PROGRESS IN RESEARCH AND DEVELOPMENT ON THE CASTOR K SATELLITE TRACKING FACILITY

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ABSTRACT

The Research and Development (R & D) stage of a project is an extremely important one, since it sets standards for the existing project and provides a template for future similar projects. After the preliminary construction of an optical satellite tracking facility, it is necessary to determine the accuracy and efficiency of each component that comprises that facility.

Research and Development on the Canadian Automated Small Telescope for Orbital Research in Kingston, Ontario (CASTOR K) has been underway since the facility was first used to track satellites in January 2000. Since then, much work has been done at the Space Surveillance Research and Analysis Laboratory (SSRAL) at the Royal Military College (RMC) to upgrade this facility for remote control and automation. The progress of this R & D will be discussed emphasizing satellite scheduling, telescope pointing and image acquisition, image analysis, and orbit determination. Finally, an overview of the concerns for the remote operation of the facility will be addressed. The results of this R & D will be beneficial for designing future CASTOR facilities.

INTRODUCTION

CASTOR K has been operational in a limited sense since January 2000. It was possible to track satellites with the facility, but in a very manual sense. Remote control and automation of the CASTOR K facility partially depends on developing hardware and software specifically tailored for it. It was decided that instead of trying to deal with the entire project at once, it was necessary to split the project up into specific modules that would eventually connect to form the entire functioning facility. Research and development on the satellite scheduling, the telescope pointing and image acquisition, the image analysis, and the orbit determination modules would be carried out separately. Eventually, these pieces will fit together to form a fully functioning remotely controlled automated optical satellite tracking facility. The advantage of this R & D strategy is that with only slight modifications, each module can be used in future CASTOR facilities.

This paper will begin by providing an overview of the CASTOR K name and purpose, its hardware and software components, and the important project milestones from December 1999 to November 2000. It will then describe the aforementioned R & D portions and the work that has been done for each from January 2000 to November 2000.

The Space Surveillance Research and Analysis Laboratory (SSRAL) is currently using CASTOR K to study the Molniya-type orbits that include the Russian Molniya communications satellites and their rocket bodies. The Molniya payload satellite will be used as the example for numerical values and illustrations throughout this paper unless the contrary is stated.

THE CASTOR NAME

The name CASTOR is an acronym for the Canadian Automated Small Telescope for Orbital Research. The star Castor (Alpha Geminorum) is the brightest one in the constellation Gemini. This suggests an astronomical connection. Castor is also French for beaver and therefore suggests the bilingual nature of Canada and one of its national symbols. The unofficial symbol for the CASTOR project is shown in Figure 1.

Figure 1: The current unofficial symbol of the CASTOR project.

THE PURPOSE OF CASTOR

The CASTOR K facility is being constructed to provide the first remotely controlled and automated optical satellite tracking facility for Canada. It will be used mainly for tracking those accessible satellites that reach ranges of 10,000km or more. The images attained will be used for extracting accurate tracking data to be used for highly accurate orbit determinations. Accurate orbit elements will in turn provide better collision avoidance, especially for those objects (like Molniya satellites) that intersect highly populated low-Earth orbit satellite belts. As an example, Figure 2 illustrates how close a Molniya satellite near perigee can get to the Canadian Radarsat satellite.

The purpose of optically tracking such high-range satellites is to acquire highly accurate high-range satellite tracking data for use in precise orbit determination. Molniya-type satellites, which can attain ranges as low as 800km when at perigee, can be tracked with radar at the lower ranges, but these occur over the Southern Hemisphere. A typical Molniya orbit can reach ranges of 40,000km or more at apogee over the Northern Hemisphere and at this range the accuracy of the range data collected by radar is severely compromised. When a Molniya satellite is being tracked over the Southern Hemisphere by radar the amount of range data collected on the object is very limited. A Molniya satellite near perigee can move as fast as a typical low-earth orbiter at the same range (such as the ISS and remote sensing satellites such as Radarsat). Thus the radar data collected for a Molniya satellite is most accurate at a very small portion of the satellite's entire orbit. This is the portion that is most strongly affected by gravitational, atmospheric and electromagnetic disturbances. An orbit determination calculation using this limited data results in mean orbit element sets that are meant to represent the entire orbit. These orbit element sets are not optimized as much as they should be. The CASTOR project is intended to provide accurate optical look-angle data for the satellites that can attain high altitudes to compliment the near perigee range data provided by radar. This will result in a highly accurate orbit determination based on the entire orbit instead of a small portion of it. Thus the orbit element sets that are produced by both radar and CASTOR K data will be much more accurate.

Geostationary satellites will also be tracked for use in more accurate orbit determination of these objects and to aid in collision avoidance within the geostationary belt. Orbiting geostationary satellites accessible to CASTOR K will be generally 38,000km in range from the facility. Nearly half of the total geostationary population can be seen with CASTOR K. Geostationary satellites do not undergo orbit decay for many years due to the fact that their roughly circular orbits have high semi major axes. This keeps these satellites out of the atmospheric and gravitational disturbances that lie near the Earth. Molniya satellites decay much sooner because of their low perigee altitudes. Figure 3 illustrates the number of geostationary objects that CASTOR K can access optically.

Plans are also underway for using CASTOR K as a near-Earth asteroid detection facility. Since the facility is an optical one, it can provide optical images for use in detection of comets and asteroids that could threaten Earth.

CASTOR K will also be used in graduate courses and astronomy labs at RMC. It will serve as an excellent training centre for those cadets who require training in astronomy or satellite tracking. Two RMC Space Science graduate students working at SSRAL have already used CASTOR K to aid them with their theses.

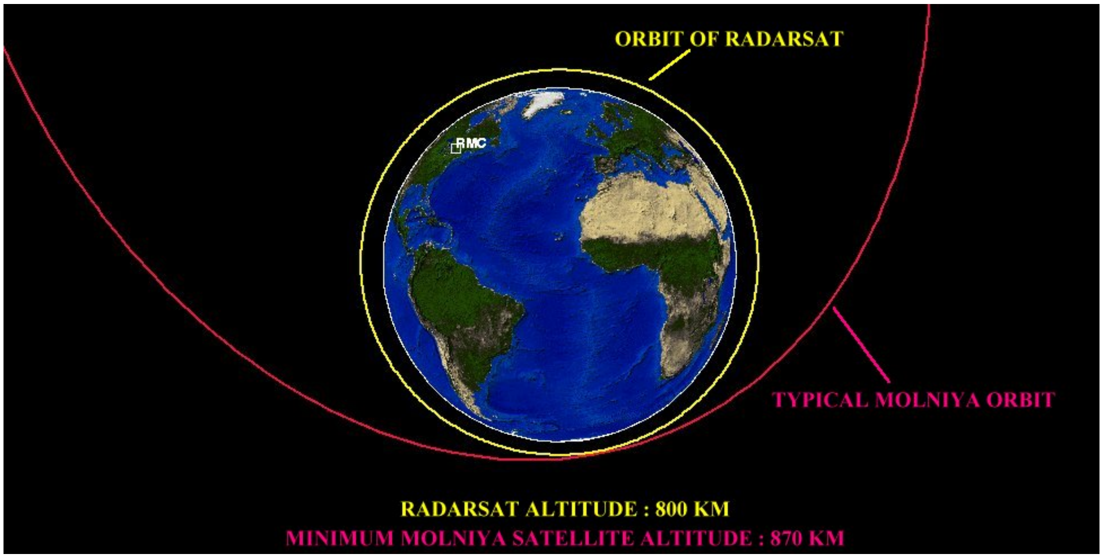


Figure 2: The Orbits of Radarsat and a Typical Molniya Satellite. At perigee, a Molniya satellite can be a potential hazard to low earth orbiting satellites such as Radarsat. Analytical Graphics' Satellite Tool Kit (STK) software generated this illustration.

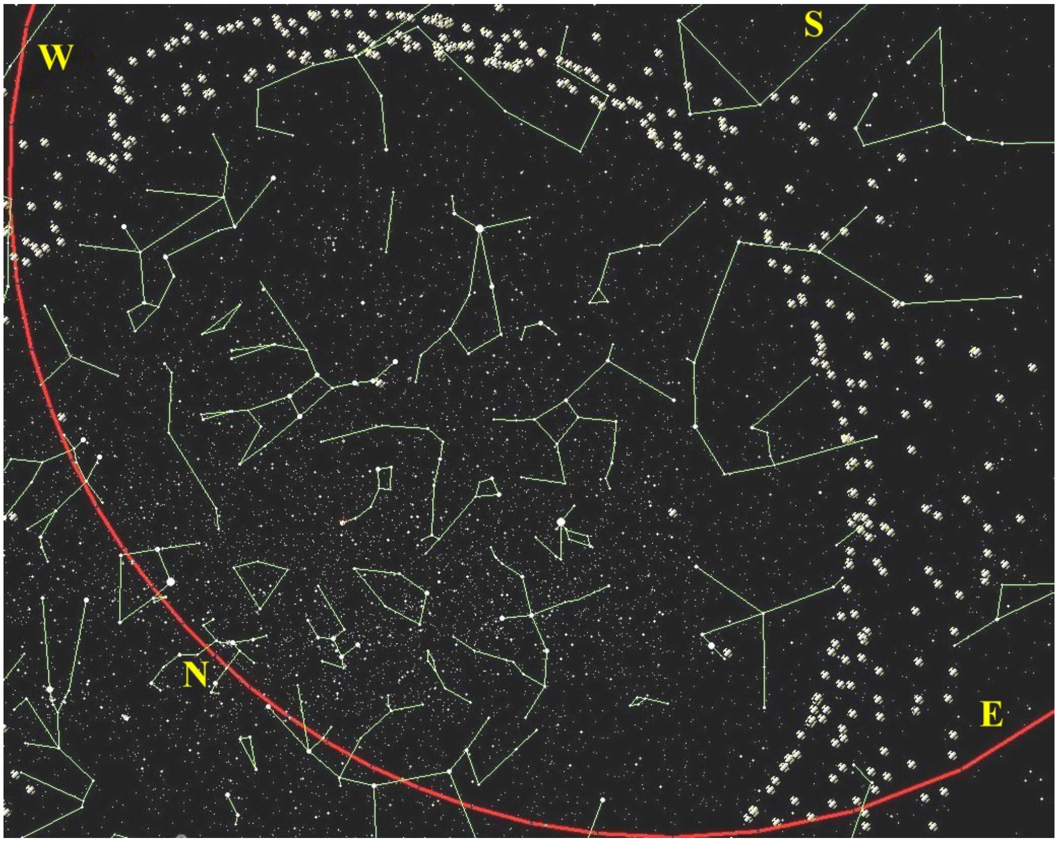


Figure 3: The Geostationary Satellites Plotted Against the Stellar Background as Seen from RMC. The dotted semi-circle of objects are the geostationary satellites that can be seen from RMC. The thick red line denotes RMC's local horizon. CASTOR K would be very beneficial in the reconnaissance of these objects. Software Bisque's TheSky Astronomy Software generated this illustration.

CASTOR K HARDWARE AND SOFTWARE

Table1 and Table 2 list and describe the main hardware and software components of CASTOR K as of October 2000. For a project such as CASTOR, hardware and software upgrades will constantly be needed as satellite tracking technology constantly progresses, expands and gradually enters the commercial-off-the-shelf (COTS) realm. See Figure 4 to see the main hardware of the CASTOR K facility along with the Senior Technician of SSRAL.

Celestron Model CG-14 0.36m (14") Aperture Schmidt-Cassegrain Reflecting Telescope	This telescope is the optical tube assembly (OTA) of CASTOR K. Figure 4 shows the telescope used for CASTOR K.
Software Bisque Paramount Model GT-1100 Robotic Telescope Mount	This German Equatorial telescope mount is one of the most accurate robotic telescope mounts for amateur astronomy. See Figure 4 to see this robotic mount.
Apogee Model AP-7 Charge-Coupled Device (CCD) Camera	This CCD camera has a quantum efficiency of 85% over a wide range of visible wavelengths and has a back-illuminated design.
Datum Inc. Model bc620AT Global Positioning System (GPS) Receiver	This GPS receiver provides an accurate time base for the satellite tracking data used for final orbit determination.
Ash Manufacturing Model REA 10 Foot 6 Inch Diameter Observatory Dome	This observatory dome contains the CASTOR K hardware mentioned above. See Figure 4 to see this dome.
Meridian Controls Dome Control Hardware for Ash Dome	This hardware enables the dome to automatically line up the dome opening to the telescope's aperture whenever the scope is moved.

Table 1: The Hardware Used by the CASTOR K Satellite Tracking Facility.

Figure 4: Mr. Michael A. Earl, Senior Technician of SSRAL, with the CASTOR K Satellite Tracking Facility

Software Bisque's TheSky Astronomical Software Level IV Version 5	This is the main astronomical software for CASTOR K. Satellite two-line element sets (TLEs) can be used so that the user can see the satellite position superimposed onto the simulated sky for any location and for any time, including real time.
Software Bisque's CCDSoft CCD Camera Software	This software can accommodate a wide variety of CCD camera makes and models. It is also a fine image processing and manual astrometry tool.
Software Bisque's Orchestrate Telescope and Camera Automation Software	This software allows the user to input a script containing specific targets (such as satellites) and exposure times for the CCD camera that will be run by TheSky. This allows automation of the satellite tracking process.
Analytical Graphics' Satellite Tool Kit (STK)	This is the main satellite analysis tool for CASTOR K. It allows the user to see any satellite's ground track and actual orbit and provides ephemerides for any user-defined facility.
Analytical Graphics' STK/Connect Module	This module of STK allows user interfacing with STK from any other PC or UNIX terminal. It will be used mainly for the automation of orbit determinations using the Precision Orbit Determination System (PODS).
Analytical Graphics' Precision Orbit Determination System (PODS) Module	WSPOD is the main orbit determination software used by CASTOR K.
NetCreations PinPoint Astrometry Software	This is shareware available from the Internet and can be used for accurate astrometry of any image of any scale or rotation.
Java Streak Detection Algorithm	This software has been developed by Mr. Phil Somers of the Defense Research Establishment Ottawa (DREO) for use in image analysis.
Software Bisque's Automadome Dome Automation Software	This software will be the main interface between TheSky and the Meridian Controls dome automation hardware.
RMC SSRAL Satellite Scheduler Software	This software will generate an Orchestrate script designed to provide the best telescope slewing path for the maximum image acquisition for a satellite tracking session for any number of satellites.

Table 2: The main software used by the CASTOR K satellite tracking facility.

Figure 5 illustrates how these components fit together to comprise the CASTOR K facility. This illustration denotes a closed loop automated remotely controlled optical satellite tracking facility. This illustration is by no means complete, as new hardware and software will undoubtedly be added to the facility as the R & D into automation continues and new technologies present themselves. For example, weather is a major concern for the facility. There will no doubt be weather and all-sky sensors added to the facility to aid in the remote control and automation process. This illustration does not take refitting into account as well. Many components of the facility will eventually be replaced by a better version in order to improve accuracy and efficiency. This is one aspect of the R & D that will continue as long as the project continues.

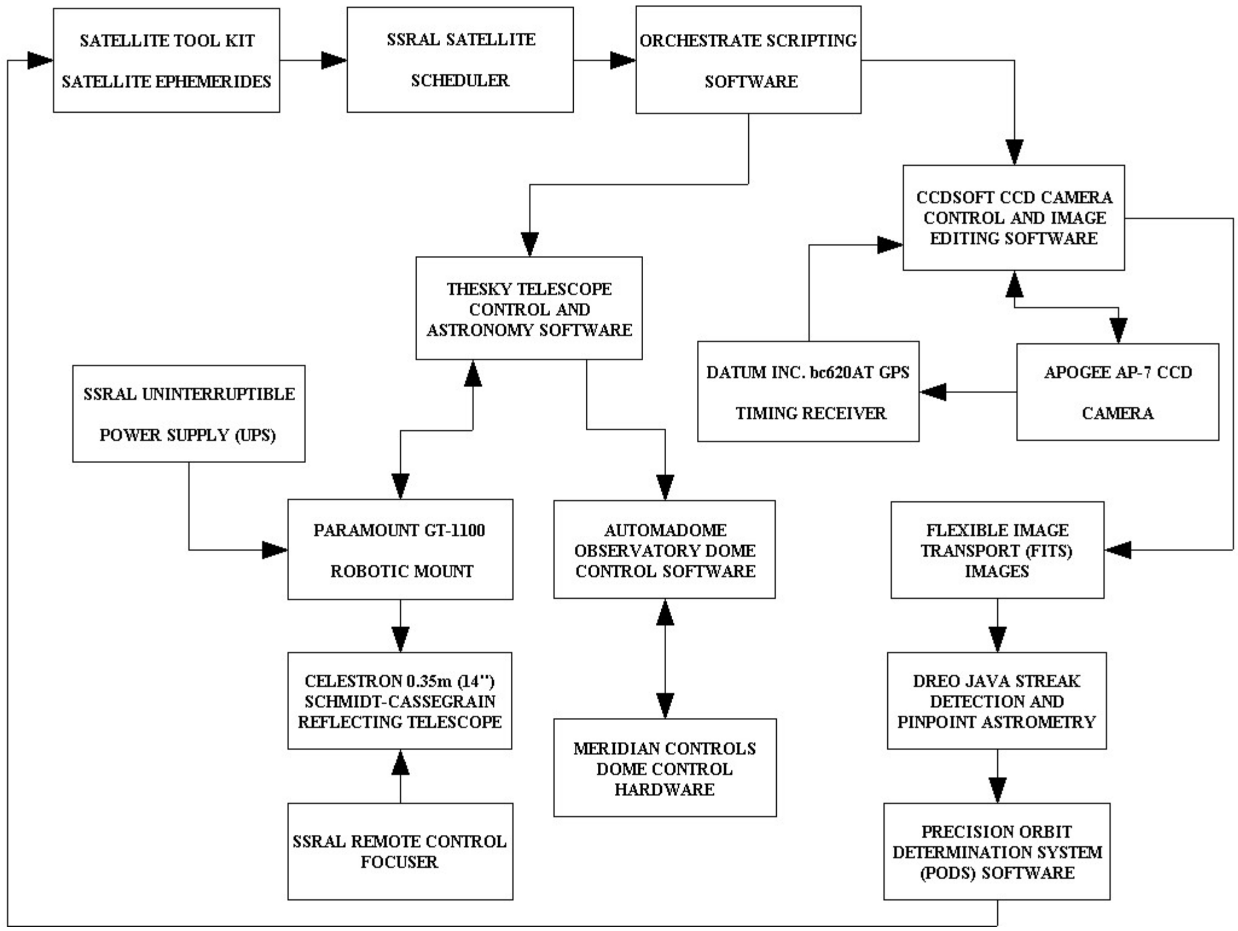


Figure 5: A Chart Describing How the Hardware and Software of CASTOR K Interconnect. Double arrows denote a link between hardware and software such that two-way communication is necessary. See Tables 1 and 2 for the descriptions of the major components.

CASTOR K MILESTONES: DECEMBER 1999 TO NOVEMBER 2000

The milestones mentioned here were the result of many hours of work performed by Mr. Michael Earl, Senior Technician of the SSRAL unless otherwise noted.

December 09, 1999: CASTOR K sees first light. SCC 19807 (the Molniya 1-75 payload) was tracked manually for half an hour. The controlling computer was located inside the dome itself. The wiring plans for the dome, camera and telescope controls for the lab were being drawn up.

January 10, 2000: Wiring for SSRAL lab communications with the robotic mount and CCD camera was completed. A manual dome controller designed by SSRAL was first used to control the dome's azimuth and shutter from within the SSRAL lab.

January 28, 2000: CASTOR K was accurately polar aligned using the CCD camera. The satellite SCC 22255 (the Molniya 3-43 payload) was successfully imaged using CASTOR A controlled completely from within the SSRAL lab itself. An experimental tracking run resulted in the imaging of the SL-12 ASTRON rocket body (SCC 20413) that was 140,000km in range from RMC at the time. This is the most remote object that CASTOR has imaged to November 2000.

April, 2000: The CASTOR S (Suffield, Alberta) and CASTOR V (Valcartier, Quebec) names are adopted for two future CASTOR sites.

May 16, 2000: A satellite scheduler, designed by SSRAL, ran for the first time to determine the optimal path for the robotic mount to take for the optimization of satellite image acquisition. The script generated by this software was run by Orchestrate to do an all night satellite tracking run for Molniya satellites.

May 25, 2000: Accurate GPS timing was added to the CASTOR K facility in order to greatly improve the CCD shutter "open" and "close" time determination for use in the final satellite tracking data.

June 1, 2000: A CCD camera mechanical shutter accuracy determination was done by SSRAL to determine the delay time between the camera triggering and the actual opening of the shutter itself. This resulted in a millisecond CCD camera timing accuracy for the CASTOR K facility. The first draft of the CASTOR Ground-Based Concept Demonstrator Project Plan is released by the Defense Research Establishment Ottawa (DREO).

June 24 to August 26, 2000: Four astronomy open houses are held for the staff of RMC and the local chapter of the Royal Astronomical Society of Canada (RASC) to demonstrate CASTOR K's capabilities at that time.

September 7, 2000: CASTOR K is used for the first time from outside the SSRAL using the pcAnywhere trial software. It was used from another building at RMC (Yeo Hall) for the promotion of the RMC Astronomy Club. Remote dome control was not yet possible.

September 18, 2000: CASTOR K is used for the first time from outside Kingston. The remote terminal was located in the Senior Technician's sister's house in Ottawa, Ontario. Remote dome control was still not possible, so someone had to be within the SSRAL lab to control the dome azimuth.

September 19, 2000: Automatic dome control hardware was successfully installed and initialized by Meridian Controls. It became possible to control the dome using TheSky through Automadome. The dome slit could be opened and closed and the dome azimuth would move according to the telescope mount's destination such that the telescope's entire aperture could see through the dome opening at all times. Total remote operation became possible.

September 28, 2000: Phil Somers of DREO uses CASTOR K remotely using a DREO terminal using AT&T's Virtual Network Computing (VNC) remote PC software. He did not do the total initialization through to shutdown procedure, however.

October 8, 2000: The first total satellite tracking run was performed using CASTOR K from a remote terminal in Ottawa, Ontario by Mr. Michael Earl of SSRAL. Opening the dome, initialization and linkup to the telescope, camera, and dome were performed as was a satellite tracking run of the satellite SCC #22178 (Molniya 3-42 payload). A total shutdown of the software and dome was also performed with excellent results. The images obtained, however, were slightly out of focus due to an ambient temperature fluctuation at the CASTOR K site.

November, 2000: A remote control focusing apparatus designed at SSRAL was completed and attached to the telescope body. An automatic temperature control may later be added such that the focus knob of the telescope will be automatically adjusted according to the ambient temperature fluctuations within the CASTOR K dome.

SATELLITE SCHEDULING

When performing an automated satellite tracking run, the controlling software must know which satellites to track for a specific facility's location and viewing constraints. It must also know how to track these satellites, i.e. it must follow a specific path to optimize the image acquisition rate. The specific hardware factors to consider are:

Type of Telescope Mount Used: Different types of telescope mounts have different concerns as far as target acquisition rates are concerned. CASTOR K uses a German Equatorial type of telescope mount. The main concern with such a mount is crossing the meridian. The meridian is an imaginary boundary drawn from due north to due south through the observer's Zenith. When crossing the meridian is necessary, the mount has to slew the telescope through the North Celestial Pole (NCP) which is currently located 3/4 degrees from the star Polaris. No matter where the telescope is pointing beforehand, it will have to slew through this point in order to cross the meridian. This wastes much time because one or more satellites could be being imaged during this long slew time. The satellite scheduler has been programmed such that it will first provide a script for those satellites on one side of the meridian only. Once those satellites have been exhausted, the satellites on the opposite side are scripted and so on. As a result, when the telescope is being automated, it will stay on one side of the meridian until all the scripted satellites on that side has been imaged. The telescope will then cross the meridian to start imaging those satellites on the opposite side of the meridian and so on.

Telescope Mount Slew Rates: The telescope mount can only move so fast in both Right Ascension (RA) and Declination (Dec) axes. For CASTOR K's GT-1100 robotic mount, the fastest slew speed is 1.5 degrees per second. In order to calculate the total time of slew, it is necessary to determine the slew times for different slew angles in both RA and Dec. The relation between the angle of slew and time to slew is not a linear one. Factors such as computer delay times, gear friction, telescope balance and acceleration rates complicate this calculation. An empirical determination will do, extrapolating where necessary. In order for the Orchestrate script to run correctly, the telescope must stop its slew before the camera shutter opens for an image. If this condition is not met the script halts. Figure 5 shows the most recent results of the slew times for both the R.A. and Dec. axes of the GT-1100 robotic mount.

Figure 6: The Total Slew Times for Various R.A. and Dec. Slew Angles for CASTOR K's Paramount GT-1100 Robotic Mount.

Dome Azimuth Slew Rates: The dome azimuth may take longer to slew to its destination than the telescope mount takes to slew to its own destination. When the command is given by the scheduler script to slew the telescope, both the dome and telescope will move to the new destination. The dome will move to keep the dome opening aligned to the telescope's aperture. TheSky will continue to report that the scope is slewing even if the scope has already reached its destination while the dome is still slewing. If the dome is still slewing at the time the command for the image to be taken is given the script will halt. The concerns that were mentioned for the telescope slew rates also apply for the dome slew rates. An empirical determination will be sufficient here as well. See Figure 6 to see the latest results of the dome azimuth slew times.

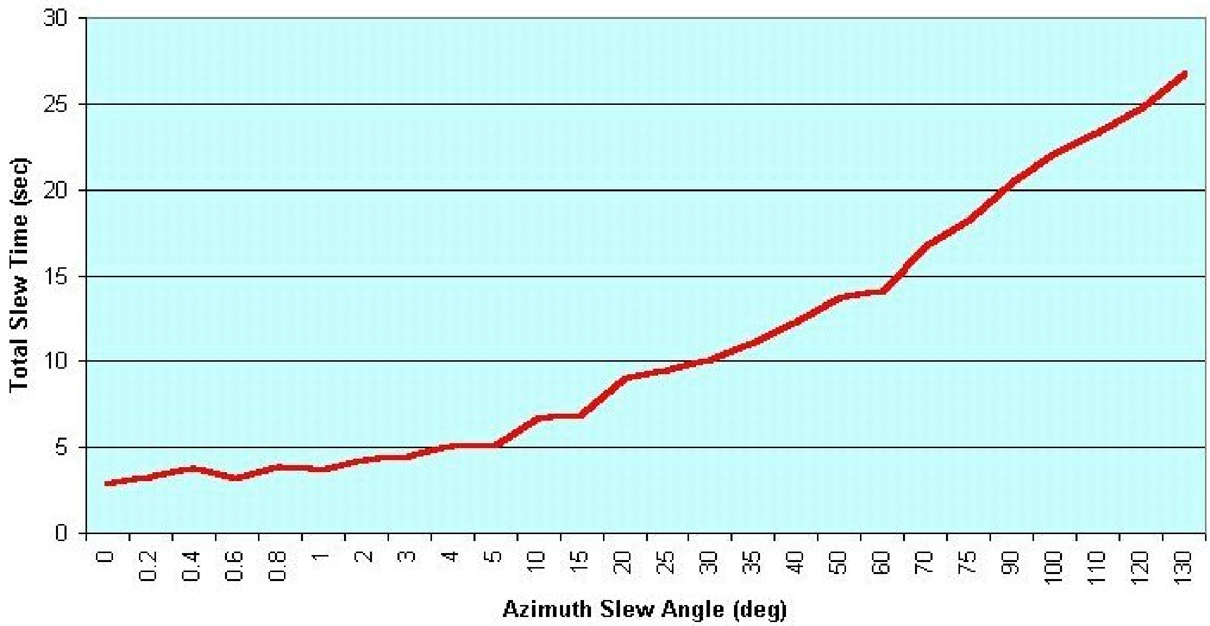


Figure 7: The Total Slew Times for Various Azimuth Slew Angles for the CASTOR K Observatory Dome

CCD Camera Total Exposure and Download Time: The CCD camera will obviously add time to the total satellite tracking process. The smaller the download time of the CCD, the larger the target acquisitions. The download time of the Apogee AP-7 CCD camera that CASTOR K currently uses is 10 seconds. The actual exposure time of the camera depends on the satellite's angular velocity and the camera's field of view. In order to minimize the total exposure time needed per satellite, it is necessary to cool the camera chip to the lowest temperature possible for the season (approximately -20 degrees Celsius in the summer and -50 degrees Celsius in winter). This is done in order to avoid taking dark current images, as they often double the total exposure time. Temperature sensors placed near the camera may be added to automate the temperature setting of the CCD chip.

The satellites themselves introduce concerns for the satellite scheduler to deal with:

Apparent Angular Velocity of the Satellite: On an image, the satellite streak must have well-defined end-points in order to perform accurate astrometry on it. To obtain the maximum amount of data from an image, the entire satellite streak must be located within the field of view of the camera when the image is taken. In order to ensure this, it is necessary to know the apparent angular velocity of the satellite with respect to the tracking facility. The field of view of the CASTOR K facility is currently 11.5 arc-minutes by 11.5 arc-minutes. The scheduler must know how long an exposure time the CCD camera must have for a particular satellite to remain within its field of view. This is done within the scheduler by sampling two predicted coordinates of a specific satellite for two times 10 seconds apart. The angular separation of the predicted coordinates is divided by the 10 seconds of time to produce the apparent angular velocity.

Apparent Position Angle of Satellite Travel: The apparent position angle of satellite travel (rotation angle with North being 0 degrees and East being 90 degrees, etc.) is also calculated so that the maximum allowable angle for the satellite to travel within the field of view is predicted. The configuration of the CCD camera to the prime focus of the telescope is such that the Right Ascension (East-West) lines are roughly horizontal and the declination (North-South) lines are roughly vertical. There is more space for the satellite that is at a 45, 135, 225, or 315 degree position angle than one with a 0, 90, or 270 degree position angle. If the satellite enters the western (lower R.A.) section of the image first, the streak will have a position angle of between 0 and 180 degrees. If the satellite enters the eastern section first (higher R.A.), then the position angle will be between 180 and 360 degrees. The position angle can also be calculated from two predictions separated by 10 seconds in time. Figure 8 illustrates the position angle of a specific Molniya satellite imaged during a routine tracking run.

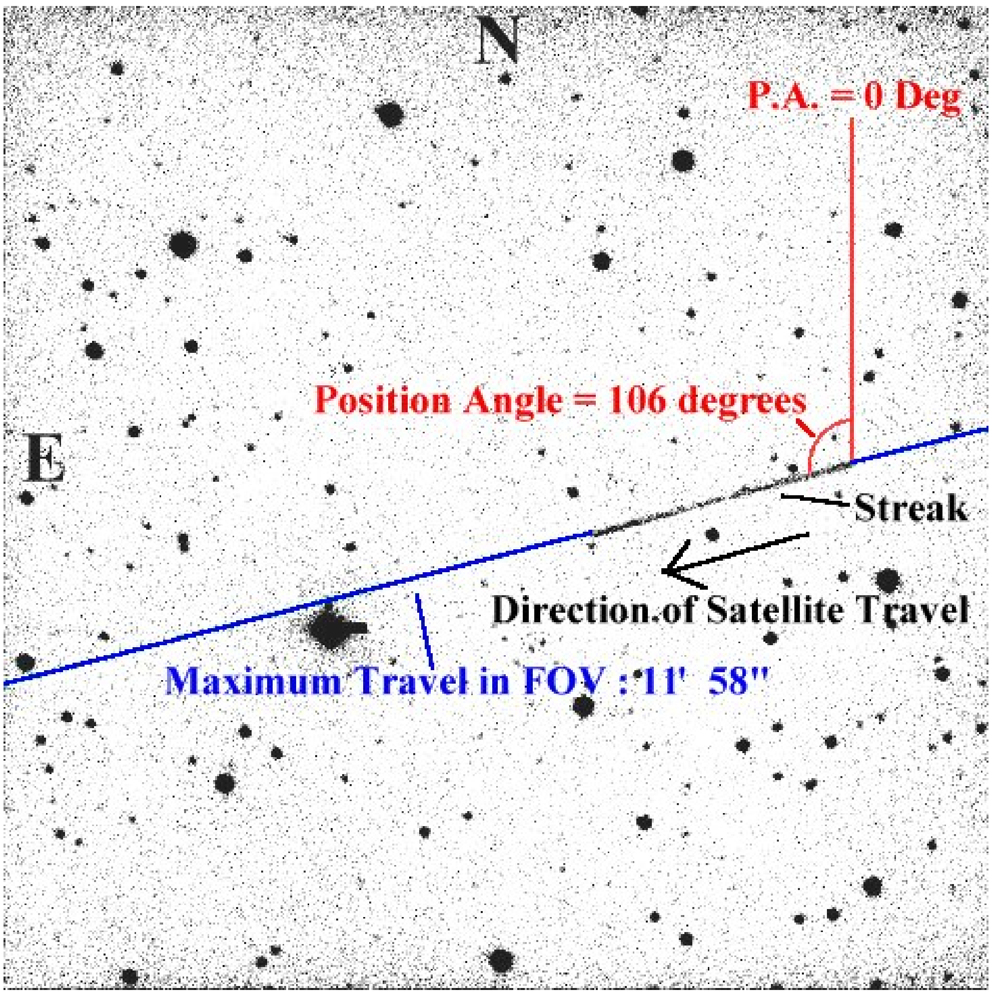


Figure 8: An Illustration of the Position Angle (P.A.) of a Molniya Satellite Streak. The scheduler calculates the P.A. using two predicted coordinates of the satellite. The times of these predicted coordinates are 10 seconds apart in the ephemeris file. The P.A. is used to determine the largest theoretical apparent satellite travel angle possible that keeps the satellite in the field of view (FOV) over two consecutive CCD camera exposures. The position angle also gives an indication of the satellite's apparent direction of travel in the image.

Variation in the Satellite's Apparent Brightness: Most of the satellites orbiting Earth are inactive pieces of space debris. These objects will undoubtedly be tumbling about an axis of rotation. When seen form the ground, these objects will appear to change in brightness since each different side of the satellite exhibits a specific reflectivity, unless the satellite is spherical and has a uniform reflective surface. Many satellites have extremely reflective solar panels. These objects can exhibit spectacular "flashes" of light as they tumble in space. The Iridium satellite flares are a famous example of this phenomenon. On the other hand, these satellites may also have very dark surfaces and at specific orientations an optical tracking facility cannot detect it. The result could be a broken streak with a highly varied light curve. End points may not be seen well unless a flash happens to coincide with the shutter opening or closing. Figure 9 illustrates the varying light curve of a Molniya tumbling satellite.

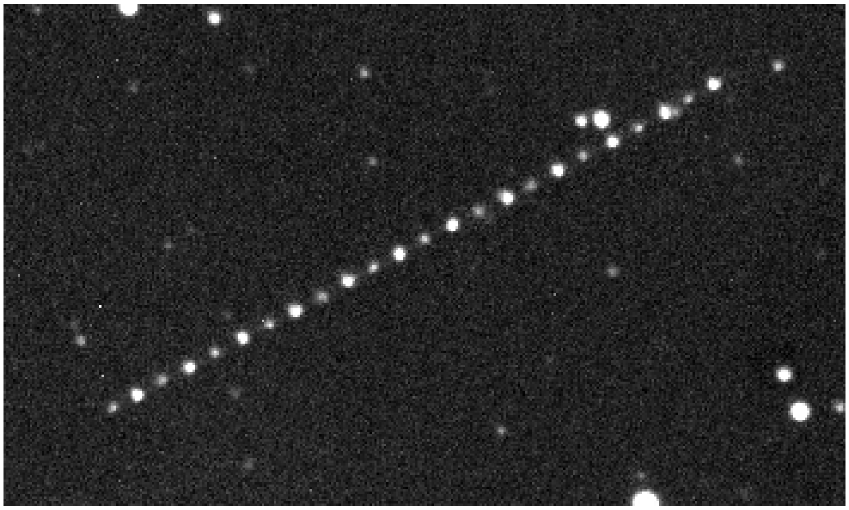


Figure 9: An image of the satellite SCC #20813 (Molniya 3-39) taken by CASTOR K. The highly reflective surfaces are easily detected by the CASTOR K facility. In periodic sections, however, the satellite disappears below the background noise of the image. It was therefore not possible to find the endpoints of this highly broken streak simply because of the high variability in the satellite's apparent light curve.

Satellite Phase Angle: A satellite's apparent brightness greatly depends on the angle at which the observer is seeing it. The phase angle of a satellite is simply the angle at the target satellite subtended by the observing facility and the Sun. If the phase angle is small (near 0 degrees) the satellite is nearly on the opposite side of the facility from the Sun. In this case, the satellite is nearly fully illuminated and is easily seen, unless the Earth blocks the sunlight to the satellite, in which case it will be eclipsed. If the phase angle is large (near 180 degrees) the satellite is nearly between the facility and the Sun. The satellite will nearly be silhouetted and therefore will be very dim. The satellite scheduler can be programmed to calculate this satellite phase angle using the elongation of the satellite (the angle at the facility subtended by the observing facility and the Sun), the range of the satellite, and the distance from the Earth to the Sun.

Accuracy and Age of the Satellite's Orbit Elements: Two-line element sets (TLEs) for unclassified satellites can be easily obtained over the Internet. One must be careful about the age of specific TLE's as the orbit elements change constantly for every satellite in orbit. Sometimes some Molniya payloads and their rocket bodies have out of date element sets. These objects would almost surely be missed by CASTOR K simply because the predictions based on these out of date orbit elements would have very high errors. This is particularly true of decaying satellites, as their orbit elements, especially their mean motions (orbits per day), change rapidly due to the satellite's rapidly decreasing altitude at apogee. It is not uncommon for a decaying Molniya satellite to be found a degree away from its predicted position, even though the orbit elements used to generate the prediction is only 12 hours old.

The satellite scheduler works by first importing ephemeris files generated by the Satellite Tool Kit (STK) satellite orbit analysis software. These ephemeris files contain the prediction times, the predicted Azimuth and Elevation coordinates and the range of the satellite from CASTOR K. The CASTOR K robotic mount uses an equatorial coordinate system based on R.A. and Dec. The scheduler performs the necessary coordinate transformations based on the CASTOR K facility's geodetic latitude and longitude. After new ephemeris files containing the equatorial coordinates are generated, the scheduler first finds that satellite that is at the highest elevation (nearest the Zenith). A script begins to be generated that first lists the preliminary target satellite and the appropriate CCD camera exposure times. The scheduler then looks in the ephemeris files for that satellite that is nearest in R.A. and Dec. to the last target satellite within a reasonable time after the previous satellite has been imaged. It is not desirable for the telescope to slew to the closest satellite coordinates only for the system to wait 4 hours until the satellite finally passes through those coordinates.

The mount's R.A and Dec. slew times as well as the dome's azimuth slew times are considered when determining the total time for the system to align itself on the next target satellite. The longest time among these is considered the total time of slew. The scheduler then tries to determine the time for the system to wait until taking the images of the satellite. The satellite coordinates given to the scheduler are those such that the satellite will be theoretically near the center of the field of view of the camera at the time corresponding to the predicted coordinates. In order to obtain the maximum possible access to the satellite within the field of view, it is necessary to provide a time offset based on the satellite's apparent position angle of travel and its apparent angular velocity. That way images can be taken such that the satellite will be seen within the field of view. Of course, the camera's total exposure time and downloading time have to be accounted for. Two images are taken for each target satellite so the total imaging time is doubled. The time of the end of the imaging session for the satellite is calculated and stored in order for the scheduler to determine the next satellite target.

The satellites that are on that side of the meridian that the first target satellite was on are imaged first. This is to ensure that the telescope does not have to cross the meridian until absolutely necessary. The scheduler also has to take crossing the meridian into consideration. It must find that satellite on the other side of the meridian that has the closest R.A. coordinate to the last satellite's R.A. coordinate with 12 hours added to it. This way, when the mount does slew through the North Celestial Pole (NCP), it will take the minimum possible time to reach the next target satellite. The scheduler will then generate a script listing the satellites on this opposite side of the meridian, etc. This way, the mount will cross the NCP, and therefore the meridian, only when necessary. This maximizes the target acquisition rate for an automated CASTOR K.

Total Time of Target Tracking = Longest Slew Time (R.A. or Dec Axis of Telescope or Azimuth of Dome) +
2 Images * (CCD Camera Exposure Time + CCD Download Time)

SlewToRADec, 20h50m01s +66d45m27s, 232112000273000426
WaitUntil, 09/28/2000 20h04m26s,
TakeImage, 25,
TakeImage, 25,
SlewToRADec, 21h11m54s +63d42m03s, 200522000273000600
WaitUntil, 09/28/2000 20h06m00s,
TakeImage, 20,
TakeImage, 20,

Table 3: The total tracking time calculation and the example Orchestrate script produced by the satellite scheduler.

Table 3 is an excerpt from an actual Orchestrate script generated by the Satellite Scheduler that was used for an automated Molniya satellite tracking run that was performed on September 29, 2000 (U.T.). There are two target objects listed here. The first line (SlewToRADec) is straightforward, except for the large 18-digit number following the destination R.A. and Dec. coordinates. In this number is the satellite SCC number ID and the time when the CCD shutter first opened to capture the satellite. The first five numbers comprise the SCC number. Thus, the numbers 23211 in the first line correspond to the satellite SCC #23211 (Molniya 3-46). The remaining digits indicate when the CCD camera shutter first opened to capture the image of the satellite. The year, day of year, hour, minute and second are indicated. Thus, 232112000273000426 indicates that at 00:04:26 U.T. on the 273rd day of the year 2000, the camera shutter opened to capture two images of the object SCC #23211. This comment section is used mainly for identification purposes and is not used for actual tracking or imaging. The second line (WaitUntil) is the line that tells the system to standby until such time as the satellite enters the field of view of the camera (20:04:26 E.D.T. on September 28, 2000). The third and fourth lines denote the CCD exposure lines that instruct the CCD camera to take two 25 second exposures. The cycle starts again with the 5^{th} line. The next target is SCC #20052 (Molniya 3-35) which is about 4 degrees away from the last target. The shutter is scripted to open near 00:06:00 U.T. on day 273 of the year 2000 and the camera will take two 20 second exposures. The difference in the exposure times indicates that the satellite SCC # 23211 is moving at a lower angular velocity than the satellite SCC #20052. The whole cycle repeats itself for every satellite for the remainder of the tracking run. Notice that the satellites themselves are not mentioned in the actual command script, just their predicted coordinates.

TELESCOPE POINTING AND IMAGE ACQUISITION

Accurate telescope pointing is absolutely essential to an automated satellite tracking facility, especially if the telescope is pointed to many different areas of the observable sky during a tracking session. The error between the telescope's destined coordinates and the telescope's final destination coordinates must be small enough to allow the target satellites to be imaged successfully. For CASTOR K the largest pointing error occurs when the telescope has to cross the meridian. The larger the angle that the mount has to slew, the larger the effective pointing error it will experience. Pointing error tests have been made with CASTOR K and the results are promising as long as the mount stays on one side of the meridian at all times. When crossing the meridian, it has been found that the pointing error of CASTOR K can be as high as 5 arc-minutes in Right Ascension. Because CASTOR K has an 11.5 arc-minutes by 11.5 arc-minutes field of view, this is a large pointing error resulting in a large data loss if not corrected. Figure 10 illustrates the latest pointing error determination of the GT-1100 robotic mount that CASTOR K currently uses.

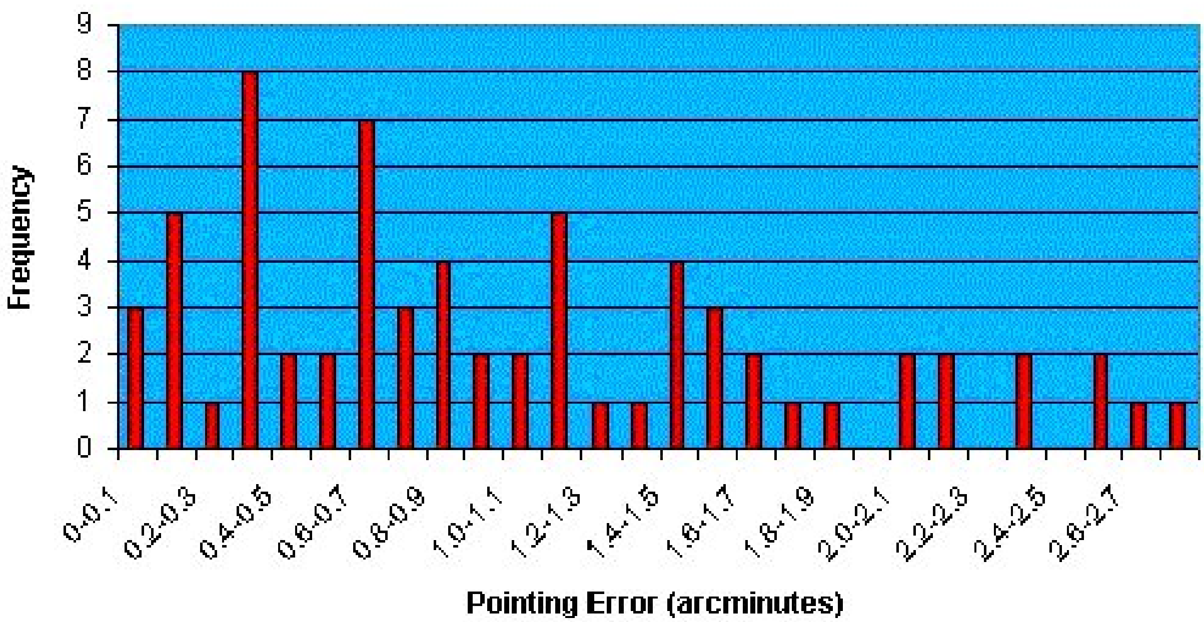


Figure 10: The Pointing Errors of the GT-1100 Robotic Mount Used by CASTOR K. This histogram was the result of 100 random slews to different parts of the celestial sphere accessible to CASTOR K. The telescope was kept at one side of the celestial meridian during the entire test. Pointing errors were determined by comparing the mount's destination coordinates stored in the image headers with the actual coordinates of the center of the image. The errors are based on a radial distribution away from the center of the image. The pointing errors of 0 to 1 arc-minute seen here are the result of angle slews of less than 20 degrees. The pointing errors of 1 to 2 arc-minutes are the result of slews of more than 20 degrees and less than 90 degrees. The errors of 2 arc-minutes and above are the result of slews of over 90 degrees or slews occurring at declinations over 70 degrees.

Image acquisition concerns also need to be addressed in order for CASTOR K to provide the most accurate temporal and metric data possible. A major concern is timing. All astrometry (metric) data for a satellite streak must be accompanied by an accurate time (temporal) for each end point. CASTOR K uses a GPS receiver to provide accurate and trustworthy timing. Every time the CCD camera shutter is triggered, the triggering time (whether opening or closing the shutter) is recorded in the header of the respective image file using the GPS timing as the standard. These times are recorded to the 7th decimal place, corresponding to 0.1 microsecond accuracy. In order for this accuracy to be true, however, the mechanical shutter of the CCD camera must clear the entire CCD chip in less than 0.1 microseconds when opening or closing, which is highly unlikely. In order to determine the true accuracy of the imaging system, it was necessary to create an apparatus that could be triggered at the same time as the camera shutter. It also had to provide some kind of display that the CCD could see itself such that when the camera shutter was triggered, the display would also be triggered such that the CCD could capture the changing display. The result would be an image with a small gap wherein the triggering is occurring, but the shutter has not quite cleared the physical CCD chip area. The time between the triggering and shutter completely clearing (or covering) the CCD chip would be the offset time for the recorded time in the image file header. The display device that was used at SSRAL was an oscilloscope. The calibration circuit used a decaying/charging 1 microfarad capacitor. The setup was prepared such that the capacitor was kept fully charged (at a specific DC voltage) until the CCD camera trigger was activated to open the shutter. After the shutter trigger was enabled, the capacitor began discharging and the camera shutter began to open. Theoretically, there would be a very small time in which the shutter had not cleared the CCD chip and the capacitor was discharging. This would show up as a gap in the CCD image of the oscilloscope display (see Figure 11). When the CCD camera shutter was triggered to close, the capacitor would be triggered to recharge. The shutter itself however would not fully close at exactly the same time, and therefore the charging capacitor (displayed by the oscilloscope) would be seen by the chip for a small amount of time (see Figure 11). The final result of this determination showed that the accuracy of the GPS/CCD recorded time was no less than 1 millisecond. The time offset for a shutter opening was 3 +/- 1 ms, while for closing it was 5 +/- 1 ms. This accuracy can be improved if a more in-depth investigation of the shutter opening/closing is done using specific sections of the chip instead of the entire chip. With great patience a timing accuracy of 0.1ms may be achieved in this way.

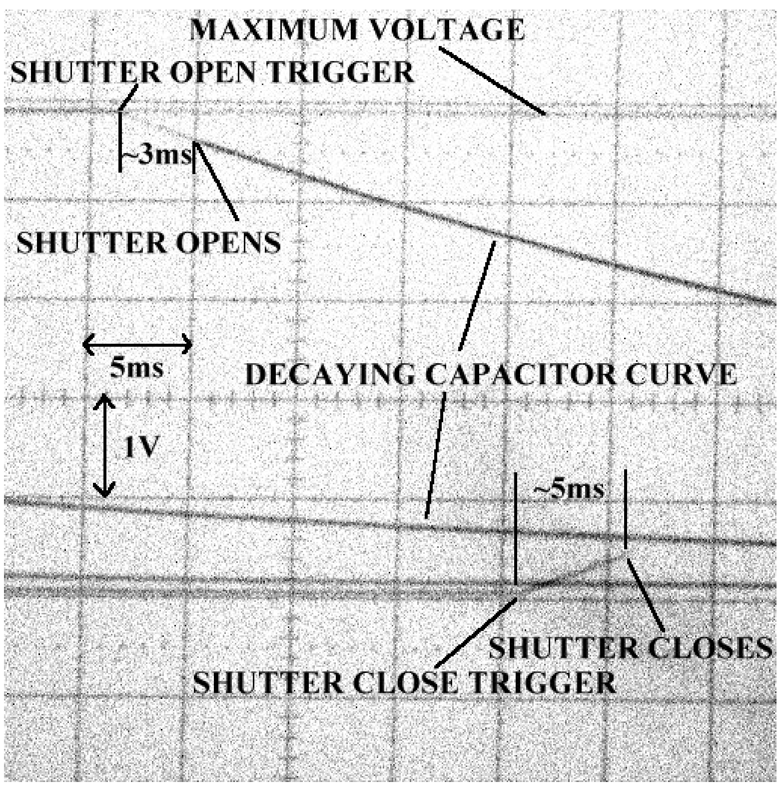


Figure 11: One of the Resulting Images from the CCD Camera Timing Accuracy Tests Performed at SSRAL. The shutter would clear the CCD chip approximately 3 milliseconds after the initial opening trigger (+4V). The shutter would then close 5 milliseconds after the closing trigger (0V). This method resulted in a 1-millisecond accuracy for CASTOR K image acquisition. This method can be refined to allow a 0.1-millisecond accuracy if specific sections of the CCD image are analyzed.

IMAGE ANALYSIS

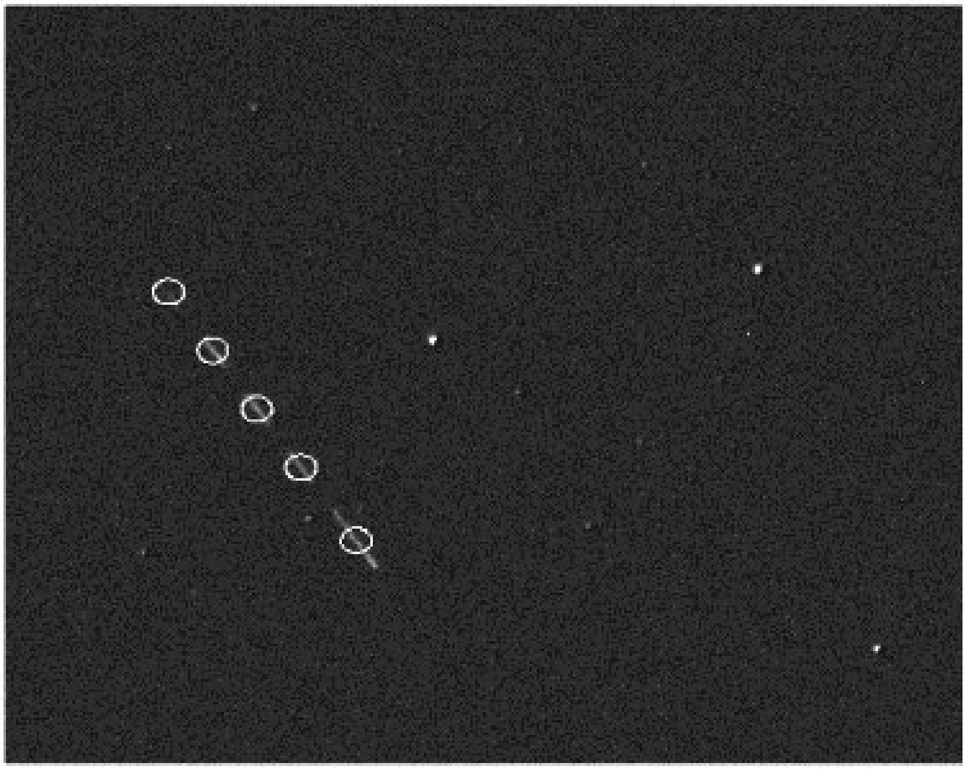
After images have been acquired, it will be necessary to extract as much astrometry data pertaining to the satellite streaks as possible. The temporal data is already stored in the image header file, but the shutter delay offsets will have to be added. It will be necessary to read the temporal data from the header file and automatically add the camera shutter offsets (+3ms when opening and +5ms when closing) to the final tracking data file. The accuracy of these times must be limited to the best accuracy obtained using the CCD camera shutter calibration apparatus.

Automated streak detection and astrometry is essential to the efficiency of the final image analysis. Manual streak detection and astrometry is currently being done at SSRAL. Obviously it would certainly take many man-hours of work to manually find streaks and to manually perform the astrometry on the detected end points for the hundreds of images that CASTOR K would be producing every suitable night. Mr. Phil Somers of the Defense Research Establishment Ottawa (DREO) has been developing a streak detection algorithm that automatically finds satellite streaks using the Hough Transform. Basically, the Hough transform uses a streak slope search technique to find satellite streaks. Since the position angle of a satellite streak (see Figure 8) is closely related to the streak's slope, a search refinement technique can be implemented that would greatly cut the slope search time. A specific satellite's predicted position angle can be added to the Orchestrate script such that when the image analysis is taking place, the script can be used to inform the streak detection algorithm of what range of slopes to look for. This range of slopes would be nearly that of the slope (derived from the position angle) of satellite travel predicted earlier by the satellite scheduler.

In order to use this automated streak detection software two images of equally identical star fields must be taken. This is the main reason why two images are produced per target object. One of the two images is automatically subtracted from the other (see Figure 12). Theoretically, the resulting image would be black except for one bright streak (above the background noise) and one dark streak (below the background noise). Thus the satellite streak in both images are contained in a single image, albeit negatives of each other. The Hough transform is then used to detect the remaining bright satellite streak. Automated astrometry software by NetCreations called PinPoint is then used to determine the coordinates of specific parts of the streak. This streak detection software has been tested in a limited sense, and results have been promising (see Figure 13). Successful streak detection takes as little as a 10 seconds per target and the astrometry accuracy is good to a minimum of about 2 arc-seconds.

Figure 12: The Subtraction of Two Satellite Images with Identical Star Fields. The first image is subtracted from the second to produce an image that contains just the satellite streak. This process is used to prevent the streak detection algorithm from accidentally confusing a bright line of stars with a satellite streak. The data contained in the streak can then be extracted using the PinPoint astrometry engine. The two images contained the satellite SCC #8601 (Molniya 1-32) a known tumbler. The exposure times for the first image were from 00:16:37.754 to 00:17:02.951 U.T. on September 27, 2000. The second image exposure times were from 00:17:19.104 to 00:17:44.301 U.T. on the same day. Note that although the satellite is tumbling in space, the endpoints for the streak are very well defined in the final subtracted image. The centers of all three images are at coordinates 23h 28m 44.0s in R.A. and +63 degrees 7 arc-minutes and 53 arc-seconds in Dec. North is at top and east is at left in all three images.

Not all the image pairs taken by CASTOR K will have identical star fields. Factors such as periodic error in the robotic mount's R.A. gear can shift the scope enough in R.A. that the image center of the first image does not match that of the second. For this problem, a periodic error correction may be necessary for the mount, or a way to shift the center of the second image during the analysis such that its star field will match the first. That way, any two images with nearly identical star fields could be subtracted. These concerns will be addressed in early 2001.



PIXEL		R.A.	Dec.
x = 190.241	y = 345.021	08:59:08.691	44:10:00.305
x = 161.095	y = 298.379	08:59:12.362	44:11:03.387
x = 137.779	y = 261.065	08:59:15.299	44:11:53.852
x = 114.463	y = 223.751	08:59:18.235	44:12:44.318
x = 091.146	y = 186.436	08:59:21.172	44:13:34.783

1CACS FORMAT

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))U00115299072760920048290000441668 0859087 22$$
))U00115299072760920048315000441843 0859124 22$$
))U00115299072760920048335000441983 0859153 22$$
))U00115299072760920048355000442123 0859182 22$$
))U00115299072760920048375000442263 0859217 22$$
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Figure 13: The Output of Phil Somers' Streak Detection Algorithm. The image is the result of the subtraction of two images with nearly identical star fields. A few of the brighter stars are noticeably left over in this example. Nevertheless, the streak detection and astrometry are successful. The image was taken using a shutter strobe option that allows more astrometry data to be extracted due to the multiple streaks. In this example, five separate streaks from the same satellite are analyzed. The pixel value, and the determined R.A. and Dec. of the center of every streak are displayed. Also displayed is the output coordinates in the "1st Command and Control Squadron" (1CACS) tracking data format. Once fully operational, this streak detection algorithm will be instrumental in the automation of the CASTOR K facility. The satellite contained in this image is SSC #7276 (Molniya 2-09), the oldest of the Molniya payload satellites still orbiting Earth. It is also a known tumbler.

ORBIT DETERMINATION

Once sufficient tracking data has been collected for the target objects specified in a satellite schedule, it is necessary to perform an orbit determination for each satellite in order to update their orbit elements. The Precision Orbit Determination System (PODS) is used for this orbit determination. One question that arises when performing an orbit determination is what tracking strategy is the best to obtain the most accurate orbit elements while at the same time minimizing the amount of data needed to achieve this accuracy. At the same time, it is prudent to ask if it is necessary to have different tracking strategies for different types of satellite orbits.

2Lt Charles MacLeod of SSRAL is investigating different Molniya satellite tracking strategies for his master's thesis. His investigation should be completed by April 2001.

REMOTE OPERATION CONCERNS FOR CASTOR K

One of the main objectives of the CASTOR project is to provide a remotely controlled satellite tracking facility. In the time that SSRAL has used CASTOR K, it was easy to correct a minor problem either in the control room or the dome by simply being there to fix the problem. This is simply not acceptable during remote operation. In order to provide a trustworthy and effective remote control system for CASTOR K, every conceivable concern regarding remote operation of the facility must be addressed. The primary concern is security. Remote operation will depend on the Internet or some other computer networking service. Hackers can cause serious damage to the CASTOR K hardware and software if they obtain full access. Using secure military computer networks is one option. Another option would be to set up a userid and password for each vital CASTOR K component.

Another concern is the remote control software that will be used. Preliminary tests with Symantec's pcAnywhere software have yielded excellent results for speed and link stability. This software also has the ability to lock the main workstation if necessary. Only the proper user id and passwords will unlock the workstation again. This is added to the initial user id and password that is needed to connect to the main computer in the first place. Remote operation using pcAnywhere has been carried out twice in the month of September 2000, once from a separate building within RMC and again from Ottawa (see the milestones section for info). AT&T's Virtual Network Computing (VNC) software has also been used for remote operation. This software has definite advantages over pcAnywhere. One such advantage is that it is a Java-based cross-platform utility. The main computer for CASTOR K is a PC. Using VNC, one can drive the CASTOR K facility using a SUN workstation (using UNIX) or a Macintosh (using MacOS) and even Linux. Another advantage is that it is a freeware application available over the Internet. PcAnywhere is only shareware in that after 30 days the software will no longer work until a license is purchased. The downfall with VNC is that its speed over long distances is very slow compared to pcAnywhere. Further tests will be carried out in 2001 to determine the best remote control software for both automated and manual remote control of the CASTOR K facility. The minimum requirement is that it must be possible to use CASTOR K remotely from any PC without having to install any other software other than the remote control software. This way, easy, but secure, access to the facility is available from anywhere in the world.

When the October 8, 2000 remote operation of CASTOR K took place from Ottawa, the images that were taken were slightly out of focus. This was due to a temperature change at the facility. The change in temperature had slightly deformed the primary mirror of the telescope so that its focal length changed slightly. No one was at the CASTOR K facility to correct this problem. It was decided at SSRAL to develop a remotely controlled focus control in order to compensate for future temperature changes at the facility. This focus assembly consists of a stepper motor attached to the focus knob that is controlled by an interface box connected to the parallel (LPT) port of the CASTOR K main computer. A simple program controls the speed and number of steps the stepper motor moves such that precise focus control is possible. Using pcAnywhere (for example) one can run this simple program remotely and thus be able to focus the telescope from the remote site. SSRAL is also pondering the addition of a temperature sensor such that when the temperature changes, the focus control will automatically compensate.

Any computer is prone to sudden hang-ups and major crashes. When using CASTOR K remotely one must be able to open the dome shutter and unpark the telescope at the beginning of the observing session and close the dome and park the telescope after the session. The occasion may arise when the main computer will hang or crash during an observing session. If nobody is at the facility to reboot or restart the computer, none of the CASTOR K components can be controlled. This is an extremely dangerous scenario, especially if a rainstorm suddenly rolls in. With the dome open, the telescope and CCD camera are exposed to rain and/or snow. PcAnywhere and VNC can send a CNTR-ALT-DEL command to the main computer if a minor hang-up occurs. If the computer should crash, the link will probably be broken and cannot be re-established until the main computer is restarted. SSRAL has developed a remotely controlled reset interface box that basically resets the main computer should it seriously crash or hang. A redundant computer located near the CASTOR K main computer will be on constant standby. If the main computer should crash, one can connect to the redundant computer using pcAnywhere (or equivalent) and launch a small program that will trip the main computer's reset switch. The main computer will reboot and normal operations can continue. It will be necessary from time to time to test the link between the remote terminal and the redundant computer at the facility in order to confirm that the redundant computer will be ready for an emergency.

SUMMARY AND CONCLUSIONS

When completed, CASTOR K will be the first totally automated and remotely controlled optical satellite tracking facility in Canada. The research and development that is being done on this facility will be used to construct the second (CASTOR S) and third (CASTOR V) CASTOR facilities. The CASTOR S and CASTOR V facilities will be located in more remote areas than the CASTOR K site is, and therefore the safeguards mentioned in this paper are especially vital to these two sites.

Automation of CASTOR K will be completed as soon as the four major pieces of research and development are completed. The scheduling software is currently in its beta version and will be modified to determine the predicted angular velocity and position angles of the satellites using ephermeris files generated by STK. The tracking and image acquisition stage is near completion. The question of correcting the telescope pointing error when the mount crosses the meridian still remains. This may be corrected by simply using a CCD camera with a wider field of view. The image analysis portion is also near completion. Phil Somers of DREO is still working on perfecting his streak detection algorithm and serious testing of this software will begin in early 2001. 2nd Lieutenant Jeremy Hansen of SSRAL has developed another streak detection and astrometry software for use in low-earth orbit satellite detection and analysis. This might be modified for high range satellites and low field of view systems. Orbit determination strategies for Molniya satellites are being investigated by 2nd Lieutenant Charles MacLeod and will be completed by mid 2001.

Remote operation of the CASTOR K facility will be investigated fully in early 2001. The remote operation of CASTOR K will be thoroughly investigated and tested in time for the construction of CASTOR S and CASTOR V in mid 2001. It is expected that the construction and automation of all three facilities will be complete by 2002.

ACKNOWLEDGEMENTS

The Space Surveillance Research and Analysis Laboratory (SSRAL) currently has four people working on the CASTOR K project. Dr. Thomas J. Racey is the Head of the CASTOR K and Molniya Satellite Tracking Projects. Mr. Michael A. Earl is the Senior Technician of the SSRAL and for the CASTOR K facility. He will also be heavily involved in the construction and maintenance of both the CASTOR S (Suffield, Alberta) and CASTOR V (Valcartier, Quebec) optical satellite tracking facilities. 2nd Lieutenant Charles MacLeod is currently working on the orbit determination strategies for CASTOR K for his master's thesis at RMC. 2nd Lieutenant Jeremy Hansen has completed a study into automated streak detection using the Hough transform for low-earth orbit satellite reconnaissance for his graduate thesis at RMC.

Thanks to Lieutenant Colonel Phil Somers (Retd.) at the Defense Research Establishment Ottawa (DREO) for his development of the automated streak detection algorithm for use in image analysis and for his research into alternative remote PC control software.

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