Automating a Telescope for Spectroscopy

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Abstract

This paper discusses the automation of a backyard telescope system for multiple resolution spectroscopy surveys. The author will first review the optical & mechanical configuration and required modifications. Then he will describe the unique software implementation using multiple virtual machines to fully automate object selection, acquisition, and auto-guiding of two spectrographs and a photometry camera. The system described is now in operation on most clear nights.

1. Introduction

Spectroscopy is a fascinating area of amateur astronomy. Most amateur spectrographs, including mine, have been designed for manual or manually assisted operation. Long exposures for objects and calibration frames limits the productivity of the system to the sleep needs of the observer and makes it difficult to obtain time-series data.

Commercial software written for the automation of imaging is not well adapted to the kind of multiple camera sequences needed to acquire objects, position them onto slits, and control calibration lamps.

This project began with goal of automating my DSS spectrograph and then quickly expanded to include the co-mounted SGS instrument and to support photometry.

2. Telescope Configuration

The system consists of two optical tubes mounted in a piggyback configuration on an overloaded G-11 mount equipped with an Astrometric Instrument's Skywalker® 2 positioning system.

The upper subsystem is a Celestron® 8 with manual flip-mirror followed by an f6 focal reducer and an SBIG® SGS spectrograph (R~2500) with and ST-7E camera. There is a fiber optic leading to the calibration lamp and. A motor operates the wavelength setting.

The main system is a Celestron 14 OTA. The optical stack begins with a 2 inch filter selector (V, I, Clear) followed by an Optec® TCF focuser, and a motorized flip mirror.

The right angle arm of the flip mirror contains an Optec NGW focal reducer, a CFW-9 filter wheel and an ST9XE imaging camera, which operates at f6.5 and provides a 15 arc-minute FOV. The axial port of the flip mirror contains a pellicle guider port (8% of the light is deflected) with another strong focal reducer and an SBIG Remote Guide Head (connected to the ST9).

The axial path from the pellicle connects to the SBIG DSS-7 Spectrograph (R~400) with an ST7E camera. A fiber enters the mechanical assembly just above the DSS-7 slit and leads to the calibration lamp.

The assembly uses about 22 inches of back focus, which brings the system to about f/13.7. The key design consideration is that all three of the imaging cameras (the ST9, the Remote Guide Head, and the DSS slit) are par focal. This allows the temperature compensation feature of the Optec TCF focuser to maintain focus through the night.

3. Automation

The mount and cameras are supported by scripting of standard Software Bisque®, SBIG, and Astrometric software.

The flip mirror, pellicle guider, SGS wavelength setting, and calibration lamp were created for this system.

The flip mirror is a standard Meade® 647 assembly. A Celestron Motofocus® unit is attached to the side using a C-8 knob adaptor to connect the motor to the existing metal knob. An L-bracket connects the motor and flip mirror housings. The flip mirror has hard limits to rotation that define the two optical paths. The motor connection is an o-ring slip clutch. To switch positions the motor is simply driven for about 3 seconds in each direction to reach the limit.

The motor, in turn is connected to one output of a switching assembly I call the "motor multiplexer". The other side of the switch connects to the output of a JMI® PCFC USB programmable focus controller.

The multiplexer itself consists of a set of X-10 "universal modules." These are low voltage SPST relay controllers. They are arranged in pairs. On pair connects the flip mirror motor, another connects the SGS wavelength motor, a third pair will be used for the future control of the wave plate rotator. This multiplexer assembly allows any number of motors to be operated by a single PCFC motor controller by adding switches.

An X10® Home Automation Pro USB controller allows programmable operation of each of these switches and of another X10 Appliance module use to operate the calibration lamp. While only 5 switches are currently in use, the X10 power line signaling mechanism provides support for up to 256 devices. The downside of this inexpensive solution is that it takes about 2 seconds to activate a switch.

4. Software Architecture

The core of the system is implemented on an Apple Macbook running OS X version 10.4. All data files and control information are kept in a set of directories in the Mac file system.

Within the native OS X environment, two Parallels® virtual machines run the Windows® XP operating system. Multiple virtual machines are used to get around the limitation of CCDSoft® to support only one imaging and one guide camera. In my system, each VM can support an imaging and a guide camera, and the selection can be changed dynamically.

Each of the virtual machines (called simply VMOne and VMTwo) runs the Software Bisque Orchestrate® application as well as CCDSoft® and other programs. Once started, Orchestrate waits until a text file appears in a pre-designated Inbox folder. Each of the virtual machines has its own Inbox folder that is, in turn, hosted in the Mac OS X file system.

The automated observing process is implemented by a collection of custom programs running in all three environments. These programs which interact via common file directories. From the Windows VM's, these are seen as logical drive W.

The primary directories are "ScopeActive", "ScopeResults", and "ScopeProjects".

ScopeActive contains a set of small files that represent the status of the current observing task and instrument settings.

ScopeResults contains a folder for each observing project and a subfolder for each observing target within which all images and data files for that object will be stored.

ScopeProjects is subdivided into 4 time period folders (Day, Evening Twilight, Night, and Morning Twilight). Within each of these folders are placed the observing project files.

5. Observing Projects

An "observing project" is a text file. Each line of the file represents one target. Each project can contain from 1 to several hundred targets. There can be any number of observing projects within each of the top-level time period folders.

An example of an observing project might be the set of B(e) stars brighter than 10th magnitude.

One line of text is used for each target. This line is divided into three sections. The first is the name of the target. The second is the "repeat period", i.e., how often to observe the target. The third section is the description of the observations to be made of the specified object. This is written in a simple format with designates the instrument and exposure time and number exposures. For example:

```
GVVS Beta Lyr ;  2;  DSS:30 SGS@Ha:300*3 V:15 I:20
```

This line tells the system that the user wants to observe Beta Lyr every two hours, if possible. Once the object is acquired, the system is to take a 30 second exposure with the DSS spectrograph, and three 300-second exposure with the SGS spectrograph set to the wavelength of Hydrogen Alpha, and photometry images in V-Band for 15 seconds and I-Band for 20 seconds.

Because this system was designed for survey and time series work, the user does not specify the order of observations. Many of the objects listed within one project may be unobservable on any given night.

6. Target Selection

To start the system, the operator manually loads a command file into the VM1 Orchestrate application. This file contains three commands. First off is a "Wait" command that is used to allow manual interruption of the sequence. Second is a "RunIdle" script that prevents the telescope from reaching the meridian limits when nothing is being observed. Finally is the "SelectTask.vbs" command.

SelectTask.vbs is complex procedure written in VBScript that determines the next target to be observed and then compiles an object specific observing script to implement the desired observations.

If SelectTask determines that nothing is to be observed, it creates a new file containing the Wait, Idle and SelectTask commands and puts this file into the VMOne inbox. This causes the Wait-Idle-Select process to repeat indefinitely. We call this the "idle loop."

6.1 The SelectTask Process

The first step is to determine the current altitude of the Sun and the Moon. The sun angle is used to determine which of the top level ScopeProjects folders (Day, EveningTW, Night, MorningTW) is used for as a source for targets. Only targets within the current folder are evaluated, so the scope idles during the day.

Next, a list of the observing project files is constructed and each of the files is read line by line. Each line is defines an observing task as previously described.

The SelectTask procedure makes extensive use of Software Bisque TheSky® database. The script takes the object name from the task line and looks up the object in TheSky's database. From this the current altitude and azimuth, hour angle, magnitude and other data are retrieved.

Objects must pass through a series of tests before they become true candidates for observation.

First we find out how much time has passed since the last observation of this object and compare it to the repeat period.

Next we use the hour angle to determine if the object is viewable by the telescope.

Next we check the angle from the Moon. Based upon the phase, a "moon avoidance" angle is determined. Objects within this angle will not be observed.

Next we preprocess the task description to determine the required observing time. Using this and the hour angle, we determine whether or not the observation can be completed within the remaining time before either the mount flip angle or the western horizon is reached. This is a real issue for spectroscopy as an observation can easily require more than an hour.

For those candidates that remain, a score is computed. The task with the highest score is selected for implementation. The scoring process gives extra weight to those observations that must be done soon to avoid horizon problems. Other factors include airmass and whether or not the object has been previously observed with priority given to first time targets.

7. Observing Scripts

The output of SelectTask is an Orchestrate script custom generated for this target. The script consists almost entirely of "RunVBScript" commands that execute the observing modules that I have written. There are about 30 modules currently in the system including the following that are described in this paper:

- *"SetupTask.vbs"*
- *"CenterTarget.vbs"*
- *"TakeSpectra.vbs"*
- *"DSSImage.vbs"*
- *"SetCamera.vbs"*
- *"FlipMirror.vbs"*
- *"TakeSGSSpectra.vbs"*
- *"SGSSpectra.vbs"*
- *"TakeImage.vbs"*
- *"ReportResults.vbs"*

The observing script is loaded into the inbox of VMOne. This VM has access to the ST9 camera and its remote guide head via CCDSoft as well as to the telescope positioning (via TheSky Telescope API).

As the script executes, it will construct and issue additional scripts for VMTwo, which has control of the flip mirror, wavelength selector, and both of the spectrograph cameras.

The two scripts communicate status and monitor completion of each other via a series of predefined files in the ScopeActive shared directory. These files contain the details of the current observation as well as the current position of the flip mirror, the current spectrograph camera, and other parameters.

Each of the observing modules observes checks a "TaskStatus.txt" file as it begins. If this file contains the word "NO" then the module exits. In this way a failure to acquire, for example, stops the entire process quickly.

8. Typical Observation Sequence

SetupTask.vbs – This module will reset all of the system flags to initial values. It will access the object from "TheSky" database and create a file recording the name, magnitude, RA, DEC, and the file folder to be used for recording data from that object along with a few other parameters.

CenterTarget.vbs – This will slew the telescope to the coordinates specified by SetupTask. Then an image will be taken. Based upon the magnitude of the object, one of two procedures will be followed. If the object is dim, the CCDSoft InsertWCS image mapping function will be used to find the coordinates of the object with respect to the image. Then a correction will be applied and the process repeated until the target point falls within a ±10 pixel window.

For bright objects, the maximum value in the image will be checked. If it is close to saturation, then the system assumes that the brightest star in the field is the target; it then uses the "inventory" function of CCDSoft to get its coordinates and makes adjustments until the target falls into the window.

Once the object is in the desired position, CenterTarget terminates.

The target point is simply a set of XY coordinates that identify where the DSS spectrographs slit is with respect to the ST9 image. These are set in a semi-automated procedure ahead of time. Once set, they remain valid until the unit is disassembled for service or some other adjustment. This stability is the result of a very solid "back end" and supporting clamps on every connector.

TakeSpectra.vbs – This is the key procedure for the DSS instrument. When started, the target is supposed to be within a 10 pixel box (~20 arc sec) surrounding the slit.

The first action is to issue a script to VMTwo. This script executes the FlipMirror.vbs procedure. When the VMTwo script is complete, the mirror will have been moved to the "Spectrograph", i.e. the inline position.

FlipMirror.vbs first connects to the X10 object and sets the muliplexer switches so that the PCFC motor controller is connected to the motofocus attached to the flip mirror. Next it loads CCDSoft and, after a delay, connects to the focuser controller. It then sends a 3 second motor move command to the PCFC via the CCDSoft focuser API. Finally it sets the status file called "MirrorStatus" to "SPECTROGRAPH" and exits.

Meanwhile, the TakeSpectra.vbs procedure has been waiting for this flag to change. Once set, TakeSpectra begins the auto-guiding process.

The Remote Guide Head of the ST9 is used to auto-guide the DSS spectrograph. The coordinates of the guide point are preset in the system configuration files. The auto-guiding process is initiated using an exposure time based upon the magnitude of the object ranging from 0.1 to 10 seconds.

At this point the target star should be within the guide window. The position of the star is monitored using the guide error values returned by CCDSoft. Once each second the errors are examined. When both the X and Y errors fall within 2 pixels of the guide point, the object deemed to be locked onto the target.

Once the target is locked, the TakeSpectra.vbs procedure writes yet another script file and loads it into the inbox of VMTwo.

This script runs the rather complex task called "DSSImage.vbs" in VMTwo. While all this is happening, the script in VMOne is auto-guiding and waiting for a "DONE" flag to be set by VMTwo in the common files directory.

DSSImage.vbs – This begins by connecting to the DSS camera. Then the temperature set point is set and the system waits until the camera has cooled to the target temperature. The first spectra of the evening will take longer that subsequent ones because of the need for initial cooling. The cooler will be left on for the rest of the night.. Once the temperature has been achieved, a series of one or more spectra images is taken. Each is named according to the object name and stored in the directory designated by SetupTask.

Next dark images are obtained unless a sky spectra has been previously captured (this is one of the observing task options).

The spectrum images are median combined. The sky or dark images are also median combined. The resulting images are subtracted and stored.

The next step is to extract the spectra from the image. This is complicated by the fact that the spectrum is not exactly aligned to the rows of pixels. The system has an algorithm to find the center point of the spectral profile at the 25% and 75% points. Using these two Y values the center point of the spectra is interpolated across the image. Then a 5 pixel wide binning window is used to extract the data and generate the intensity values for further analysis.

Although considerable effort has been expended to avoid false identification of the spectrum body some noisy images still require manual analysis.

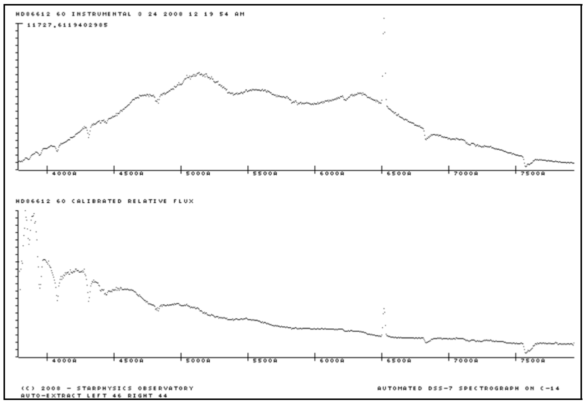
Next the pixel values (1-752) are calibrated into wavelengths. This is done using a table created earlier from a spectrum of Vega. Every spectrum on the DSS will have the same wavelength transformation so long as the mechanicals are unchanged. Generally a Vega or other A type star spectrum is taken each night to ensure proper calibration.

Once the wavelength of each pixel center is determined, the relative flux of each pixel can be calculated.

The Flux calibration originates from the same Vega spectrum used for wavelength. First the intensity of each pixel was divided by the known flux of an A2V star using the tables of Pickles. Next the resulting curve was modified to remove all the prominent Hydrogen and atmospheric lines create residual "bumps" because of the low resolution of the data and the flux standard tables. The missing segments are reconstructed by interpolation and the resulting table of response factors is smoothed by a moving average and stored.

It is this table of wavelength indexed response factors that is applied to the newly acquired spectra to produce a flux and frequency calibrated data set. The data set, containing the pixel numbers, intensity, calibrated wavelength, and calibrated relative flux is stored as a file associated with the observation.

Finally this data is used to create a .GIF image using CCDSoft. This is then available for immediate viewing.



Graphs of raw (upper) and flux calibrated (lower) intensity of the B(e) star HD86612 taken on March 24, 2008 at 3:31 AM by the DSS-7 spectrograph in a 60 second exposure. Calibration and graphing are done during the observing process.

Note that the image processing itself cannot be done in VBScript. For this purpose a custom Visual Basic 2008 COM-scriptable library was created which is called by the VBScript procedure to extract the spectra and generate the graphics. Details of this process can be found on the Starphysics website.

Once the graph has been stored, the DSSImage.vbs process sets the "DONE" flag that VMOne is waiting for and exits.

When the TakeDSSSpectra task finally sees the DONE flag, it terminates the autoguider. Then it sends yet another script to the VMTwo inbox to set the Flip mirror back into the right angle, CAMERA, position. When this is confirmed, TakeSpectra.vbs finally exits.

If photometry is requested for the object, the SelectTask.vbs procedure will compile one or more "TakeImage.vbs" command into the observing script.

TakeImage.vbs simply sets the filter and takes one or more images. These are named for the object and stored into the object's preset results folder. No photometry analysis is done in the current implementation.

If an SGS spectrum is required, the observing procedure will include two more commands, "CenterTarget SGS" and "TakeSGSSpectra.vbs."

Since the SGS camera is on a separate OTA, it is difficult to get the two scopes in perfect alignment. So we compromise by simply finding the point on the ST9 image that corresponds to the slit on the SGS. Once established, these parameters remain valid for an extended period of time. This target point is not the same as the DSS target point, so the scope must be moved to the new point before proceeding. The same methods are used as before depending upon the brightness of the object.

The **TakeSGSSpectra.vbs** procedure is a much simpler version of the DSS procedure. All it has to do is to create a script for VMTwo and wait for it to complete. The flip mirror is not moved.

The VMTwo process is more complex. First we need to switch cameras from the DSS ST7E to the SGS ST7E. Both of these are accessed as Ethernet devices at fixed addresses on the local observatory network.

The "**SetCamera.vbs**" procedure first forces the CCDSoft application to terminate. It then waits 10 seconds for this to complete. Next it set the IP address of the desired camera into the CCDSoft tables in the Windows system registry. This is easily done using VBScript. Finally it restarts the CCDSoft application and connects to the camera. This whole process switching process takes less than 20 seconds.

Next the VMTwo script runs the "**SetLambda.vbs**" process to set the position of the grating in the SGS to collect the desired portion of the spectrum. Again the X10 controller is used to set the multiplexer switches to connect the PCFC motor controller to the small focus motor that drives a belt to the micrometer on the spectrograph. First the micrometer is driven in blindly to reach a limit set mechanically by a screw and lever assembly. Next the motor is reversed to move the micrometer from this known starting point to the desired wavelength. This process sets the central wavelength to and accuracy of about 20 Angstroms, a small fraction of the 750 Angstrom bandpass.

Now the "**SGSSpectra.vbs**" process executes. First it establishes a temperature set point and waits for the camera to cool. Next, it takes a guide image using the SGS guide camera. This image spans about 8 arc minutes. We use the CCDSoft inventory function to find the brightest star in the image and then use the move commands to center the object onto the slit (whose coordinates are prestored, but which never moves). When the object is within a few pixels of the target point, the system is switched into autoguiding mode and waits until the guide errors are less than 2 pixels. Once this is achieved, one or more spectral images are taken and stored. Following this, a dark image is taken. Finally a 60-second calibration image is taken. To do this, the X10 controller and an appliance module are used to turn the mercury or neon calibration lamp on and off.

Once the images have been obtained, the SGSSpectra.vbs task sets a DONE flag, which causes the TakeSGSSpectra.vbs procedure on VMOne to finish.

The final step in each observation is the invocation of the "**ReportResults.vbs**" procedure. This creates a simple text message about the observation. This file is placed into an OS X folder of result messages. Doing so triggers an OS X process that converts the message to an email and sends it to the user as well as to an audible message reading device.

When the last step in the observing procedure is done, Orchestrate loads the next procedure from its inbox. This is always another "Wait-Idle-Select" script.

9. System Experience

The system has been in development for about four months as this paper is written. Most of the time to date is considered to be engineering time as various parts of the software have been brought online and debugged. Not surprisingly, there have been many issues to resolve when running with real images, wind, clouds and the interaction of 6 computers and 4 USB devices. On the best evenings the system has observed over 30 targets and obtained spectra automatically using both spectrographs.

The biggest hardware problems have been related to the support of the USB devices in the virtual machines.

Now that most of the programming bugs have been removed, the most serious of the remaining problems is the plate solving weaknesses of CCDSoft, which cause many false negatives. The other major problem comes from the backlash and stiction of the overloaded G-11 mount. These mechanical problems extend the centering and autoguiding setup times, reducing system throughput.

10. Conclusions

It is not only possible to automate small telescope spectroscopy, but relatively easy to do so. Only about 2 weeks of programming and testing were actually required to get the first fully automated DSS image. More important, the science output of the telescope has increased by a factor of 10 in comparison with purely manual operation. The ability to collect data all night allows time series spectra to extend across entire seasons. All in all, this has been a very satisfying project.

11. Future Work

The next step for the instrumentation is to add a rotating wave plate into the ST9 optical path. This, working in conjunction with the Savart plate that is already installed in the CFW9, will enable high precision linear V-Band polarimetry of many stellar objects.

The next step on the software side is to more fully automate the data pipeline so that both spectra and photometry data are delivered in IRAF and AAVSO formats without manual intervention.

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