The Sloan Digital Sky Survey monitor telescope system

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1. Introduction

The Sloan Digital Sky Survey† will perform a five color imaging survey of π steradians of the Northern sky to a depth of $m_r \approx 23$ and obtain the redshifts of 10^6 galaxies and 10^5 quasars. The survey will be performed on a specialized 2.5m telescope equipped with a 30 CCD imaging camera and a 4 CCD dual beam fiber spectrograph for spectroscopy. It is expected to take five years to complete.

A five color image of a quarter of the night sky with seeing limited resolution is unprecedented. So is the volume of data to be obtained and archived, $\sim$10 TBytes. The data rates of $\approx$10 Mbytes/sec have precedence only in high energy physics. (Hence the involvement of Fermilab in the survey.)

Such a large and unique dataset deserves and demands an excellent calibration. We have taken as a goal 1% photometry. In normal astronomical projects, one could expect to spend up to half the program time on calibrations to obtain this precision. In project of the scale of the Sloan Digital Sky Survey (SDSS), the cost of this is prohibitive. We have decided to pursue an alternative approach involving a separate telescope to to supply calibrations for the survey data and monitor the photometric conditions of the atmosphere.

2. The Monitor Telescope Hardware System

The monitor telescope (MT) is an equatorial mount 0.6m telescope designed and built by Autoscope. The optics consist of a Hextek primary mirror in a f/10 Ritchey-Chrétien configuration. A Gascoigne corrector is included to provide $0.6''$ images over the entire $40'$ diameter field of view, and a field flattener on the dewar window increases the astrometric precision. Autoscope specializes in automated telescopes, and we have decided to purchase their telescope control system which should enable us to run the MT semi-autonomously.

The MT camera is a Janus dewar containing a thinned, anti-reflection coated Tektronix/SITe 2048^2 CCD at a pixel scale of $0.8''$/pixel. The camera electronics are flexible enough to support a 512^2 array, and drift scanning at variable rates.

The data acquisition system[1,2] was designed and constructed at Fermilab. The center of the system is a VMEbus connecting a host computer (supporting the astronomer) and an instrument control computer (supporting the instrument). The VMEbus connection allows both machines to access shared memory but maintains a separation that allows either computer to continue to function when the other is inoperable.

The instrument control computer (ICC) is a Motorola MVME167 single board computer containing a 25MHz 68040 cpu and 32Mb of memory. The ICC acts as master during data acquisition, controlling the

† The SDSS is a collaboration between the Fermi National Accelerator Laboratory, the Institute for Advanced Study, the Japan Promotion Group, Johns Hopkins University, Princeton University, and the University of Chicago

Figure 1. A block diagram showing the main components of the monitor telescope hardware system.

activities of the front end system. The ICC runs the camera electronics through a RS-232 line and uses a Fermilab designed VMEbus Camera Interface board (VCI) to acquire the data from the camera over a fiber optic link. The VCI buffers the data for the ICC to grab via DMA. Once the ICC has the data it sends it on to a Vigra MMI 250 module that displays the data in real time on a Nanao Flexscan Monitor. ICC writes the data directly to host memory over the VMEbus using a HVE Engineering VME Repeater. This system is capable of obtaining data and writing the FITS files to disk at rates of 461 Kbytes/sec.

The MT host computer (MTH) is a Silicon Graphics 4D/35 workstation with 6 Gbytes of disk and an Exabyte 8500 8mm tape drive. The MTH commands the data acquisition system by writing to a status database residing on the ICC. When the ICC sees relevant commands on the database, it operates without further communication from the MTH. The primary purpose of the MTH is to allow the astronomers access to the data, and to run the on-line analysis code described in the next section.

The monitor telescope data acquisition system is part of an evolutionary program of data acquisition development which started with Fermilab's Drift Scan Camera system[1,3] and will end in the full SDSS survey data acquisition system[2]. The Drift Scan Camera was built as a prototype to the much more complex SDSS system. It is now deployed and obtaining data at Yerkes Observatory. The monitor telescope design was a relatively simple modification of the Drift Scan Camera design to the problem of obtaining staring frames. The SDSS system is considerably more complicated, but still recognizable as a descendent of the drift scan camera system.

3. The Monitor Telescope Software System

Software for the monitor telescope was written in the SDSS standard software environment. Because the collaboration is spread over many institutions and we wish to allow many users to work on the same code, we keep versions of the development code in a central repository using the Concurrent Versioning System software of SLAC. In order to allow the many collaborators to view the documentation, we keep it online in HTML format, allowing use of the Xmosaic program to browse it via the World Wide Web. We enforce a standard directory hierarchy for each software product in order for us to use a flexible makefile system to maintain links to the many libraries in our code.

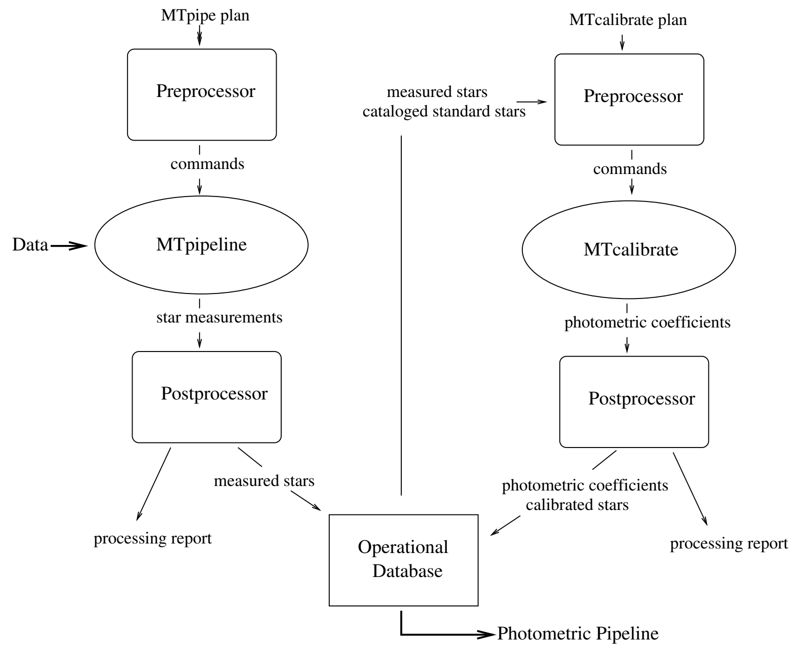

Figure 2. This block diagram shows the flow of the off line monitor telescope pipeline. The main pipelines, shown in the ellipses, are written only in Shiva and ANSI C to maintain maximum portability. All communication between processors is carried it with FITS format files. Only the pre– and postprocessors interact with the database.

We have assembled several public domain software packages to form the foundation of an analysis environment. We chose Tcl[4], a UNIX-shell like programmable command interpreter as our central language. Because it is an interpreted language, it is easy to program in, the price paid in speed of execution. For uses that require more speed or flexibility we have provided standard interface routines so users may add their own C, C++, or Fortran code as extensions. We also added interfaces to PGPLOT from CalTech for use as our plotting package, and a modified version of SAOIMAGE from the Smithsonian Astrophysical Observatory as our display package. Since we run Tcl even on our VME instrument control computer, we have added the Fermilab instrument error reporting package MURMER.

These packages were merged into an analysis package named Shiva[5]. Shiva is designed to manipulate large images quickly. Perhaps the largest difference between it and IRAF is that Shiva maintains the images in memory in between processing steps rather than on disk. Shiva provides support for regions (as the memory resident images are called), masks, and C–like structures in a Tcl environment. The Tcl heritage of Shiva makes it fast and easy to program and debug further extensions. Shiva was designed for pipeline reductions, in which large amounts of data are reduced in an industrial fashion. All of the survey pipelines are written in Shiva.

There are two pipelines associated with the MT. These are diagrammed in figure 2. The frames pipeline, on the left in the figure, takes raw data and locates and measures the bright stars therein. The measurements are stored in a survey operational database (we use a Versant object-oriented database). The second pipeline is the calibration pipeline (on the right in the figure), which takes the measurements of the stars and the known standard star magnitudes and determines the photometric solution. The solution itself is found by MTcalibrate and is simply a least squares matrix inversion. Much of the complexity lies in the pre– and postprocessors interacting with the database. Basic problems are taking Shiva structures and filling C++ objects with them and retrieving the appropriate measurements from the database and

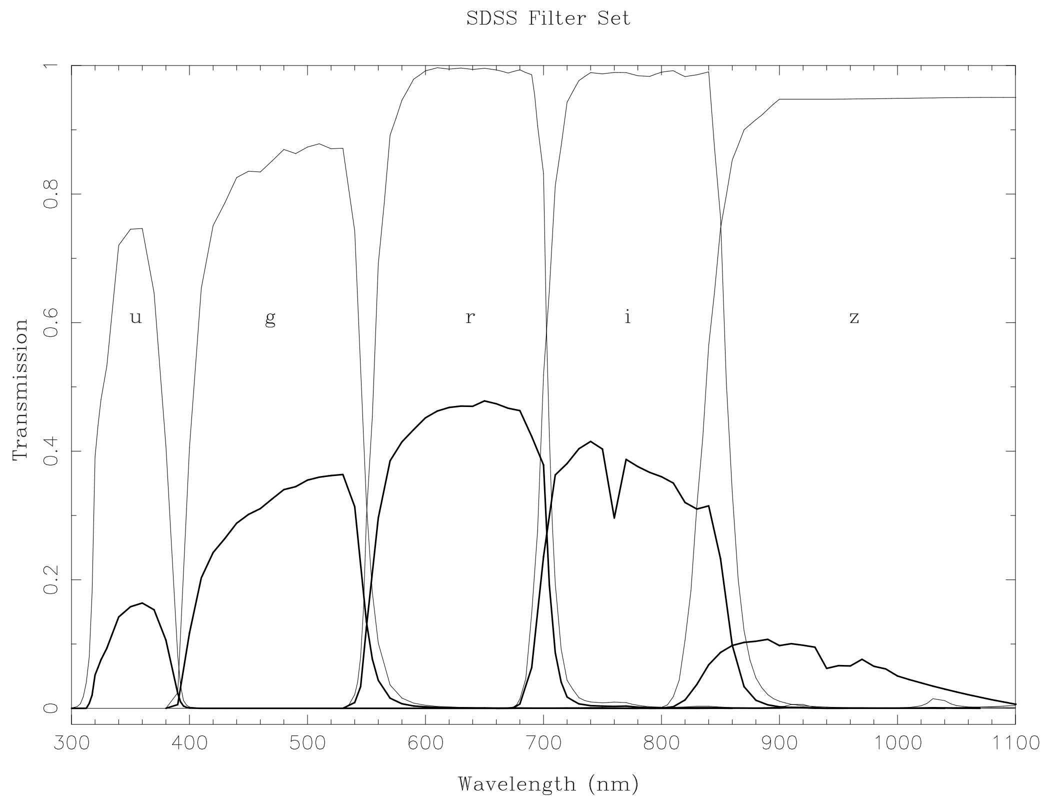

Figure 3. The SDSS filter set. The light curves show the transmission of the filters alone. The dark lines show the effective transmission after including the effects of the atmosphere, telescope, and CCD.

putting them into a form usable by the pipelines. Once the photometric coefficients are found, for instance, they must be stored in a calibration object in the database, with appropriate date and time stamps for easy retrieval.

A second set of code on the MTH prepares an observing program of standard stars for each night. The survey calibration fields are incorporated as they are sent from the survey host computer during the night. Once the data are obtained, they are sent through the MT on–line analysis code. The purpose of this is to determine the photometric coefficients on hourly timescales and report them to the observers running the survey camera. The observers use this data to determine whether the night is sufficiently photometric to continue with imaging or whether spectroscopy is called for. The on–line code is a version of the off–line code. The primary difference lies with the pre– and postprocessors interacting less with the Versant database. The pipelines themselves, MTpipeline and MTcalibrate, will be identical.

4. The Monitor Telescope Standard Star System

The primary scientific product of the monitor telescope will be the establishment of a new high precision photometric system. We have chosen a filter set related to the Thuan-Gunn system[5]. It is not a standard system, but because the SDSS will provide two orders of magnitude more photometry than currently exists it seems reasonable to optimize the survey filters for throughput, transmission, and wavelength coverage. We have chosen the *ugriz* filters shown in figure 3 as our standard filter set. A full description of the system will be postponed to a later date.

We will choose a set of 20–30 stars over the entire survey region to be the standard stars. The standards will be fairly bright ($m \approx$10–12). The standards will include a subset of the Oke–Gunn[6] standards to place our system on an absolute energy flux density scale. We will, in any case, need to define a similar set of spectrophotometric standards in order to calibrate the spectrophotometry. The survey standard stars will be observed multiple times on most photometric nights for 5 years.

5. Monitor Telescope Operations

5.1 The operational plan

The survey camera itself will not be obtaining photometric calibrations. The pipeline which reduces the imaging data will be calibrating the objects along a scan by using equations of the following type:

$$g = g_o - a_0 - a_1 X - a_2(u - g) - \ \ldots \tag{1}$$

where u, g are magnitudes on the survey filter system, g_o is the observed, instrumental magnitude, X is the airmass, a_0 is the photometric zeropoint, a_1 the extinction term, and a_2 the color term. The question is how many of these coefficients the monitor telescope can determine, and how often does it is required to do so. Since this is central to our 1% accuracy goal, we will examine this in some detail.

The zeropoint – The survey camera scans along great circles on the sky. This necessitates placing the camera on an instrument rotator to keep the CCD columns aligned with the direction of rotation of the earth. Since the rotation causes the CCDs to see different optics as a function of time, it will undoubtedly induce variations in efficiency. The time scale of variations is unknown; a reasonable guess is an hour. This sets the required frequency of measuring a_0. The monitor telescope cannot directly measure the a_0's for the survey telescope as they are different for each telescope and CCD. It is possible, however, to provide the survey camera with stars of known magnitudes every hour.

Our scheme is to designate certain places along the scan as calibration patches (see figure 4). The survey camera has 30 CCDs placed in a 6×5 array, with 6 columns perpendicular to the scan direction, each column containing 5 CCDs. Each of the rows has a different filter. Each column is separated by slightly smaller than a CCD width, so a scan consists of 6 separated scan lines. A second scan offset from the first is needed to fill in stripes. We need to calibrate all 30 CCDs of the survey camera, which we can do by obtaining five color images on each scanline. We can do so by placing calibration patches every hour along the scan. The field of view of the monitor telescope covers two scanlines so in a given night we can observe 3 patches in a 15° strip. When the survey camera passes through the region for a second time to fill in the stripe gaps, we will again observe 3 fields, thereby gaining zeropoint calibrations for for each scanline every hour along the strip.

The extinction – The great circle scans vary in airmass as a function of time. To calibrate the survey scan we need a measurement of the extinction during the night, preferably every hour. Since the extinction is an atmospheric phenomena, a measurement of a_1 by the MT should be valid for an entire site. The MT will observe six standard stars an hour in all five filters and the online system solving equations of the form:

$$g_o = g + a_{0,m} + a_1 X + a_{2,m}(u - g) + \ \ldots \ , \tag{2}$$

where the subscript m denotes coefficients applicable only to the monitor telescope. The coefficient a_1 so measured can be applied directly in eq. 1.

The color terms – This leaves the color term coefficient, a_2. The monitor telescope will define the SDSS filter system. The MT will use the same CCD and filters that the survey camera does, but inevitably there will be a slight mismatch inducing small color terms. From previous experience, we know that such color terms vary only slowy over time.

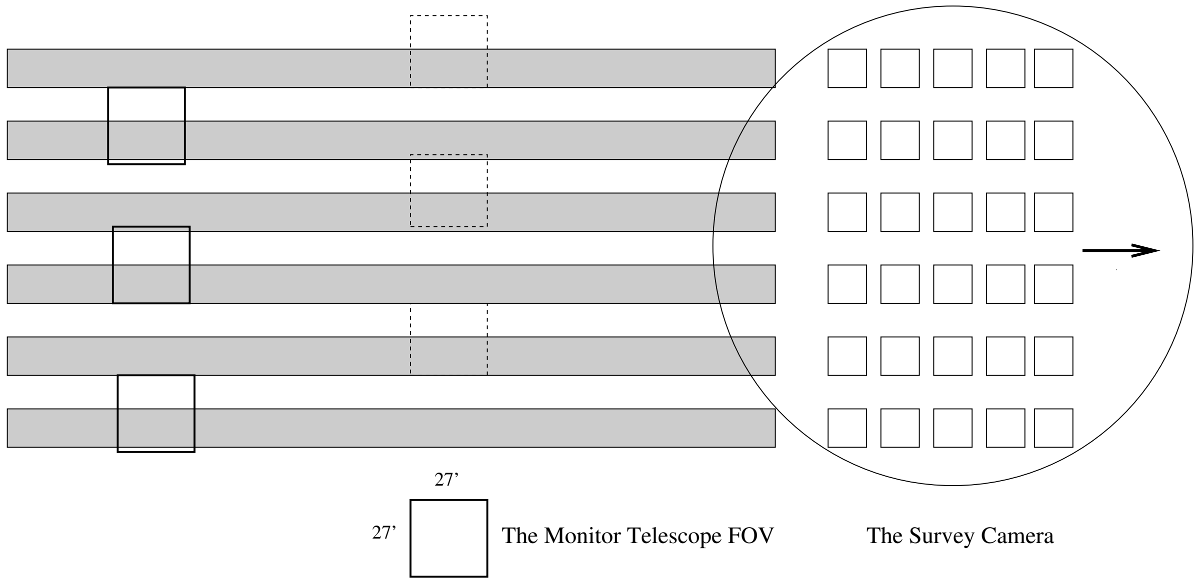

Figure 4. The layout of a calibration patch with a schematic of the survey camera. The filled in regions represent 20 minutes of a survey scan. The boxes are the monitor telescope field of view. During a single night the MT will observe three fields, shown as squares on the strips. When the second scan is made to fill in the stripes, the MT will observe the three dashed squares, thereby providing measurements of all 12 scanlines on an hour timescale.

We will designate a small number of color calibration patches in order to measure a_2. Each patch will be a single monitor telescope field known to have a collection of stars with a wide distribution of colors. All six scanlines of the survey camera will be run across the field individually. We plan to do this once or twice per month. The colors of the patches will have to known very well, but there will be only a few such patches and they will be in continuous use over the 5 year survey.

The calibration of the survey – Given that we know a_2 from the color patch scans, a_1 from the monitor telescope measurement of that hour, and the known magnitudes g of the stars in the calibration patch (again from monitor telescope measurements), the photometric pipeline preprocessor can solve for the survey camera's a_0's via:

$$a_0 = g - g_o + a_1 X + a_2(u - g) + \ \dots \tag{3}$$

From thence the pipeline can calibrate the survey using eq. 1, by interpolating the a_0 between calibration patches along the scan and interpolating a_1 between measurements of the monitor telescope. We intend to measure the magnitudes of the calibration patches as close in time to the survey scan crosses them as possible. This is made easier by the survey strategy to use only truly photometric nights with seeing $\leq 1''$ for the imaging survey, and to use other nights for spectroscopy.

5.2 Spectrophotometry

During the nights spectroscopy is being performed, we will follow a similar scheme to calibrate the spectra. We will identify 2 or 3 F–subdwarfs (using the imaging data) in the $3°$ circular field of each spectroscopy plate. Fibers will be allocated to observe these stars as standards. The MT will observe them with ten 10nm wide filters ranging from 350nm to 950nm, calibrating them with a photometric program similar to that described above but using the spectrophotometric standards.

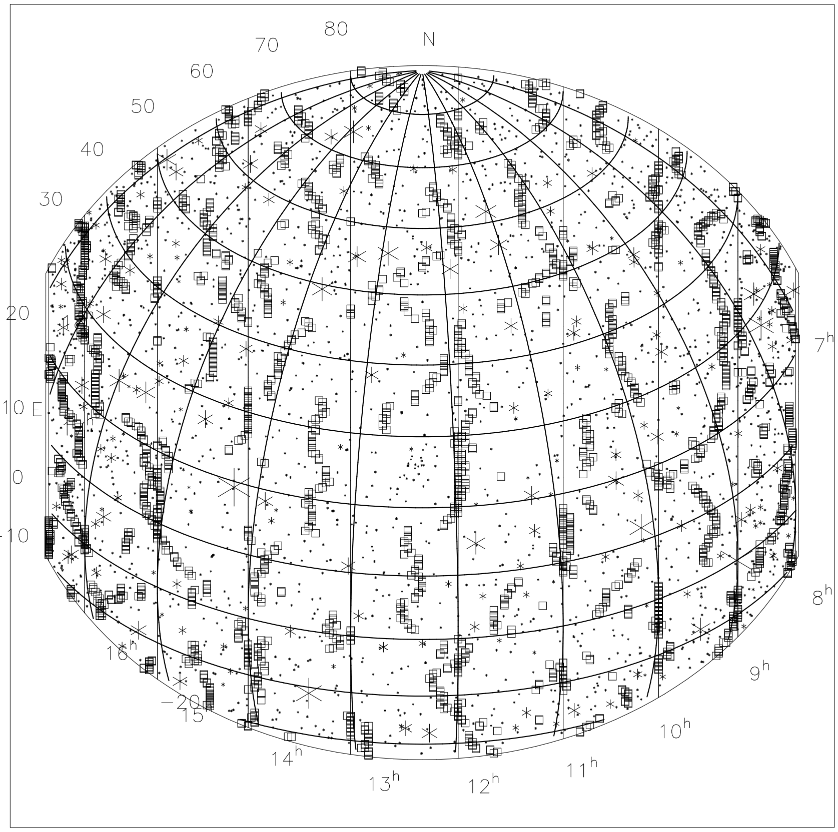

Figure 5. The location of the calibration patches on the sky. This plot shows the entire survey region. The dots and asterixes are the stars of the Yale Bright Star Catalog with the size of the symbol proportional to the star's magnitude. The vertical lines are spaced every 15°, the nominal spacing between zeropoint calibrations. The squares are each a monitor telescope calibration patch. Each patch was placed using an algorithm that avoids the bright stars, weighting with the square of the distance.

5.3 The timing

The monitor telescope will be busy on photometric nights. The need to determine the extinction every hour requires observations of 6 standards in an hour. Calibrating the survey requires observations of three calibration fields an hour. An estimate of the timing can be made assuming 60s for slewing to the field and 5s for moving the filter. Then for the standards we will take 10s exposures, and read out the central 1024^2 in 8s. That is 23s per image; we need one image per color (115s total) plus a slew to the field to give 175s. We do this six times an hour and use 17.5m. The calibration fields require a full 2048^2 readout requiring 32s. For the gri filters 60s exposures will suffice (97s with filter move and readout), while for the u and z bands 120s exposures will be necessary (157s per image, total). For all five images, plus a slew, we need 665s, and we need to do this 3 times using a total of 33.3m. Performing the extinction and calibration measurements, then, will take us 50.8m. We retain a 20% safety margin for the inevitable time budget overruns.

5.4 The volume of the data

The volume of the data to be obtained is large. One can get a feel for this by looking at figure 5, which shows the location of the calibration fields over the survey area.

During a night of operation, we expect to obtain 1.4 Gbytes, comfortably filling an 8mm tape. If we assume 1 week of photometric time per month, and operate 11 months a year for 5 years, we see that we will obtain 554 Gbytes, or roughly 400 8mm tapes. The spectroscopic data will likely fill an equal amount of space, accounting for data obtained during non-photometric time. The full calibration dataset will be on order of a terabyte in size.

6. Summary

We plan to calibrate a large Northern sky imaging survey by using a 0.6m monitor telescope. The data acquisition system is a robust, fast VMEbus based system. A workstation is attached to the bus, providing a means to reduce the data as they are taken and thus to measure the photometricity of the night. The monitor telescope observations will measure extinction every hour and calibrate survey fields three times an hour. These data should be sufficient to calibrate the survey data.

The monitor telescope system should be operational in July, 1994. We will spend the next year testing this novel approach to calibrating long drift scans, and establishing the standard star network.

7. References

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