODS, and the results published for the observatory community. Likely useful data products are sensitivity curves giving the expected number of electrons/sec/Angstrom for the different spectroscopic modes. These data are useful for monitoring instrument health and observing planning.

8 Image Scale Calibration

There are two types of image scale calibrations required for MODS. Both are used primarily in service of creating multi-object slit masks.

1. Astrometric Calibration: maps the CCD detector frame onto the sky in standard celestial coordinates (RA, Dec), otherwise known as a World Coordinate System (WCS) calibration.
2. Focal-Plane Calibration: maps (x,y) coordinates in the instrument's slit-mask plane onto CCD pixel coordinates.

These calibrations need only be done on an annual basis at most, with the baseline calibrations being done as part of the MODS commissioning effort.

8.1 Astrometric Calibration

Astrometric calibration measures at least the imaging pixel scale of the instrument (in arcsec/pixel), and also measures higher-order coefficient as a basis for absolute astrometric calibration of images. This calibration is accomplished by taking direct images of star fields with high-precision astrometric measurements (e.g., open star clusters with good proper motion data), and reducing them using standard procedures. Our standard will be to reduce the coordinates to the ICRS reference frame. It will be measured in all filter bands, to be able to account for any systematic optical differences from u through z bands.

The basic astrometric calibration of the field will be done during MODS commissioning, but should be repeated at least annually (or more) to monitor the overall astrometric stability of the LBT f/15 active Gregorian secondary mirror system.

In general, the MODS basic 2D image reduction procedures will not compute a WCS calibration for images, but tools that can accomplish are widely available as 3rd party software from a variety of sources. The MODS team will evaluate current options, and adopt a package for WCS calibration as part of the commissioning procedure.

8.2 Focal Plane Calibration (Image-to-Mask Transformation)

The focal-plane calibration is critical for mapping objects in a direct image (e.g., faint galaxies or stars) into the slit-mask plane in order to create a slit mask from MODS direct images. Both of these calibrations combined can be used to map known celestial coordinates of targets (α,δ) into slit-mask position (x,y in millimeters) for slit mask generation without resort to MODS direct images. While we will generally recommend pre-imaging with MODS as the best way to create MODS masks (it requires only one level of geometric transformation), it should in principle be possible to generate masks "blind" using only good astrometric coordinates of targets.

The focal-plane calibration is accomplished by making flat-field observations through a special precision "pinhole" mask that is inserted into the MODS focal plane. The mask will likely be machined out of invar or other very-low-expansion materials, with a regularly-spaced grid of pinholes with relative positions accurate to ±5μm RMS (corresponding to approximately ±8mas on the sky, or ~0.067 pixels for 15μ pixels at the nominal design pixel scale of 0.125" pix^{-1}). These artificial "stars" are easily measured in direct images and geometric transformations will allow users to easily convert from pixel coordinates to physical coordinates in the mask plane and back with confidence.

The focal plane scale needs to be measured at least annually using the pinhole mask, and the best-fit transformation coefficients recorded and introduced into the MODS/LBT mask-making software. Especially diligent observers, however, may wish to obtain a pinhole-mask image contemporaneous with pre-imaging of MODS fields for future mask generation, so a provision for leaving the pinhole mask in the instrument as one of the "reserved" masks should be considered part of the baseline operating mode.

In general, the focal-plane calibration should be a one-time measurement, as the optical system should be very stable. However, a benefit of annual (or bi-annual) focal-plane calibration is to provide a way to monitor the optical stability of the MODS instrument, as small misalignments in the optics that might be difficult to detect otherwise would emerge as subtle systematic residuals when comparing pinhole mask transformations taken in different epochs.