



Sloan Digital Sky Survey photometric telescope automation and observing software

Eric H. Neilsen, Jr.^a, Alan Uomoto^b, Stephen Kent^a, James Annis^a

^aFermi National Accelerator Laboratory, Batavia, IL

^bThe Johns Hopkins University, Baltimore, MD

ABSTRACT

The photometric telescope (PT) provides observations necessary for the photometric calibration of the Sloan Digital Sky Survey (SDSS). Because the attention of the observing staff is occupied by the operation of the 2.5 meter telescope which takes the survey data proper, the PT must reliably take data with little supervision. In this paper we describe the PT's observing program, MOP, which automates most tasks necessary for observing. MOP's automated target selection is closely modeled on the actions a human observer might take, and is built upon a user interface that can be (and has been) used for manual operation. This results in an interface that makes it easy for an observer to track the activities of the automating procedures and intervene with minimum disturbance when necessary. MOP selects targets from the same list of standard star and calibration fields presented to the user, and chooses standard star fields covering ranges of airmass, color, and time necessary to monitor atmospheric extinction and produce a photometric solution. The software determines when additional standard star fields are unnecessary, and selects survey calibration fields according to availability and priority. Other automated features of MOP, such as maintaining the focus and keeping a night log, are also built around still functional manual interfaces, allowing the observer to be as active in observing as desired; MOP's automated features may be used as tools for manual observing, ignored entirely, or allowed to run the telescope with minimal supervision when taking routine data.

Keywords: Astronomical observatories, astronomical photometry, automated telescopes, telescope operation

1. INTRODUCTION

The Sloan Digital Sky Survey¹ 2.5m telescope takes imaging survey data in a drift scanning (time delay and integrate, or TDI) mode, and dedicates no observing time to photometric calibration of imaging data. Instead, a companion 0.5m telescope (the photometric telescope, or PT) takes the data needed to derive a photometric solution. During a night of observing, the PT images patches of the sky overlapping the 2.5m imaging data to be calibrated ("secondary patches"), and fields containing the standard stars ("primary standards") needed to derive a photometric solution for the night. The data reduction team then calibrates the 2.5m imaging data using the extinction measured by the PT for the night the data was taken and the PT photometry of stars found in that data (from secondary patches).

The PT, therefore, has two responsibilities: to create a set of secondary standard stars present in imaging data that needs to be calibrated, and to measure the extinction for nights on which imaging data are taken.

To accomplish this, the PT must make several types of observations:

bias frames for each night of observing;

dome flat field images for each night of observing;

twilight flat field images for each night of observing, when conditions allow;

Further author information: neilsen@fnal.gov; Telephone: 1 630 840 6720; Address: Mail Stop 120, Fermi National Accelerator Laboratory, P. O. Box 500, Batavia, IL 60510-5011

primary standard star fields containing one or more well calibrated standard stars from the SDSS standard star system^{2*}; and

secondary standard fields containing stars also present in imaging data. The immediacy of the need for the calibration of particular sets of imaging data drives the choice of secondary fields.

Ref. 3 describes the calibration of the survey in greater detail.

Two observers staff both the PT and the 2.5m SDSS telescope. Because the attention of both observers is generally occupied by 2.5m operations, the PT observations must be automated, or nearly so. The consistent and well defined requirements for PT observations make this possible.

The photometric telescope observing program (MOP) is the observers primary user interface for PT operations. It includes automation of routine survey observing, tools for planning and execution of more general observing programs, and an interface for lower level control of the instrument.

2. THE PROCESS OF OBSERVING

A standard night of observing consists of the several steps.

1. The observers start the observing software and instruments if necessary, and check for equipment problems. They read out the CCD once to remove any cosmic rays and dark current which have accumulated.
2. The telescope is pointed at the flat field screen in the dome, the flat field lamp turned on, and 5 sequences of exposures are taken. Each sequence of exposures consists of one exposure in each filter. The flat field lamp is then turned off.
3. Bias data are taken by reading out the CCD 11 to 17 times in succession.
4. When the sun is low enough in the sky that it will not warm the telescope, the dome is opened.
5. At sunset the telescope is pointed to a uniformly illuminated section of the sky, and a sequence of 5 exposures taken, each with an exposure time appropriate to the brightness of the sky.
6. The telescope is pointed at an FK5⁴ star, an exposure taken, and a correction to the pointing applied based on the position of the star in the resulting image.
7. A list of targets to be observed is created.
8. Observations of the first target on the list begin, and the target being observed is removed from the list.
9. The focus is checked and corrected. Because the PT is slightly astigmatic, a focus correction may be derived from the ellipticity of the star images in a frame.
10. An appropriate new target is chosen and added to the end of the list of planned targets.
11. If morning twilight has not begun, observing is continued by returning to step 8.
12. The dome is closed at twilight.
13. The data are written to tape and shipped.

Although it is tempting to build the list of targets for the entire night in advance, thereby eliminating step 10, this is not practical if the list is constructed by hand. Observing stops frequently because of changes in weather, and the list would need to be reconstructed each time observing restarts.

MOP may be used in a variety of ways to complete these tasks. Under routine survey observations, MOP automates most steps not requiring physical manipulation of the equipment (such as opening the dome). It also provides tools for interacting with the telescope at a lower level, or for the observer to intervene at a lower level during automated observing.

*Standard star measurements must be taken at a range of times and airmasses that allow the stability of the photometric solution through the night to be monitored.

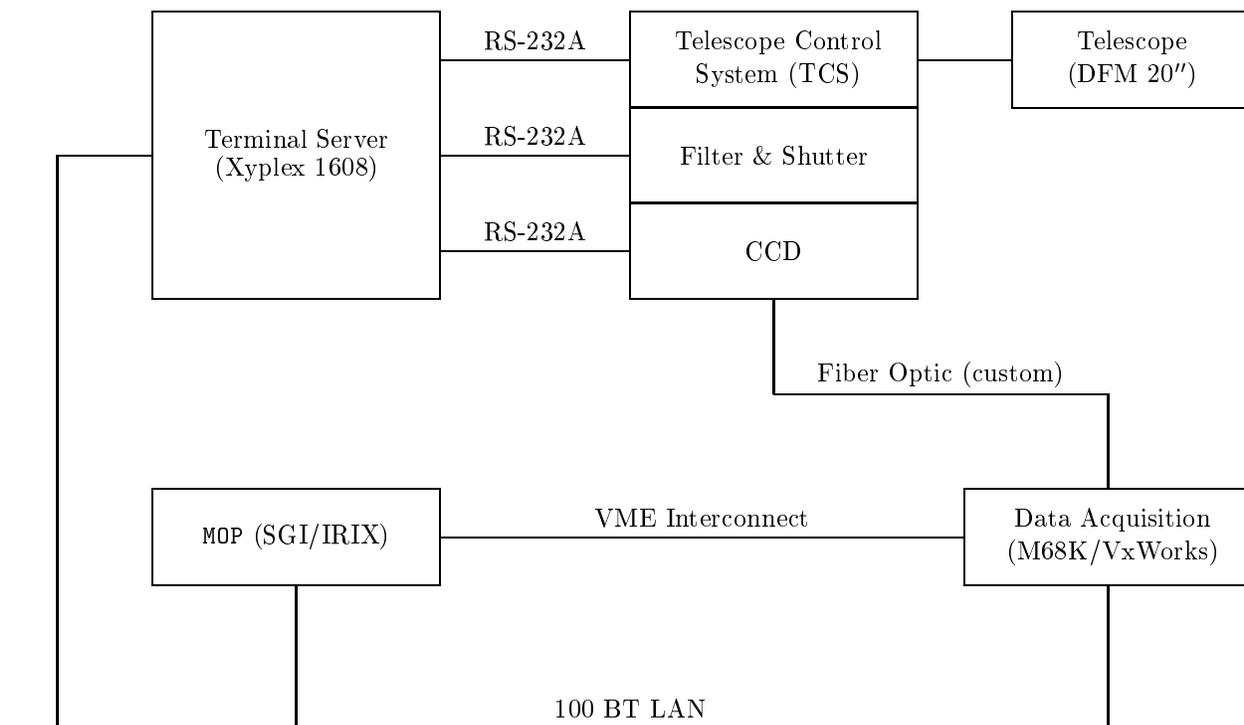


Figure 1. Overview of the PT observing system.

3. INFRASTRUCTURE AND ENVIRONMENT

Fig. 1 illustrates the high level architecture of the PT observing system. MOP runs on a four processor SGI Challenge L running IRIX 6.5, and provides the observer’s primary interface to the other systems. It communicates with the data acquisition system through a VME interconnect, and with other systems through a terminal server.

Like all SDSS observing programs, MOP is built around the Imager Observing Program (IOP). MOP proper consists of a set of `tcl` scripts that use the `tcl` interface to utilities provided by IOP and various libraries IOP itself is built on. These libraries include:

astrotools: an integrated environment of utilities and libraries with `C` and `tcl` interfaces, which itself includes:

slalib: a positional astronomy library,⁵

lapack: a linear algebra library,⁶

slatec: a general mathematical library,⁷

fftw: a fast Fourier transform library,⁸ and

dervish: a set of utilities for manipulating, plotting, and displaying images and other data from either `C` or a `tcl` interpreter;⁹

astroda: the “host” portion of the data acquisition system (DA),¹⁰ and

murmur: a message generating and reporting system developed at Fermilab, used primarily for logging.¹¹

Users interact primarily with MOP’s graphical user interface, written using the `tcl/tk` toolkit. They may also issue commands to a `tcl` interpreter, or write their own `tcl` scripts.



Figure 2. The MOP GUI window with controls for sending low level command to the camera, shutter, and filter wheel.

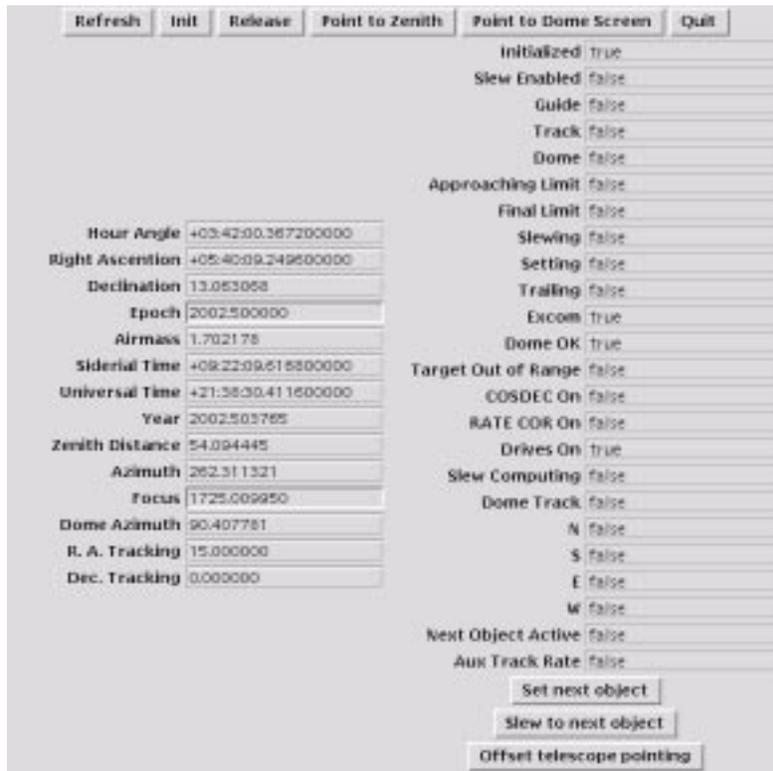


Figure 3. The MOP GUI window with telescope controls and status information.

4. MOP USAGE

4.1. Basic Telescope, Filter Wheel Box, and Camera Control

MOP provides a convenient user interface for the various systems used in PT observing. The MOP GUI includes controls that send commonly used low level commands to these systems. Text commands may be used to write scripts or send arbitrary instructions to these systems.

Fig. 2 shows the GUI control window for the filter wheel box and the camera. Fig. 3 shows the GUI control and status display for the telescope itself.



Figure 4. The MOP night log editor.

4.2. Log Creation

Each night of observing requires an accompanying human readable night log, which should include the names of observers on duty, a table of observations made, and any other data needed by data reduction or developers to interpret that night's data properly. MOP assists in keeping the night log by providing an editor (shown in fig. 4) that encourages the observers to keep data in a standard format, and that MOP itself supplements as necessary. For example, at the completion of each exposure MOP adds a line to the end of the log's table of exposures. If there are no problems during a nights observing, the user may not need to edit the night log at all; at other times, it may be necessary for the observer to add descriptions of problems and other observing details. In addition to this user editable night log, MOP records a considerable amount of data in a format convenient for processing by software. The data analysis software uses these logs to determine proper reduction parameters.

4.3. Target Field Management

MOP's target management window contains the controls and information displays needed to plan and carry out observations of calibration frames and astronomical targets. It consists of four sections:

1. the controls needed to create a table of candidate targets,
2. the table of candidate targets itself,
3. the controls that initiate observing and govern observing behavior, and
4. a list of targets planned for observation.

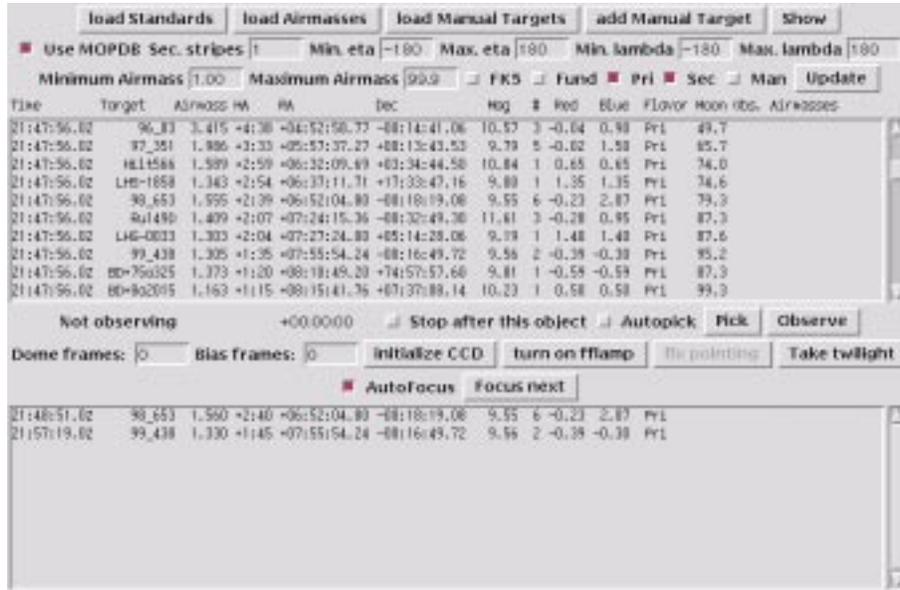


Figure 5. The MOP observing and target management window.

On startup, the table of planned targets is empty, and the table of candidate targets shows a default list of candidate targets. Users add targets from the list of candidates to the list of planned observation by clicking on the desired target's entry in the candidate table, and remove entries from the list of planned targets by clicking on the entry in the table of planned targets. Users may add and remove targets from the planned target list at any time, even during observations.

Each list displays a variety of data on the targets:

time: the extrapolated time of observation,

target: the name of the target,

airmass: the airmass at the extrapolated time of observation,

HA: the hour angle of the target at the extrapolated time of observation,

RA: the right ascension of the target,

dec: the declination of the target,

mag: the approximate V magnitude of the target (when available),

#: the number of photometric standard stars in the target field,

red: the color of the reddest standard star in the field of view,

blue: the color of the bluest standard star in the field of view,

moon: the angular distance between the target field and the moon at the extrapolated time of observation,

flavor: the flavor of the target field ("pri" if the field contains primary standards, "sec" if it is a secondary standard field, "FK5" if it contains a star from the FK5 catalog, or "man" for a manually entered target),

obs. airmasses: the airmasses at which this target has already been observed this night (if any).

The table of planned targets shows the values of time dependent parameters (time, airmass, hour angle, and moon distance) expected at the time of observation. The table of candidate targets shows the values that would be expected were the target to be added to the end of the current list of planned targets.

When MOP starts, it loads three sets of candidate targets: primary photometric standards, a subset of the FK5 catalog used to correct pointing, and secondary fields. Each target has an associated set of data describing the sequence of exposures appropriate to that target, its location on the sky, the standard stars in the field, and its priority. While MOP reads most target data from disk, it loads additional data (particularly that which might change on a regular basis) from a database, `mopDB`. This data includes the priorities of the secondary standard fields and new fields which may have been added at the last minute. Additional targets may also be entered by the user, either from a file on disk or interactively using the MOP GUI.

The observers can use the controls at the top of the target field management window to load targets from disk, add new targets by hand, and specify subsets of targets to be displayed in the table of available targets. Limiting the set of targets displayed is particularly useful when observing manually. The observing programs often call for a particular type of target, or an observation made under specific conditions. For example, a user observing manually may need to choose a target field containing both red and blue standard stars that is currently at a high (but still observable) airmass. MOP therefore provides controls that let the observer reduce the targets listed to those meeting specific conditions based on target type (or flavor), airmass, and SDSS survey coordinates.

4.4. Observing

The bottom half of the MOP observing and target management window holds the controls that govern observing itself. Several operations, such as focus sequences, CCD initialization and flushing, and twilight flats, simply have corresponding buttons. Other controls can be used to create a sequence of planned observations. The “Observe” button initiates the next planned observation. Observers designate planned observations using the dome frame entry box, the bias frame entry box, and the table of planned targets. If the user has requested one or more bias frames (by setting the “Bias frame” entry box to the number of bias frames desired), the “Observe” button will take a bias frame and decrement the value of the “Bias frame” entry box; if no bias frames are requested, MOP examines the “Dome frame” entry box, and takes a dome sequence if one or more are requested. If no bias or dome frames are planned, MOP begins observing the first target on the list of planned targets.

Additional controls (the “AutoFocus,” “Autopick,” and “Stop after this object” checkboxes) specify activities to take place at the conclusion of the observation:

- if the “autoFocus” checkbox is checked and an appropriate exposure was taken in the last sequence of observations, MOP analyzes the exposure and adjusts the telescope focus if necessary, as described in section 5.2;
- if the “Autopick” checkbox is checked and the exposure just completed was a target exposure (as opposed to a bias or dome exposure), MOP chooses a new target from the available target table (as described in section 5.3) and adds it to the list of planned targets;
- if the “Stop after this object” checkbox is *not* checked, MOP begins the next planned observation. The observation begun and the behavior at completion are exactly the same as if the “Observe” button were hit again.

5. AUTOMATION ALGORITHMS

5.1. Twilight Flats

When an observer initiates a sequence of twilight flats, MOP slews the telescope to a region of the sky expected to be of nearly uniform surface brightness,¹² begins repeated short exposures of the sky, and measures the count level in each resulting image. Because an exponential decline is a good model of the change in sky brightness

during twilight far and from the horizon,¹³ MOP can estimate the required exposure time for future exposures after two unsaturated exposures have been taken. Once observers have initiated a sequence of twilight flat exposures, MOP can be left to complete them automatically.

5.2. Focus

At the beginning of observing, users take a traditional exposure sequence consisting of 5 exposures each taken at a different focus. Observers can then estimate the focus from the size of the point spread function (PSF) of stars taken at each focus value. This procedure requires significant time from the instrument and attention from the observers, and so cannot be regularly repeated during the night.

MOP can make small corrections in the focus by taking advantage of the astigmatism in the PT optics. Because the pixel scale of the PT camera is large enough that PT images are roughly critically sampled even with this optical property, the astigmatism does not significantly degrade the scientific value of the data. Instead, it provides a convenient method for checking the focus. If an image is taken when the telescope is significantly out of focus, the point spread function will be elongated. Because the direction in which the telescope is out of focus determines the angle of elongation, focus corrections can be made based on the angle of elongation.

After an observation of a primary field, MOP automatically measures the ellipticity and orientation of the PSFs of several bright stars near the center of the field of view. If the median ellipticity of the PSFs is small, it does nothing. If it falls within a range typical of that caused by shifting focus, it makes a correction in the proper direction. If the ellipticity is very large (or if too few stars are found), it rings an alarm alerting the observing staff to a potential problem.

5.3. Target Selection

Observers can have MOP choose targets from the available targets list and add them to the planned targets list. They make this request explicitly using the “Pick” button, or use a checkbox to have new targets chosen automatically whenever a planned target is observed and removed from the planned targets list. MOP’s autopick routine has two major components. First, it evaluates the existing list of planned targets to determine what properties are needed in a new target. Then, it evaluates each target in the available targets list for suitability and adds the “best” target to the planned targets list. If several targets are equally good, it chooses randomly among them.

In the first stage, MOP evaluates the list of planned targets to determine which of the following criteria the list has not met:

1. the list should include observations of at least 6 standard stars from the SDSS standard star catalog (“primary standards”), with no single field contributing more than 4 stars to the total;
2. the list should include an observation of at least one primary standard with a red color ($g' - r' > 1.0$);
3. the list should include an observation of at least one primary standard with a blue color ($g' - r' < 0.2$);

Choosing targets to fill these criteria helps ensure that the list of planned targets will include enough standard star observations for the derivation of a photometric solution.

Where possible, MOP also constructs “red/blue pairs.” A red/blue pair consists of a pair of observations of a field containing both red and blue standard stars where the observations are taken at significantly different airmasses. These observations are useful because they form a minimal set from which the extinction and color coefficients of the photometric solution can be derived. They are not used in routine reduction, but have been used occasionally for quality assurance.

When observations of primary standards stars are not needed for the photometric solution, MOP observes secondary standard fields according to their observability and priority.

After evaluating the current planned target list, MOP assigns each target in the candidate target list a score according to how well that field meets the planned target list’s current requirements. MOP assigns points based on the following criteria:

1. Fields which cannot be usefully observed, either because they are too low in the sky or because they are too close to the moon, will not be chosen even if they are the only targets “available.”
2. Fields already present in the current list of planned targets will be avoided if any other fields are available.
3. Fields whose observations are required to complete a pair of observations of red/blue stars will be preferred.
4. Other observations of fields previously observed during the night will be avoided.
5. If the current planned target list contains no red primary standards (where $g' - r' > 1.0$), fields containing one are preferred.
6. If the current planned target list contains no blue primary standards (where $g' - r' < 0.2$), fields containing one are preferred.
7. If the current planned target list contains fewer than 6 standard stars, fields that can contribute more standard stars will be chosen over those that can contribute fewer, and fields whose airmasses at the time of observation will increase the range of airmasses observed will be preferred over those that will not. Recall that no single field can contribute more than 4 to the desired total of 6.
8. If no currently planned fields are red/blue pair observations, a field that is will be preferred.
9. Secondary standard fields listed as higher priority in the mopDB will be preferred over those at lower priority.

This list shows criteria in order of descending point value. In most cases, the point value of a criterium exceeds the total value of all criteria listed later in the list, so that lower priority considerations are important only as tie-breakers between fields of otherwise equivalent value.

As a consequence of this procedure, if MOP begins with an empty list of planned targets, the first two to four fields chosen by MOP will be primary fields covering a range of airmasses and standard star color. Once these target are present in the planned target list, the only targets awarded points are secondary standard fields: further targets selected will all be secondary standard fields. The length of the list of planned targets therefore determines the ratio of time spent observing primary standards to time spent observing secondary standard fields. If the planned target list is maintained at five targets, any set of five consecutive targets observed during the night will contain two to three secondary standard fields, and the remainder of the target fields will contain primary standards.

To test the effectiveness of this method of automatic target selection, we constructed a utility that returns the list of targets this algorithm would choose over a given time frame, letting us examine in advance what fields would be observed on any given night. MOP produced suitable distributions of observations throughout the year, providing enough suitably distributed observations of primary standards to monitor the photometric solution for each night, without taking unnecessary time away from observing secondary standards.

6. DISCUSSION

In addition to the basic set of controls needed to command the PT and its instruments, MOP provides a set of tools for designing, editing, and carrying out a specific type of observing program. Most of these tools were designed for the convenience of a human operator. The automation tools were then built into this framework. Maintaining the “for human” framework allows observers to supervise and intervene in automated observing when necessary without interfering with its proper function.

For example, the target management window was designed to simplify the task of choosing targets from a database to form an observing plan, and to modify the observing plan as conditions changed during the night. MOP provides tools for tracking and displaying important target characteristics, such as what standard stars were present in what fields, and what airmass they would be observed at if they were scheduled for a particular time. The automated target selection routine works within the same framework used by human observers to

choose targets; it simply performs the operations a human observer might. This has two advantages: first, observers supervising semiautomated observing can conveniently track and modify automatically generated observing programs without disturbing automated observing more than desired; and second, the automated target selection can be used as a tool for selecting targets for manual observing programs.

Just as the automated target selection selects targets in the same framework (and using similar criteria) as a human observer, other automated aspects of observing are integrated naturally into the framework used for manual observing. For example, someone observing manually will regularly examine images to ensure stars are present, and use the elongation of the PSF to determine what focus corrections should be applied, if any. MOP's method of automatic focus duplicates this procedure.

The result is an operators program that takes SDSS calibration data with minimal supervision, at the same time providing the flexibility required to conduct variant or entirely new observing programs conveniently. MOP has seen only minimal changes in the past year, over which observers have used it to take SDSS calibration data with routine success; we expect to complete the survey with MOP nearly in its current form.

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