PROGRESS REPORT FOR THE CANADIAN AUTOMATED SMALL TELESCOPE FOR ORBITAL RESEARCH (CASTOR) SATELLITE TRACKING FACILITY

Mr. Michael A. Earl and Dr. Thomas J. Racey: The Space Surveillance Research and Analysis Laboratory
Department of Physics, Royal Military College of Canada, Kingston, Ontario, Canada

Abstract

Planning and constructing an optical satellite tracking facility is a difficult task, especially when considering the various hardware and software packages that are available. Once the initial construction has been completed, the different components of that facility have to be tested for accuracy. This paper will describe the progress of the planning and testing of the CASTOR satellite tracking facility located in Kingston, Ontario, Canada.

Introduction

The CASTOR satellite tracking facility has been manually operational since January 29, 2000. Testing of the CASTOR facility involves four specific concerns. The first of these concerns is the scheduling of those satellites that will be accessible to CASTOR at any given time of night. The second is the tracking and the image acquisition of the aforementioned satellites. The third is the analysis of the acquired images. Lastly, the final orbit determined from the data extracted from the images has to be addressed.

Completion of the CASTOR system is expected by the summer of 2000. At that time it is hoped that it will be routinely tracking Molniya and other high eccentricity satellites on a regular basis. Once the entire system is operational, it will provide a blueprint for future CASTOR sites across the country.

The Space Surveillance Research and Analysis Laboratory (SSRAL) are using the CASTOR facility to track and study Molniya payload satellites. The Molniya payload satellite will therefore be used as the example throughout this paper.

CASTOR Hardware and Software

The SSRAL had to address both accuracy and expenditure concerns when choosing the hardware and software that would comprise the CASTOR apparatus. Table 1 describes the hardware that CASTOR is comprised of and Table 2 describes the software that controls it.

Celestron Model CG-14 14 Inch Aperture Schmidt-Cassegrain Reflecting Telescope	This telescope is the optical tube assembly (OTA) of CASTOR.
Software Bisque Paramount Model GT-1100 Robotic Telescope Mount	This telescope mount is boasted to be one of the most accurate robotic telescope mounts for amateur astronomy. It is a German Equatorial design.
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	The GPS receiver will provide a millisecond accuracy time base for satellite streak end-point determination.
Ash Manufacturing Model REA 10 Foot 6 Inch Diameter Observatory Dome	This observatory dome contains the CASTOR hardware mentioned above. A Lanphier shutter window provides a weather-tight environment for the hardware contained within.
Merlin Controls Dome Control Hardware for Ash Dome	This hardware will enable the dome to automatically line up its Lanphier shutter window to the telescope's pointing position.

Table 1: The hardware used by the CASTOR satellite tracking facility.

Software Bisque's TheSky Astronomical Software Level IV Version 5	This software is the main astronomical software for CASTOR. Satellite two-line element sets (TLEs) can be loaded so that the user can see the current satellite position superimposed onto the simulated sky for his/her location.
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 astrometry tool.
Software Bisque's T-Point Telescope Pointing Software	This software is used to correct for any predictable pointing error, such as inaccurate polar alignment.
Software Bisque's Orchestrate Telescope and Camera Automation Software	This software allows the user to write 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 software is the main satellite analysis tool for CASTOR. It allows the user to see any satellite's ground track and actual orbit and provides access data 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. This module will be used mainly for satellite scheduling.
Analytical Graphics' Precision Orbit Determination Software (PODS) Module	WSPOD is the main orbit determination software used by CASTOR.
NetCreations PinPoint Astrometry Software	This software is freely available from the Internet and can be used for accurate astrometry of any image of any scale or rotation.
JavaScript Streak Detection Algorithm	This software has been developed by Mr. Phil Somers of the Defense Research Establishment Ottawa (DREO)
Software Bisque's Automadome Dome Automation Software	This software will be the main interface between TheSky and the Merlin Controls dome automation hardware.

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

The Merlin Controls dome hardware and the Software Bisque Automadome software will not be installed until the summer of 2000. In the meantime, the other hardware and software components will be thoroughly tested so that a smooth transition between manual and automatic mode can be attained. Figure 1 demonstrates how the various hardware and software components will be used when CASTOR is fully automated.

Scheduling

When performing any satellite tracking routine, one must know which satellites will be available to track for that facility's location and viewing constraints. The Satellite Tool Kit (STK) from Analytical Graphics can be used to do a preliminary assessment of those Molniya payloads that are accessible from SSRAL at any time. STK is run on a Unix platform, while TheSky and Orchestrate is run from a PC. It is obvious that a user could simply run STK and determine the accessibility of a satellite, generate tables, manually transfer the data files over to the PC and create an Orchestrate script from that. This would be a time consuming effort, since many satellites will be accessible to the facility in question. The solution would be to use an interface tool between the STK (Unix) software and TheSky (PC) software. This tool is the STK/Connect module. It enables the user to run STK from a PC as well as interface to download and upload information. A scripting utility can be used in order to automate the process of starting up STK, loading in the satellite element sets (elsets) desired, generating accessibility text files, and uploading these files to the PC. The files are then automatically analyzed and the Molniya elsets pertaining to those accessible Molniya payloads are extracted and saved in TheSky's local satellite elset directory. An Orchestrate script is automatically created as this is occurring. This script will contain the accessible Molniya satellites and the correct integration times for the CCD camera pertaining to each of the respective ranges. Therefore it will be possible for CASTOR to determine which Molniya payloads it will track for any specific night.

Scheduling must also involve the preliminary determination of the facility's constraints. Factors such as the lowest tolerable elevation of the satellite, the satellite's observed angular velocity (dependent on the range), and the satellite's phase angle are critical. The scheduling software can determine these quantities while it writes the Orchestrate script. As a result those satellites that are at a high elevation at the beginning of a session will appear in the Orchestrate script until such time as the satellite drops below the threshold elevation defined by the user.

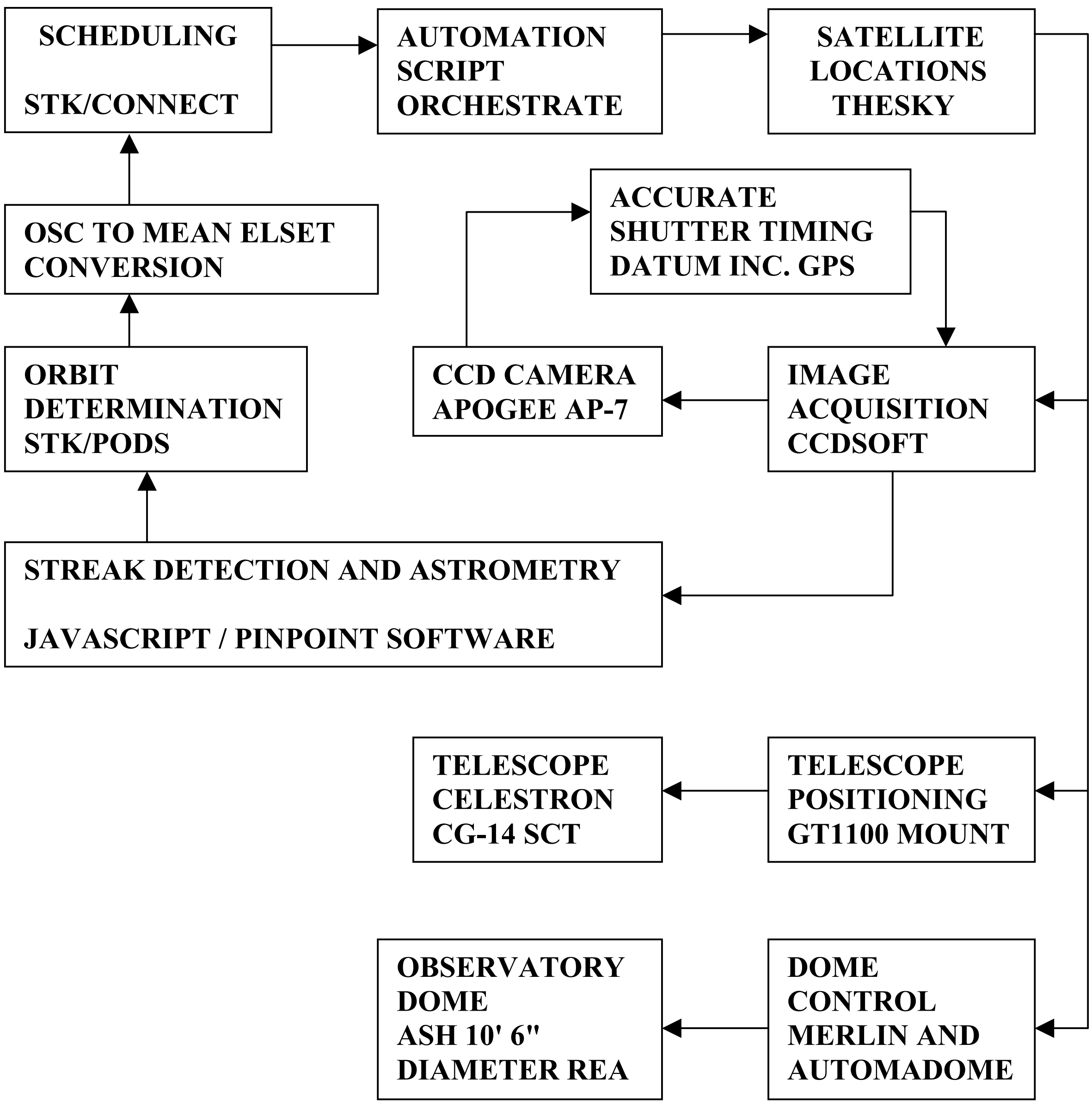


Figure 1: The integration of the CASTOR hardware and software.

Satellite Tracking and Image Acquisition

Once the Orchestrate script is written TheSky will access the elsets that pertain to those objects in the Orchestrate script. The Orchestrate script can then be run to perform the satellite tracking for that night. This portion of the CASTOR facility is operational with the exception of the automatic dome control. The robotic mount (GT-1100) will slew the Celestron telescope to point to the satellite that pertains to the Orchestrate script. The CCD camera will then take an image for the specified exposure time. The CCD camera and the GPS receiver are connected in the sense that when the shutter of the camera opens/closes the time (accurate to a millisecond) of both events are stamped on to the FITS header of the image file. Thus, the precise times pertaining to the endpoints of the satellite streaks are known. The image will then be downloaded and automatically saved. The CCD camera also has a shutter strobe capability whereby the camera can be turned on and off for specified lengths of time within the main exposure time. This is used to determine the direction of the satellite's travel in the image and provides a larger set of data points to analyze per image. This may improve the accuracy of the final orbit determination. Figure 2 is an actual image taken with CASTOR that demonstrates this shutter strobe feature.

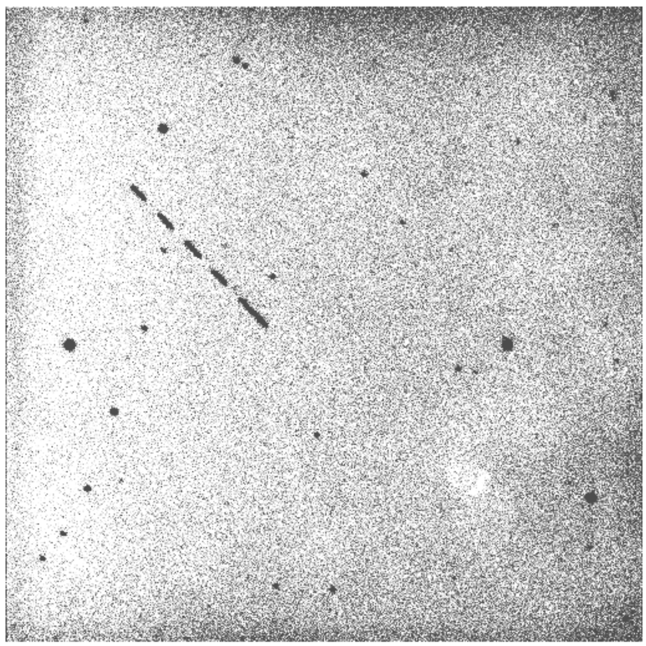


Figure 2: An image of the Molniya 1-77 payload satellite (SSC 20583) taken by CASTOR. The shutter strobe option has been engaged and has been set for a larger exposure time at the beginning of the main exposure (the longest streak) and for smaller off-on exposures afterward. This was a 30-second exposure in which the first exposure was six seconds, followed by an off-on strobe of three seconds each. The satellite is therefore travelling right to left in the image. The satellite was 35000 km in range from the CASTOR facility at the time of imaging.

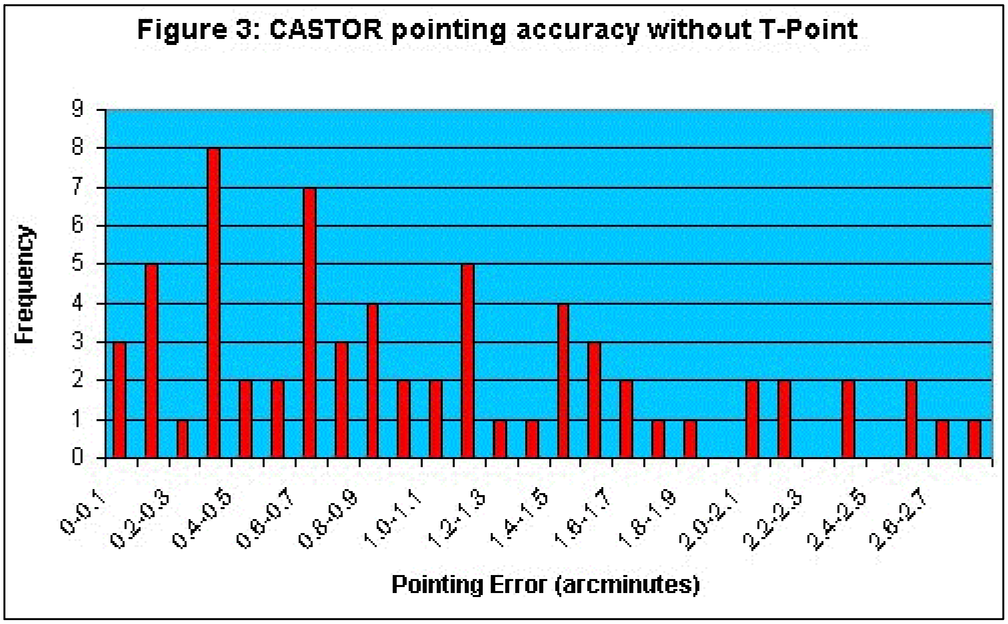
The shutter strobe option is also useful for those circumstances where the satellite either exits or enters the CCD camera's field of view while the camera shutter is still open. This is often the case when decaying satellites are being tracked. If the strobe were not employed in this situation, only one data point pertaining to the only endpoint in the image would be recorded. It would be necessary however to define standard strobe times for specific main exposure times. Since the exposure times would be dependent on the range (or apparent angular velocity) of the satellite, this can be done in a reasonable time by trial and error. During one such tracking session of Molniya payloads such a list was created. Table 3 lists the results. To describe the table, the first row will be used as an example. If the Molniya payloads were 5000 to 10000 km in range from the CASTOR facility the main exposure time would be one second. This would be the exposure time in which the entire satellite streak could be kept within the field of view of the camera. During the main exposure time (of 1 second) the camera shutter would first stay open for 0.2 seconds. The camera shutter would then close for 0.1 seconds and then open again for 0.1 seconds, etc. until the main exposure time has elapsed. This would produce a long streak, followed by four streaks of equal length that would be half the length of the first streak. If the satellite does exit the field of view during this exposure, it is possible to recover the times of each endpoint that can be seen in the image using the strobe times. Those Molniya payloads whose ground tracks are over North America generally reach ranges of 40,000 km at apogee. Those Molniya payloads whose ground tracks are over central Russia can still be seen by CASTOR but at lower elevations and ranges that typically reach 43,000 km at apogee. This is what range of 40000 + km is referring to in Table 3.

Range (km)	**Main Exposure (sec)**	**Strobe Times (sec)**
5000 to 10000	1	0.2, 0.1, 0.1
10000 to 15000	2	0.4, 0.2, 0.2
15000 to 20000	5	1.0, 0.5, 0.5
20000 to 25000	10	2.0, 1.0, 1.0
25000 to 30000	20	4.0, 2.0, 2.0
30000 to 40000 +	30	6.0, 3.0, 3.0

Table 3: CASTOR exposure and shutter strobe times for different Molniya payload ranges.

The field of view (FOV) of the CASTOR system has been determined to be 11.5 by 11.5 arc-minutes. This means that a very small area (about 1/132 of a square degree) is being imaged per exposure. In order to ensure that the satellite is within the FOV during the entire CCD exposure the telescope mount must have accurate pointing over the entire visible celestial hemisphere. Since the GT-1100 is a German Equatorial mount, precise polar axis alignment is necessary to ensure that the pointing accuracy is at or under 1 arc-minute. Polar alignment of the mount was done through a high power eyepiece. The polar axis of the scope was first found by disengaging the right ascension (R.A.) gear so that the R.A. axis moved freely. The star field was viewed through the eyepiece while the R.A. assembly was rotated. The scope was then carefully slewed in declination until the star field would not move out of the FOV while the R.A. assembly was rotated. Once the polar axis had been found, it was aligned to the epoch 2000 North Celestial Pole (NCP). Once the mount was polar aligned, it was necessary to determine the pointing accuracy over a wide range of slew angles and declinations. Since Molniya payloads were being used as an example, the pointing accuracy was determined by slewing the scope within the northern part of the equatorial sphere. This area is where the Molniya payloads (as well as the SL-6 rocket bodies that placed these payloads in their orbits) are most likely to be found. A total of 100 slews were performed in this region of the sky at declinations ranging from 0 degrees to +80 degrees. The results were both surprising and encouraging. The majority of the pointing errors were between 0.1 and 1.9 arc-minutes. A closer inspection of the results revealed that the smaller pointing errors were encountered with small slew angles, which was expected, and that the larger pointing errors resulted from large slews and/or high declination slews, which is again not surprising. What was surprising was that although the polar alignment was done totally by eye (no CCD cameras involved) the pointing error did not exceed 3 arc-minutes over the entire (northern) sky for all declinations between 0 and +80 degrees. Figure 3 briefly illustrates the pointing errors encountered. The pointing error was determined by calculating the angular separation between the destination coordinates (contained in the FITS header of the image) and the true coordinates of the center of the image. The pointing error in Figure 3 is therefore the radial pointing error. Closer inspection of the pointing errors of the individual axes (R.A. and Declination) will be performed shortly.

The pointing accuracy of the robotic mount may be improved by using the T-Point telescope pointing software. T-Point can compensate for any naturally occurring source of pointing error (such as an inaccurate polar alignment). A T-Point model for CASTOR will be performed shortly. Judging by the encouraging results so far, a T-Point model may not significantly improve the pointing accuracy of the mount since the mount is rated as having an average radial pointing error of 2 arc-minutes. The decision whether or not to use a T-Point model would also depend on whether or not the pointing error encountered thus far is accumulative, i.e. the pointing error grows larger with each consecutive slew performed.



Looking at Figure 3, the lower pointing errors encountered (those from 0.1 to 0.5 arc-minutes) were those for slew angles of less than 10 degrees and for declinations between 0 and +60 degrees. The pointing errors of 0.6 to 2.0 arc-minutes were experienced for slew angles of between 10 and 30 degrees and for declinations of between 0 and +60 degrees. The higher pointing errors of 2.0 to 2.9 arc-minutes were experienced for slew angles of 10 to 20 degrees at declinations between +60 and +80 degrees. It may be necessary to use a specific T-Point model for the higher declinations in order to ensure optimum pointing accuracy in all parts of the observable celestial hemisphere.

While the robotic mount is pointing the telescope to the satellites' positions the shutter opening of the observatory dome must remain in synch with the telescope aperture. In order to have a totally automated tracking facility the dome must also automatically slew its shutter in azimuth and elevation. The Automadome dome control software and the Merlin Controls automatic dome hardware will provide this automation process. This component of the CASTOR facility will not be in place until the summer of 2000. In the meantime a manual dome control hardware system has been developed at SSRAL in order to make the facility functional manually. A wide-field video camera is installed on top of the telescope. This camera is connected to a monitor that is placed within the lab. This system provides real-time monitoring of the CASTOR hardware as it is being used. When the telescope is being slewed, the dome shutter opening can be manually lined up with the telescope aperture. When the facility becomes fully automated this system will remain in place as the manual override system.

Another concern to be addressed is the satellite acquisition rate. Both the R.A. and Declination axes of the robotic mount have maximum slew speeds of 1.5 degrees per second. The satellite acquisition rate can be maximized through careful scheduling. An automatic scheduler can be made to search for that satellite on the main schedule list that is the closest to the one last chosen i.e. search for that satellite that requires the smallest slew angle. This will ensure that the slew angles will be kept to a minimum and therefore keep the pointing errors small (with or without a T-Point model in place). The results of this planning would be automatically entered into the Orchestrate script. One major drawback in using a German Equatorial mount is that when the telescope has to slew to an area of the sky that lies on the opposite side of the celestial meridian from its last known position, it has to slew through the NCP to get there. If it doesn't do this it will slew the scope into the mount base causing damage. An automatic scheduler would have to take this into account in order to avoid a higher pointing error and a longer slew time that could decrease the satellite acquisition rate considerably.

Image Analysis

Once the images have been acquired, streak detection and astrometry on the detected streak end-points must be performed in order to extract the tracking data needed for the orbit determination process. At the present time the satellite streaks contained within the image are detected manually by eye. A JavaScript automatic streak detection software is currently being developed by Mr. Phil Somers of Defense Research Establishment Ottawa (DREO). This streak detection software will be used with auto-astrometry software called PinPoint. This auto-astrometry software uses the World Coordinate System (WCS) and the Hubble Guide Star Catalog (GSC) to perform astrometry that should be accurate within 1 arc-second provided that the streak detection software properly centroids the streak end-points and the GSC stars within the image. Testing of this software will begin shortly.

Orbit Determination

SSRAL currently uses the Precision Orbit Determination Software (PODS) for performing orbit determination. This software is a module of the Satellite Tool Kit (STK) therefore STK/Connect may be used to perform the orbital determination task automatically. PODS will use the tracking data files generated by the PinPoint astrometry software to update the osculating orbital elements of the satellite. To be able to use these orbital elements to track the satellite at a later time an osculating to mean element set conversion must take place. SSRAL has obtained a software package that can perform this conversion. Once the mean element set has been created, the scheduler can use it and the other determined elsets in STK to begin the tracking process once again. Once CASTOR is fully automated, an investigation into the most accurate technique of orbit determination will be undertaken. This will involve a study into which part(s) of the Molniya orbit to analyze in order to maximize the accuracy of the orbit determination. It will also involve different techniques of image acquisition and timing that will simplify the image analysis and increase the accuracy of both the streak detection and the astrometry process.

Present and Future Plans for CASTOR

At the present time, CASTOR is still in its planning and testing stages, but it can be used for high eccentricity orbit satellite tracking (such as Molniya payloads) and geo-stationary payload and rocket body tracking. At this time scheduling and image analysis is still time consuming but steps will be taken to automate both processes. At present only a small amount of satellites can be tracked at a time in order to prevent a data glut from occurring.

CASTOR will be one of a trio of automated closed-loop satellite tracking facilities located across Canada. The first CASTOR facility is in Kingston, Ontario, Canada. The second will be located somewhere in western Canada and the third will be located somewhere in eastern Canada. This trio of optical sensors will be used to provide an optical deep sky satellite tracking net in Canada.

The CASTOR facility will have to be approved by the U.S. Air Force Space Command (AFSPC) in order for it to be a contributing sensor for Cheyenne Mountain. There are a number of standards that CASTOR will have to meet in order to be a viable candidate. The first is an acceptable metric accuracy. The accuracy for each R.A. and Declination quantity for the optical sensor will have to be within 10 arc-seconds. The shutter open/close times will have to accurate to within 1 millisecond. This is a concern as far as the shutter strobe option is concerned. Only the first shutter opening and last shutter closing times are stamped onto the FITS header of the image. The timing accuracy of the other end-points depends on the shutter accuracy. The ground site location must be known to at least 0.0001 degrees in latitude and longitude and to within a few meters in altitude.

The prototype CASTOR system known as CASTOR B will still be used for low priority satellite tracking and geo-stationary belt surveys. It is theoretically possible to automate this system as well but it will be prone to the weather conditions because CASTOR B has no observatory dome to protect it.

Summary

The CASTOR satellite tracking facility is currently in its planning and testing stages. By the summer of 2000 it is expected that CASTOR will be fully automated and accurate enough to be accepted as an AFSPC sensor.

Full automation of the CASTOR facility will involve the creation of a carefully planned scheduling routine that will automatically select those satellites that fall within the acceptable constraints of the facility. These constraints include the range of the satellite, the satellite phase angle, the lowest acceptable elevation, and especially the determination of the highest satellite acquisition rate. A major problem with the planning of this automated scheduler is that it will have to integrate with the other three branches of interest (tracking and imaging, image analysis and orbit determination). The STK/Connect software should facilitate the scheduling process.

The tracking and imaging stage of the project is completed with the exception of the automated dome component. That piece of the project will be installed by the summer of 2000. It is presently possible to do satellite tracking with the system but both scheduling and image analysis are time consuming so that the number of images are kept to a minimum to prevent data glut.

The image analysis stage has been the most difficult and time-consuming one to this point. New streak detection and astrometry software are being developed in order to automate this process and to provide more accurate end-point determinations and metric data.

The STK/Connect module should be able to automate the orbit determination process. Once CASTOR is fully automated steps will be taken to determine the best scheduling, tracking, image acquisition, image analysis and orbit determination methods in order to ensure that the CASTOR facility is the most practical and accurate it can be.