Remote and Robotic Operation of the Dominion Astrophysical Observatory 1.2 m Telescope and McKellar Spectrograph

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ABSTRACT
We present a summary of efforts to automate the operation of the Dominion Astrophysical Observatory’s (DAO) 1.2 m telescope located at the Herzberg Institute of Astrophysics in Victoria, BC. The telescope is used exclusively for the acquisition of stellar spectra with the McKellar coudé spectrograph, configurable with a variety of gratings and cameras to provide resolutions up to $R = 60,000$. Starting in 2004, approximately 30 to 40% of the time allocated on the telescope has been conducted robotically on a shared-risk basis. The telescope can also be operated by staff remotely from anywhere in the world. Incremental enhancements have enabled increasingly sophisticated remote, automated operation of the telescope and subsequent data processing including radial velocity measurements. Future planned improvements include an increase in the wavelength coverage and maximum resolution with the acquisition of new CCDs, integration of the DAO all-sky camera and cloud detection software with the automated operation of the telescope, improvements in target selection and tracking, and real-time archiving and processing of the acquired spectra. Programs conducted with the automated system have included continuous monitoring of single bright stars, bi-weekly and monthly monitoring of spectrum variables as faint as $V = 10.5$, and surveys consisting of hundreds of targets.

Keywords: Autonomous Telescopes, Remote Observing, Spectrographs

1. INTRODUCTION
The 1.2 m telescope at the Dominion Astrophysical Observatory (DAO) began operation in March 1962. It is used exclusively at the coudé focus where the McKellar spectrograph, configurable with a wide variety of gratings and two cameras, provides resolutions up to $R = 60,000$. Three available coudé mirror sets (mirrors #2 through #5), with high-reflectivity enhanced aluminum, super blue, or silver coatings, are rapidly interchangeable and self-aligning. Wavelength-optimized Richardson image slicers are used at the entrance slit to ensure high throughput. The two available spectrograph optical paths include the 32 inch (short) camera which can be paired with one of six available gratings to yield dispersions ranging from 5 to 41 Å mm$^{-1}$, and the 96 inch (long) camera which, coupled with the 830 g mm$^{-1}$ grating mosaic, provides 4.8 Å mm$^{-1}$ spectra in first order and 2.4 Å mm$^{-1}$ in second order. Corresponding resolutions for all of the possible spectrograph configurations range from 0.07 to 1.2 Å. The SITE-4 2K×4K CCD provides 150 Å of wavelength coverage at the highest resolution.

2. THE CHALLENGE
Both of the DAO telescopes faced mounting challenges beginning in the 1990’s. DAO service observing support was discontinued in the early 1990’s because of staff reductions and reassignments. The latter occurred because of the changing priorities which arose from the development of new NRC-supported facilities such as the CFHT, JCMT and Gemini observatories and, more recently, TMT and ALMA. The two DAO telescopes have obviously become quite modest facilities in the Canadian (and global) astronomical landscape.

Until recently, because of the lack of service observing support, astronomers interested in using the DAO facilities for their own research have had to travel to Victoria to carry out their observing programs. This might be fine during the spring and summer months, but the infrequent (but long!) usable nights from mid-October through mid-March tend to discourage possible applications for DAO telescope time from astronomers outside of Victoria during the Canadian winter because of the risk of having a completely unproductive observing run.
The availability of new, larger observing facilities, combined with a decrease in the number of local users interested in the capabilities of the DAO telescopes, the lack of DAO service observing support, reduced basic telescope and instrument maintenance, and little in the way of new development on the DAO telescopes, resulted in relatively low subscription rates (80-100%) for the 1.2m and 1.8m telescopes from 1990 to 2000. There was a strong sense that an increase in demand for time on both DAO telescopes was needed to justify the continued scientific support of both facilities.

3. THE OPPORTUNITY

The Canadian Long Range Plan of 1998 (LRP1998) and the subsequent LRP Mid-Term Review recognized the continuing importance of the DAO telescopes, Canada’s only national optical observing facility, in their recommendations:

*The LRPP recommends that the two DAO 1.2 and 1.8 metre telescopes be supported over the coming decade. These facilities should be provided with the extra staff and support needed to maintain their scientific productivity.*

*The MTRC recommends that the current LRP support for the enhancement of the scientific capabilities of the DAO telescopes be continued.*

It was also recommended that $100,000/yr be provided to support the enhanced operation of both telescopes through 2015. Thanks to the strong support provided by the LRP recommendations, with the retirement of the sole observing assistant dedicated to the telescopes in the early 2000’s we were able to hire an upgraded Technical Officer (a PhD astronomer) dedicated to the operation and development of the DAO telescopes. The HIA has also been able to allocate approximately $50,000 of additional operating funds each year to enable us to undertake modest development efforts to improve the performance and capability of both telescopes. For the 1.2m telescope, we have used some of these funds to undertake a program to automate the operation of the telescope and spectrograph. Shared-risk operation with limited capabilities began in 2004.

4. ROBOTIC OPERATION OF THE DAO 1.2 M TELESCOPE

In this section we present a summary of various aspects of the robotic operation of the DAO 1.2m telescope.

4.1 Acquisition and Guiding (A/G)

The DAO 1.2m telescope pointing model gives a typical RMS pointing error of about 10 arcsec. This is usually sufficient to ensure that the desired target appears in the field of view of the acquisition camera. The pointing model is normally updated each year. More frequent RA and/or Dec offsets are applied when deemed necessary.

A single inexpensive, cooled, QSI CCD is used as an A/G camera. The camera is fed by a 10% pellicle beam splitter and has an unvignetted field of view with a diameter of approximately 1 arcmin. For acquisition, a simple finding algorithm spirals out from the center of the field of view. A search is made for a feature of at least 9 adjacent pixels with a flux exceeding a threshold determined by the overall frame statistics. When an object is found the telescope pointing offsets are applied a few times to move the target to the last recorded location of the entrance slit or “hot spot” of the spectrograph. This is the end of the so-called acquisition phase. A current limitation of the system is that when there are two objects in the current field of view, the object closest to the center of the field is acquired.

After acquisition, the CCD is sub-rastered for fast guiding at up to a 7 Hz frame rate. Except for very bright or faint targets we normally guide at just 2 Hz. Stellar images have 2 to 3 pixel FWHM during the rather poor median seeing conditions of 3 arcsec experienced at the DAO. When robotic operation was first implemented the active guiding was performed with a pair of tip/tilt plates in front of the entrance slit to the spectrograph. Active correction is now accomplished by translating the coudé mirror train’s f/30 transfer lens. The motion resolution is set to 0.1 arcsec with an update rate of 7 Hz to match the fastest possible CCD readout. In reasonably good weather and seeing conditions the current A/G limiting magnitude is approximately $V = 10.5$ when performing
active correction at the normal rate of 2 Hz. With longer A/G exposure times (e.g. 5 s), and hence a substantially slower correction rate, the A/G limit can be pushed to $V = 13$.

Slower guiding corrections are off-loaded to the TCS to ensure that the active corrections remain within the dynamic range of the transfer lens motion. A very simple, low-amplitude dithering algorithm is used to maximize the spectrograph’s exposure meter count rate during an exposure and the current position of the guiding “hot spot” is updated to reflect this.

4.2 Dome Control, Weather Monitoring, and Telescope Focus

The 1.2m telescope’s lower and upper dome shutters can both be controlled remotely. An OPEN DOME command is typically the first instruction executed by the script that controls the robotic operation of the telescope (see Section 4.3 below). A weather station located next to the dome prevents opening if the relative humidity exceeds 95%. (Note: the DAO is not a particularly dry site. An 80% relative humidity limit at DAO - the nominal limit for many Mauna Kea observatories, for example - would eliminate any possibility of observing on many clear winter nights.) The dome is also forced to close during an observing sequence if the relative humidity exceeds this level during the night. All weather station data, the telescope control system (TCS) status, as well as A/G camera, DAO sky camera and dome camera images can be monitored via the WWW (see Figure 1). An interior

![DAO Environment Data](image)

The table and images below contain real-time data pertaining to the status of the DAO telescopes and their environment. Note: if weather information in the table appears in a red font then you should likely NOT have the dome open because of high winds or humidity. The CCD temperature appears in red if the temperature is higher than the normal operating value.

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<tr>
<td>05:15:28</td>
<td>1.2m 1.8m</td>
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<td>Coude Spectroscopy</td>
<td>1.310</td>
<td>2011.0</td>
<td>04:07:48</td>
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<td>+02:03:38</td>
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<td>161.16</td>
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<td>12</td>
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![Last 1.2-m A/G Image](image)

Last 1.2-m A/G Image

![1.2-m Dome Camera](image)

1.2-m Dome Camera

![Last 1.8-m A/G Image](image)

Last 1.8-m A/G Image

![1.8-m Dome Camera](image)

1.8-m Dome Camera

![T vs RH](image)

Figure 1. DAO weather station data, the TCS and detector status, and A/G camera, DAO sky camera and dome camera images can be monitored from various WWW pages.
dome light can be controlled remotely if required to illuminate the inside of the dome for inspection of the dome or telescope location.

A rain detector also forces both of the dome shutters to close if the weather deteriorates. The sensor is heated to prevent false triggers from dew and to remove moisture after any precipitation has stopped. It is also active during classical observing. This occasionally creates mild annoyance for observers since it takes a total of approximately 15 minutes for the sensor to reactivate after any precipitation has ended and to open the dome shutters again before they can resume observing.

The telescope focus is normally controlled automatically throughout the night using weather station and details of the spectrograph configuration. Based on focus position and ambient temperature values saved in the FITS headers of data obtained during classical observing nights (during which observers usually focus manually) we have found that the telescope focus varies approximately linearly with temperature. A separate linear relation has been established for each image slicer and every 60 s the telescope focus is adjusted according to the current temperature. The focus can also be set to a desired value remotely.

4.3 Program Control

The robotic operation of the DAO 1.2m telescope is controlled by shell script with the name of a simple text file as the only input parameter. An entire night of observing can be carried out by connecting to the Linux workstation that controls the telescope and spectrograph operation and then typing a single command, for example, auto.csh 2011-03-02.parm. An example of such an input text file is provided in Figure 2.

```
OPEN_DOME 17 30 # Open the dome at 17:30 PST
ARC_LENGTH 20  # Set the comparison arc spectra exposure time to 20 seconds
BIAS 16        # Take 16 bias exposures
ZENITH         # Move the telescope to the zenith and wait until the...
WAIT_EXP 15    #...sky background is down to 15 counts/second on the exposure meter
VERBOSE        # Increase the verbosity level of the log file
WS_FOCUS ON    # Turn automatic telescope focus on (using Weather Station data)
MID_ARC TRUE   # Take an arc exposure after science exposure of a sequence
# # Each OBJECT command requires an identifier, RA, Dec, equinox, exposure time (s), and the # number of exposures in a sequence. Any additional content is interpreted as comments #
OBJECT HD206773 21:42:24.2 +57:44:09.8 2000.0 2700 1 18:25
OBJECT SXCas 00:10:42.1 +54:53:29.4 2000.0 3600 1 19:15
OBJECT KXAnd 23:07:06.2 +50:11:32.5 2000.0 2700 1 20:20
OBJECT ksiTau 03:27:10.1 +09:43:57.6 2000.0 500 1 21:10
OBJECT 27Tau 03:49:09.7 +24:03:12.3 2000.0 500 1 21:25
OBJECT HD35502 05:25:01.2 -02:48:55.6 2000.0 1800 1 21:40 Bohlender
OBJECT HD35298 05:23:50.4 +02:04:55.8 2000.0 1800 1 22:15 Bohlender
OBJECT HR2142 06:04:13.5 -06:42:32.2 2000.0 1800 1 22:50
OBJECT KSCMa 06:49:15.9 +12:40:04.5 2000.0 2700 1 23:25
OBJECT AXMon 06:30:32.9 +05:52:01.2 2000.0 1800 1 00:30
OBJECT UXMon 07:59:16.4 -07:30:17.9 2000.0 3600 1 01:05
OBJECT HD87901 10:08:22.3 +11:58:01.9 2000.0 300 6 02:10 Bohlender
OBJECT HD61273 07:38:51.0 +07:57:59.7 2000.0 3600 1 02:45
OBJECT CXDra 18:46:43.1 +52:59:16.7 2000.0 1200 9 03:50
WS_FOCUS OFF   # Turn off the autofocus
CLOSE_DOME     # Close the dome
BIAS 16        # Take another 16 bias exposures
```

Figure 2. An example of a simple text control file used to execute a night of observations on the DAO 1.2m telescope.
As the comments included in the sample indicate, the input file provides the opening time, a description of the calibration sequences desired, and a start time or sky count rate to wait before attempting to acquire the first target. Currently only bias, comparison arc, and sky calibration exposures can be obtained automatically. The flat field calibration system for the spectrograph has not yet been upgraded for remote control. Each `OBJECT` line in the input file then provides a target identifier, coordinates and equinox, the desired exposure time, and the number of exposures to obtain before continuing to the next target. A different form of the command can instead expose to a desired exposure meter count level.

Normally, when the sky is relatively clear and the local weather forecast is good, we power up the telescope systems and open the mirror covers manually and then start the observing script at the end of the working day. Usually no interaction is required by staff for the remainder of the night although one of us will typically monitor progress remotely from home until about halfway through the night, especially when conditions are marginal. On such nights, for example, an occasional cloud can cause the A/G system to lose an object but the CCD exposure continues. We therefore occasionally interrupt an observing sequence, reacquire the target manually, and then resume observations. The robotic operation can be controlled from anywhere we have access to the Internet, a terminal window, and `ssh`. We have made use of this capability to control the telescope from remote locations in Canada and even as far away as Chile and Austria.

5. SCIENCE PROGRAMS

Robotic operation of the DAO 1.2m telescope has proven to be very popular from the first time it was offered to users on a shared-risk basis in 2004. We have typically scheduled about 30 to 40% of the nights on the 1.2m telescope each quarter as robotic, but in more recent observing quarters this fraction has exceeded 60% and even 70%.

Approximately a dozen different principal investigators (PI) have been making use of the robotic observing capabilities of the DAO 1.2m telescope over the last several years. This comprises about 75% of the regular users of the telescope. The observing programs that have been operated robotically have included many different kinds of research programs including studies of the interstellar medium, binary and variable stars, Be stars, chemically peculiar and magnetic stars, and even one of the first extragalactic observing programs carried out with the telescope. Variable and binary star programs have included high-resolution investigations that have intensively monitored bright, single objects over many consecutive nights to search for spectrum variability, large low-resolution spectroscopic surveys of many hundreds of stars (see Figure 3), and long-term radial-velocity surveys of various classes of both pulsating and binary stars. The latter two types of programs in particular take full advantage of the fact that robotic operation makes it possible for a PI to apply for single nights on the telescope approximately once every week or two or for several nights every month. In a number of cases the PI has been able to continue such programs for many years. Without the availability of service observing support for the telescope, such programs would be difficult (or very expensive) to carry out classically unless the PI resides in or close to Victoria.

For some users we also provide pipeline-processing of the spectra acquired on the 1.2m telescope (as well as the 1.8m) and, if they have observed radial velocity standards, we can also provide radial velocities for their program stars. While not yet automated, the processing of spectra is accomplished with a single shell command using a Perl+IRAF script we have developed. A second script executed by another single command can then use the processed spectra and a library of processed standard star spectra (obtained at the same wavelength) to measure radial velocities. The latter script employs the RVSAO IRAF package to perform a cross-correlation between the program stars and any or all of the radial velocity standard stars. The spectra shown in Figure 3 were produced with the spectrum reduction pipeline. In Figure 4 we also show an example of the radial velocity curve for the bright δ Scuti star 20CVn obtained over the course of eight hours of continuous observation. In this case one of the approximately eighty 360s exposures was used as the radial velocity ‘standard’ observation. The resulting velocity precision obtained with this package (and with no additional special processing) were 20 to 30 m s

−1 for these observations.
Figure 3. Spectra of 75 stars obtained during a single night of unattended robotic observing with the DAO 1.2 m telescope. These data are part of a large program to search for nearby young stars suitable for a future Gemini GPI survey program.

Figure 4. Robotic observations of the bright δ Scuti star 20 CVn. (Left) The average spectrum from eight hours of consecutive 360 s exposures at a dispersion of 2.4 Å mm$^{-1}$. (Right) The relative radial velocity variations derived using a single 20 CVn spectrum as the input velocity template for the RVSAO IRAF package.
6. FUTURE ENHANCEMENTS

While the first few years of robotic operation of the DAO 1.2m telescope have proven to be popular as well as scientifically productive, we hope to continue to make incremental improvements to the spectrograph, control software and supporting infrastructure which will enhance the efficiency, capabilities and productivity of the telescope. Some examples of the short- and long-term development we hope to carry out include (in likely order of completion):

- Data obtained with both DAO telescopes are now being delivered to the Canadian Astronomy Data Centre (CADC) and will soon be available via the CADCs DAO Science Archive within 15 minutes of acquisition (see Figure 5).
- The ‘intelligence’ of the current robotic operation software will be enhanced to improve observing efficiency in Victoria’s rather common less-than-optimal observing conditions. As an example of a simple first step, if an object is momentarily lost by the A/G camera because of a passing cloud the telescope will automatically try to reacquire the object for the duration of the current exposure.
- Cloud-detection software for the DAO sky camera has been developed and will be integrated with the robotic operation of the 1.2m telescope. Briefly, the software determines the extinction and sky background near Polaris and measures the small-scale image ‘structure’ over an approximately 90° × 90° area of the sky in order to detect patchy cloud cover. The script returns a 1 or 0 (observe/don’t observe) every minute and generates a more general sky condition factor, SF, every 15 minutes. The telescope will be instructed to open the dome and start a robotic run when SF > 0.8. Eventually we hope to measure a SF for different regions of the sky and to observe targets in the clearest regions.

Figure 5. A pre-release example of an archive query using the Dominion Astrophysical Observatory Science Archive WWW interface hosted by the CADC.
• A higher frame-rate A/G camera will be obtained to provide better wind-shake correction. Our aim is to guide at a 30Hz rate to provide good correction to the approximately 1Hz resonance frequency of the telescope.

• A number of potential users would like to extend the current A/G magnitude limit to objects fainter than $V = 10.5$. We will soon provide a pair of dichroic beamsplitters to enable robotic operation to $V \approx 13$ or fainter with automatic adjustment of the A/G exposure time and readout rate to accommodate the brightness of a target.

• A new E2V 2K $\times$ 4K CCD has been acquired and will be dedicated to the McKellar spectrograph’s long camera. The current SITe-4 detector will be used with the short camera. This will ease some of the current scheduling restrictions by eliminating the need to move a single CCD between the two spectrograph cameras.

• We will port the existing Perl+IRAF script to Python+PyRAF and integrate data processing (including radial-velocity measurements where applicable) into the data acquisition system. We hope to eventually also provide processed data (and possibly custom processing capability) through additional future DAO Science Archive WWW pages.

• We have begun the acquisition of new, small science CCDs with the intention of creating an 18K $\times$ 512 detector array for the McKellar spectrograph’s long camera. This will increase the wavelength coverage to about 650˚A and improve the spectral sampling (because of the smaller pixel size).

• Remote control of the flat-field calibration lamp hardware as well as the grating rotation and camera focus for both spectrographs will enable wavelength changes to be carried out during the course of a single night.

7. CONCLUSION

Our implementation of robotic observing capabilities for the DAO 1.2m telescope has drawn significant interest from prospective telescope users and has helped increase the telescope’s overall subscription rate by about 50% to more than 150% in recent years. Demand for such robotic observations gives every indication of increasing, especially in the winter months. We had typically scheduled 30 to 40% of all of the allocated time on the telescope in robotic mode for the first several years of operation but a rather remarkable 63% of all nights scheduled on the telescope in the three quarters 2010D, 2011A, and 2011B have been scheduled in robotic mode.

We feel that these new capabilities for the DAO 1.2m telescope and McKellar spectrograph will ensure their continued scientific relevance and productivity for many years to come. Funding, manpower, and community interest permitting, we also hope to use what we have learned from these efforts to eventually enable robotic operation of the venerable 1.8m Plaskett telescope in both imaging and spectroscopic observing modes. This will not, however, be without its challenges!

Finally, we remind interested observers to consider using one or both DAO telescopes for their research. Both facilities are scheduled quarterly. The nominal proposal deadlines are the 1st of December, March, June and September for the calendar quarters which start one month later. Significant amounts of observing time can be obtained for good science cases. Single lengthy runs (for example 3 or 4 weeks) and long-term programs over timeframes of months to many years are often scheduled and graduate student research projects are particularly encouraged and strongly supported. Information can be found on the DAO web page: https://www.astrosci.ca/DAO.