Defence Research and Development Canada | Recherche et développement pour la défense Canada

DEFENCE R&D DÉFENSE

Surveillance of space concept demonstrator

Presentation of one sensor: CASTOR-V

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Defence R&D Canada – Valcartier
Technical Memorandum
DRDC Valcartier TM 2005-165
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Canada

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Abstract

Defence R&D Canada (DRDC) is developing a Surveillance of Space Concept Demonstrator consisting of three geographically dispersed, ground-based, small optical sensors for satellite observation. These three sensors will be operated remotely via the Sensor System Operations Centre (SSOC). Before remote operation was undertaken, CASTOR-V, the sensor located at Valcartier, was characterized and tested to optimize operation and perform troubleshooting. This report first describes the sensor hardware and software, then presents the results of the sensor characterization, including the dome and mount slew time, CCD dark current and other important features. Two significant findings emerged from the test results. First, any displacement on one side of the meridian requires less than one minute, and second, the CCD must be cooled to around –30ºC to minimize the significant top-to-bottom dark count gradient. Finally, for the benefit of future users and system designers, particularities and issues that occurred with CASTOR-V related to hardware, software or operation are described, along with remedial measures or recommendations. CASTOR-V is now ready for remote operation through the SSOC.

Résumé

Recherche et développement pour la défense Canada (RDDC) développe actuellement un démonstrateur de concept pour la surveillance de l’espace qui consiste en trois petits capteurs optiques, situés au sol et géographiquement dispersés pour l’observation de satellites. Ces trois détecteurs seront télécommandés par le Centre d’opération du système de détecteurs (COSD). Avant que cette opération soit entreprise, CASTOR-V, le capteur situé à Valcartier, a été caractérisé et testé afin d’optimiser son opération et d’effectuer un diagnostic d’anomalies pour ce détecteur en particulier. Ce mémorandum décrit, dans un premier temps, les diverses composantes d’équipement et de logiciel du capteur, il présente ensuite les résultats de sa caractérisation incluant le temps de déplacement du dôme et de la monture, le courant d’obscurité et d’autres importantes caractéristiques. Après la période de test, deux principaux constats se sont imposés. Le premier atteste que n’importe quel déplacement fait d’un même côté du méridien nécessite moins d’une minute, le deuxième témoigne de l’importance de refroidir la caméra CCD à environ –30 ºC afin de minimiser l’important gradient de haut en bas dans le courant d’obscurité. Finalement, pour le bénéfice des futurs utilisateurs et concepteurs de systèmes, les particularités et les problèmes liés à l’équipement, aux logiciels ou au fonctionnement de CASTOR-V, sont décrits avec les solutions ou recommandations respectives. CASTOR-V est maintenant prêt pour la télémanipulation à partir du COSD.

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Executive summary

The Department of National Defence (DND) initiated the Surveillance of Space Project (SoSP) in autumn 2000 in order to gain assured access to orbital data and information on space objects of national interest. The strategy behind this project is first to re-establish partnership in the US Space Surveillance Network (SSN) by providing a Canadian sensor system, and second, to share the burden of NORAD's Aerospace Warning Mission. The SoSP, which has the mandate to acquire a space-based optical (SBO) surveillance of space sensor, SAPPHIRE, has given its financial support to Defence R&D Canada (DRDC) to implement a ground-based Concept Demonstrator (CD) during the definition phase of the SoSP. The CD consists of three geographically dispersed, amateur-grade optical sensors designed for ground-based observation of satellites. The CD will specifically assist the SoSP in the development of networking arrangements with the US SSN. The sensors will be operated remotely, and eventually autonomously, via the Sensor System Operations Centre (SSOC) located at DRDC – Ottawa. The sensors are upgraded versions of the CASTOR instrument developed at Royal Military College (RMC), which was based on the US RAVEN. Prior to any remote operation initiative and any development of networking abilities, all the individual sensors must be fully operational.

Following from the above considerations, the sensor located at Valcartier, CASTOR-V, was properly characterized and extensively tested to optimize operation and perform troubleshooting. In addition, since all three sensors use the same COTS components, the lessons learned from CASTOR-V troubleshooting are potentially applicable to the other two sensors.

The slew time results showed that the mount right ascension, mount declination and dome azimuth have displacement speeds of about 3.2, 4.7 and 6.0 degrees/sec respectively. Based on this information, the time needed for any slew command can be determined. This time is less than one minute for any displacement on one side of the meridian, which is reasonable given the requirement of one observation every 5 minutes. CCD camera testing revealed that the camera must be cooled to around –30ºC to minimize the significant dark count (noise) gradient, and that the highest binning mode that will not incur resolution loss must be selected in order to minimize image download time, which is related to dark count gradient. Troubleshooting yielded a number of findings: pointing accuracy must be checked periodically, and in any event must be updated at least once a year; the CCD should be turned on for about one hour before cooling to expel humidity from the CCD chamber; and the telescope mount is fairly sensitive to cold, which can cause various malfunctions. Two modes were used to acquire images: 1) sideral tracking, producing satellite streaks and point-like stars, and 2) satellite tracking mode, producing star streaks and point-like satellites, which is especially useful for tracking faint satellite signals.

By the end of summer 2003, CASTOR-V was deemed ready for remote operation through the SSOC, although allowance must be made for the different particularities and issues highlighted by the extensive testing performed at DRDC – Valcartier.

Buteau, S., Lévesque, M. and Bernier, A.-P., 2007. Surveillance of space project concept demonstrator – Presentation of one sensor: CASTOR-V. DRDC Valcartier TM 2005-165, Defence R&D Canada-Valcartier.

Sommaire

Le ministère de la Défense nationale (MDN) a entrepris le projet de surveillance de l'espace (SdE) à l'automne 2000 afin d'acquérir un accès assuré à l'information et données orbitales des objets spatiaux d'intérêt national. La stratégie qui sous-tend ce projet est premièrement d'établir un partenariat avec le réseau de surveillance de l'espace des États-Unis (US SSN) en mettant en œuvre le développement d'un système de détecteurs canadiens; et deuxièmement, de partager le fardeau de la mission d'alerte aérospatiale de NORAD. Le projet SdE dont le mandat est d'acquérir un détecteur optique pour la surveillance de l'espace à partir de l'espace, SAPPHIRE, a donné son soutien financier à R & D pour la défense Canada (RDDC) pour implanter un démonstrateur de concept (DC) situé au sol durant la phase de définition du projet SdE. Le DC consiste en trois détecteurs optiques de grade amateur, dispersés géographiquement et conçus pour prendre des images optiques de satellites à partir du sol. Le DC va spécifiquement aider le projet de SdE dans le développement des arrangements de réseautage avec l'US SSN. Les détecteurs seront commandés à distance, et enfin de façon autonome, à partir du Centre d'opération du système de détecteurs (COSD) situé à RDDC Ottawa. Les détecteurs sont des versions améliorées de l'instrument CASTOR développé au Collège militaire royal (CMR), inspiré de RAVEN aux États-Unis. Avant que la télémanipulation puisse être mise en œuvre, la performance de chaque détecteur doit être précisément validée.

Compte tenu des conditions ci-haut mentionnées, le détecteur situé à Valcartier, CASTOR-V, a été caractérisé adéquatement et testé de façon approfondie afin d'optimiser son fonctionnement et d'effectuer un diagnostic d'anomalies pour ce détecteur en particulier. De plus, puisque les trois détecteurs utilisent les mêmes composantes disponibles sur le marché, les leçons apprises grâce à CASTOR-V seront potentiellement pertinentes pour les deux autres détecteurs.

Les résultats des temps de déplacement montrent que les vitesses de la monture en ascension droite et en déclinaison ainsi que la vitesse de rotation du dôme sont respectivement de 3,2, 4,7 et 6,0 degrés par seconde. Le temps nécessaire à tout déplacement situé d'un côté du méridien est inférieur à une minute, ce qui est raisonnable étant donné la période minimale d'observation de 5 minutes exigée par le SdE. La caractérisation du CCD a permis de faire état de l'importance de la refroidir à environ –30 ºC afin de minimiser l'important gradient de haut en bas dans le courant d'obscurité (bruit), et utiliser le mode de stockage (binning) le plus élevé sans perte de résolution afin de diminuer le temps de téléchargement d'images lié au gradient du courant d'obscurité. La période d'entraînement du système a mené à diverses conclusions : la précision de pointage du télescope doit être vérifiée périodiquement et mise à jour au moins une fois par année; la caméra CCD devrait être mise en opération environ une heure avant son refroidissement afin d'éliminer toute trace d'humidité de la chambre du CCD; et finalement, la monture du télescope est sensible aux températures froides, ce qui peut entraîner différents types de mauvais fonctionnement. Deux modes ont été utilisés pour faire l'acquisition d'images de satellites : 1) mode sideral, produisant des traces de satellites et des étoiles ponctuelles, et 2) mode poursuite de satellites, produisant des traces d'étoiles et de satellites ponctuels, ce qui est particulièrement utile pour les satellites à faible signal.

Dès la fin de l'été 2003, CASTOR-V a été jugé prêt pour sa télémanipulation tout en tenant compte des particularités et anomalies mises au jour par le travail d'étude fait par RDDC Valcartier.

Buteau, S., Levesque, M. and Bernier, A.-P., 2007. Surveillance of space project concept demonstrator – Presentation of one sensor: CASTOR-V. DRDC Valcartier TM 2005-165, R&D pour la défense Canada-Valcartier.

Table of contents

List of figures

List of tables

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Michael A. Earl	Calian consultant

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1. Introduction

1.1 Space debris

The space around Earth has become progressively populated over the last 30 years owing to increased interest in satellite technology among government agencies and private companies. In fact, approximately 11,000 large objects (>10 cm) are known to exist. The estimated population of risk objects (between 1 and 10 cm) and small debris (<1 cm) is greater than 100,000 and tens of millions, respectively [1]. Figure 1 presents a computer-generated view illustrating the population of Earth orbit satellites on December 14, 1990, and is typical of such a view at any time. Most orbital debris resides in low Earth orbit, i.e., within 2,000 km of the Earth's surface. Within this volume, the amount of debris varies significantly with altitude. Regions of debris concentration are found near 800 km, 1,000 km and 1,500 km.

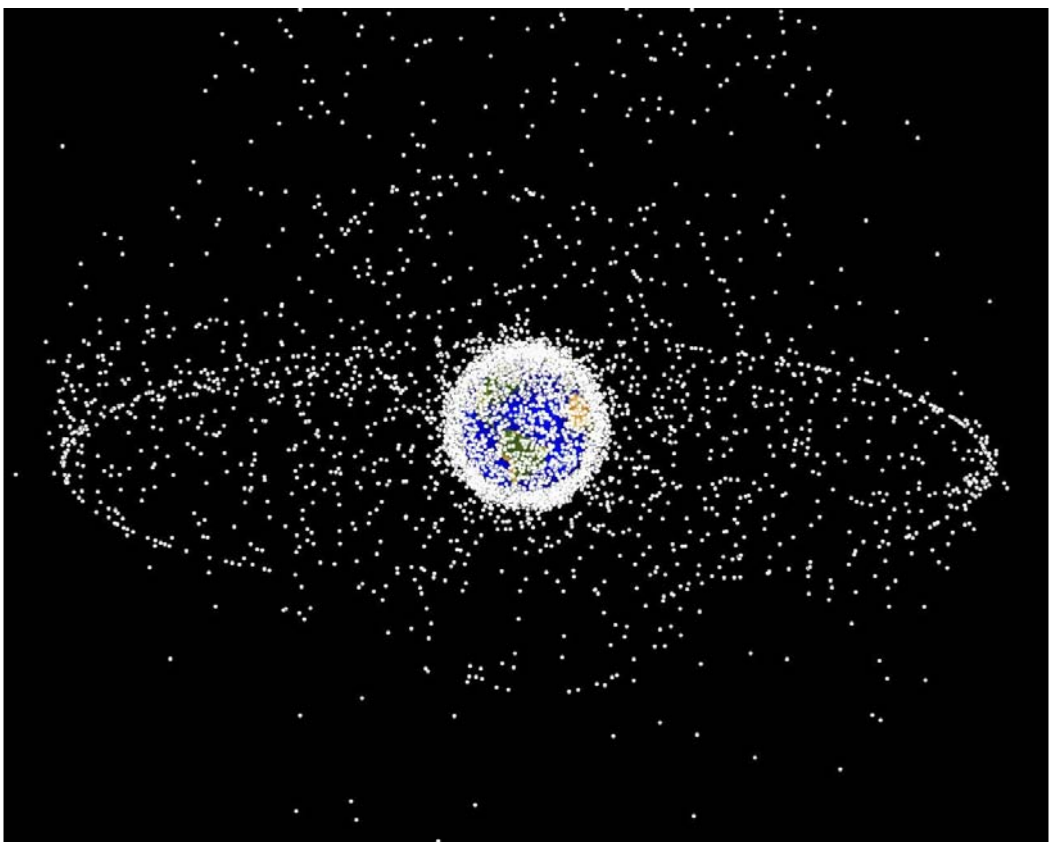


Figure 1. Computer-generated population of Earth orbit satellites on December 14, 1990. This view is from far out in space; one can see the highly populated low Earth orbit (LEO), the geostationary arc over the equator and the highly inclined Molniya orbits used by the Russians for communication at very high latitudes.

1.2 Mission of the Space Surveillance Program

The growth of space pollution has become an international concern, inducing more and more countries to initiate a space surveillance program. The United States has taken the international lead in this field. Their space surveillance program is a part of the United States Space Command (USSPACECOM) mission, and involves detecting, tracking, cataloguing and identifying man-made objects orbiting Earth. Space surveillance accomplishes the following:

- predict when and where a decaying space object will re-enter the Earth's atmosphere;
- prevent a returning space object, which to radar looks like a missile, from triggering a false alarm in missile-attack warning sensors of the US and other countries;
- chart the present position of space objects and plot their anticipated orbital paths;
- detect new man-made objects in space;
- produce a running catalogue of man-made space objects;
- determine which country owns a re-entering space object;
- inform NASA whether or not objects may interfere with the space shuttle and Russian Mir space station orbits.

1.3 Space Surveillance Network (SSN) Capability

The Space Surveillance Network (SSN) of the US Army, Navy and Air Force is tasked with performing all the above functions. This is accomplished by conducting ground-based and space-based observations of the orbital debris environment. Data is acquired using ground-based radars and optical telescopes (Figure 2), space-based telescopes, and analysis of spacecraft surfaces returned from space. The SSN currently tracks more than 11,000 orbiting objects. The space objects consist of active/inactive satellites, spent rocket bodies and fragments. About seven percent are operational satellites, 15 percent are rocket bodies, and about 78 percent are fragments or inactive satellites. The SSN is primarily interested in active satellites, but space debris items are also tracked. Indeed, all space objects orbiting Earth that are 10 cm or larger are tracked and catalogued.

All the in-service sensors make a combined total of up to 80,000 satellite observations every day. This enormous amount of data is transmitted directly to USSPACECOM's Space Control Center (SCC) via satellite, land line, microwave and telephone. Every available means of communication is used to ensure a backup is readily available if necessary. The SCC at Cheyenne Mountain Air Station is the terminus for the SSN's abundant and steady flow of information. The SCC houses large, powerful computers to process SSN information and accomplish the space surveillance and space control missions.

The SSN uses a predictive technique to monitor space objects, i.e., it spot-checks them rather than tracking them continuously. This technique is used because of the limitations of the SSN (number of sensors, geographic distribution, capability and availability). Today, data measurements as well as data management limitations significantly affect the capability of the SSN to detect and track smaller debris objects [2]. The need for new sensors is growing constantly. Indeed, over the past 40 years, the satellite catalogue has grown at a rate of 250 objects annually. This rate has remained fairly constant over the past 40 years, but the emergence of personal communication system satellite networks, the launch of the international space station and a capable national and theatre missile warning system may increase that rate.

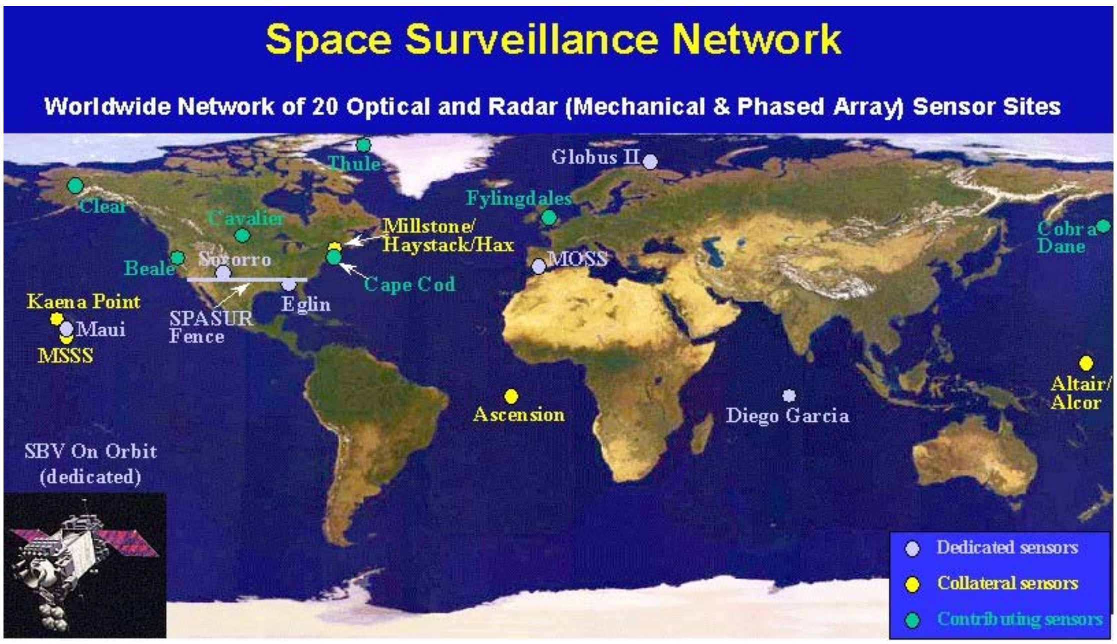


Figure 2. Space surveillance Network sensor sites

1.4 Canadian Contribution to the SSN

Historically, the Canadian Forces (CF) have been active participants in the surveillance of space mission, contributing data to the SSN from 1960s until 1992, when the Baker-Nunn and Space-Object Identification (SOI) telescopes at St. Margaret's were decommissioned due to their archaic film-based detectors. The CF have continued to contribute to the surveillance of space mission through NORAD positions in the Cheyenne Mountain Operation Center. Canada lacks definitively a capability to monitor space. Indeed, its space assets are vulnerable and the CF are exposed to foreign satellite surveillance. In autumn 2000, Canadian DND hence initiated the Surveillance of Space Project (SoSP) in order the gain assured access to orbital data and information on space objects of national interest. The strategy behind this project was first to re-establish partnership in US SSN by providing a Canadian sensor system and second, to share the burden of NORAD's Aerospace Warning Mission.

The mandate of SoSP is to acquire a space-based optical (SBO) surveillance of space sensor (Sapphire). During the definition phase of the SoSP, the implementation of a ground-based Concept Demonstrator (CD) will be performed and will assist:

- in the development of networking arrangements of the SBO system with the US SSN;
- the development and tasking procedures and algorithms for the SBO system ; and
- the validation of resources required to support the overall system.

Defence R&D Canada (DRDC), with financial support from DND and D-SPACE-D through the SoSP, is actually developing the CD, a satellite tracking sensor system composed of three geographically dispersed, ground-based, small optical sensors. These latter can be operated remotely, and eventually, autonomously, via the sensor system operations center (SSOC) located at DRDC Ottawa. The sensors are up-graded version of the RAVEN [3] [4] inspired CASTOR (standing for Canadian Automated Small Telescope for Orbital Research) instrument developed at the Royal Military College (RMC) [5] [6]. The sensors use commercial off-the-shelf (COTS) equipment as much as possible to minimize costs while maximizing reliability. The sensors are located in Canada at the DRDC sites in Valcartier, QC; and Suffield, AB, and at RMC in Kingston, ON (Figure 3). The geographic distribution of the sensors provides two concrete benefits to the SSN: first, it minimizes probability of overcast weather on the system, increasing its availability and, second, it increases the extent of the geostationary (GEO) belt that the CD will be able to observe.

This technical memorandum will present CASTOR-V, the sensor located at DRDC Valcartier in Québec. Once the different objectives exposed, the hardware and software components of CASTOR-V will be presented. Then, the several system characterization tests and obtained results will be detailed. Next, the different encountered issues, either hardware or software, will be clearly described and the related solution presented. Several tracking results will then be shown. Finally, a conclusion describing the system actual state will be presented. This work was performed under the 15et13 element of the Surveillance of Space Project (15et) from March 2002 to October 2003.

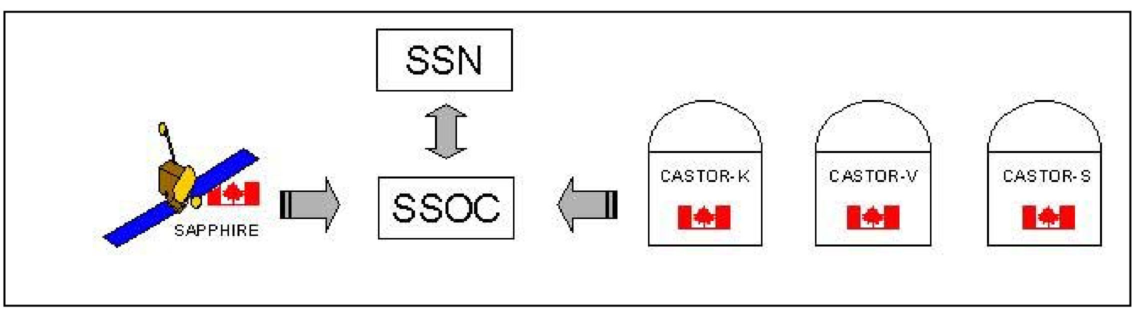


Figure 3. Surveillance of Space Project basic scheme

2. Objectives

The objectives along the hierarchy line of the Surveillance of space project are specific to each structure level. The present section intends to clarify the particular objectives of each level.

2.1 Surveillance of Space Project

The fundamental objective of the Surveillance of Space Project (SoSP) is to gain assured access to orbital data and information on space objects of national interest. Concretely, the SoSP has the mandate to acquire a space-based optical surveillance of space sensor (Sapphire).

2.2 SoSP Concept Demonstrator

The objective of the SoSP Concept Demonstrator (CD) is to build and demonstrate a ground-based satellite tracking sensor system consisting of three remotely controlled, autonomous, geographically dispersed small optical sensors for surveillance of deep-space objects. The sensors of the CD are up-graded versions of the CASTOR instrument developed at the RMC by M. Earl in 1999, which was supervised by Dr. Racey [5] [6]. CASTOR stands for Canadian Automated Small Telescope for Orbital Research. A Sensor System Operation Center (SSOC) shall be established to operate the three telescopes without human intervention. The SoSP CD system shall demonstrate that it meets the following requirements:

a. Automated Scheduling

   From a list of possible observations for the three sites over a one-night period, the CD system shall be able to automatically schedule those observations in an efficient sequence at each site location. This scheduling shall be able to optimize the number of observations done while achieving the minimum acceptable level of accuracy for each observation.

b. Satellite Acquisition Rate

   Assuming clear skies and availability of accessible distinct orbiting objects at the three sites, the CD system shall be able to continuously perform observations at an average rate of one observation every 5 minutes at each site. This acquisition rate shall be sustainable through most nights.

c. Automated Image Acquisition and Analysis

   In the sideral tracking mode, the CD system shall autonomously perform streak detection of orbiting objects within its detection range.

From the streak image, the CD system shall perform **astrometry** on the detected streak end-points and extract the tracking data needed for orbit determination.

2.3 CASTORs

The objective of each individual sensor of the SoSP CD; CASTOR -V, -K and -S, is to track orbiting objects reflecting sun light throughout the visible and near infra-red (NIR) at a total intensity level equivalent to a **visual magnitude** of 14. This tracking shall be possible for target altitudes ranging from 15,000 to 40,000 km. The data provided from each individual telescope shall meet at least the following standards:

- An angular accuracy for each right ascension/declination quantities within 10 arc-seconds;

- The shutter open/close times to be accurate within 1 millisecond based on the Universal Time Coordinate (UTC); and

- The telescope site locations to be known to at least 0.0001 degrees in latitude and longitude and to within ten meters in altitude.

However, before any requirements shall be meet, the sensor must be reliable in order to be able to simply respond to any task coming through the SSOC. In order to achieve a proper reliability with CASTOR-V, different testing procedures were undertaken during 2002-2003 period. As a result, CASTOR-V has been deeply characterised and in the mean time, all the different hardware and software problems came out and were properly solved. Through this debugging period, the hardware and software reliability could hence be statistically characterised.

3. System description

CASTOR-V construction was initiated in winter 2001-2002 and the completion of the optical set-up took place in June 2002. It is located on Defence R&D Canada Valcartier site (Figure 4), in building #316, to the south and west of provincial highway #369. CASTOR-V is situated at 46º 52’ 31.98’’ of latitude North; 71º 28’ 14.48’’ of longitude West and at an elevation of 177 m. The different hardware components and the diverse software tools comprised in CASTOR-V are extensively described in the present section.

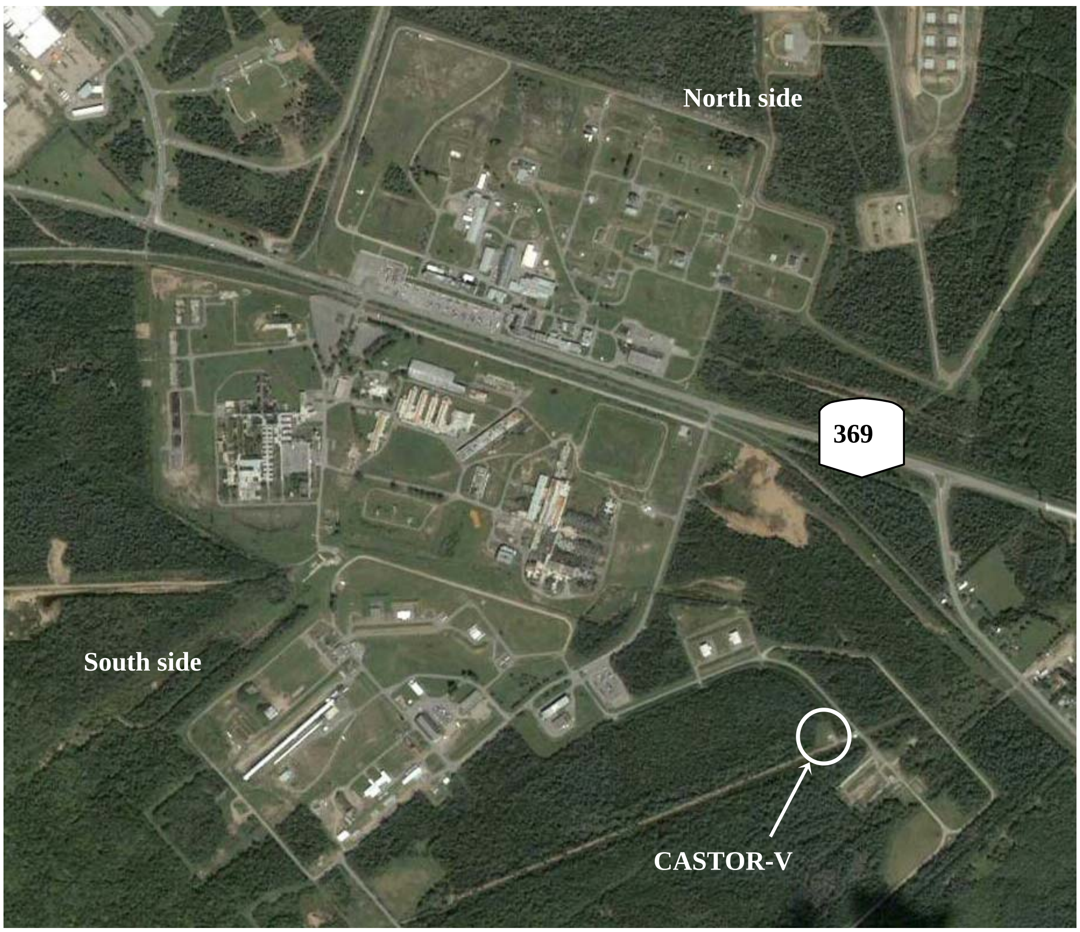


Figure 4. CASTOR-V location on DRDC Valcartier site

3.1 Hardware

CASTOR-V is globally composed of an observatory dome, a dome controller, a telescope, a mount, a temperature compensating focuser (TCF), a CCD camera, a GPS Timing Receiver and a computer. Table 1 presents briefly the different hardware components, which will be detailed in the following sub-sections. Figure 5 represents schematically the different main hardware components of CASTOR-V.

Table 1. *Hardware components of CASTOR-V*

COMPONENT TYPE	MODEL AND MANIFACTURER
Observatory Dome	Ash manufacturing Model REA 10.5 foot
Dome controller	Meridian Controls Corporation
Telescope Mount	Paramount GT-1100 ME from Software Bisque Inc.
Optical Tube Assembly	Celestron Model CGE-1400
Temperature Compensating Focuser (TCF)	TCF-S from Optec Inc.
CCD Camera	AP8p from Apogee Inc.
GPS Timing Receiver	bc637PCI from Datum Inc.

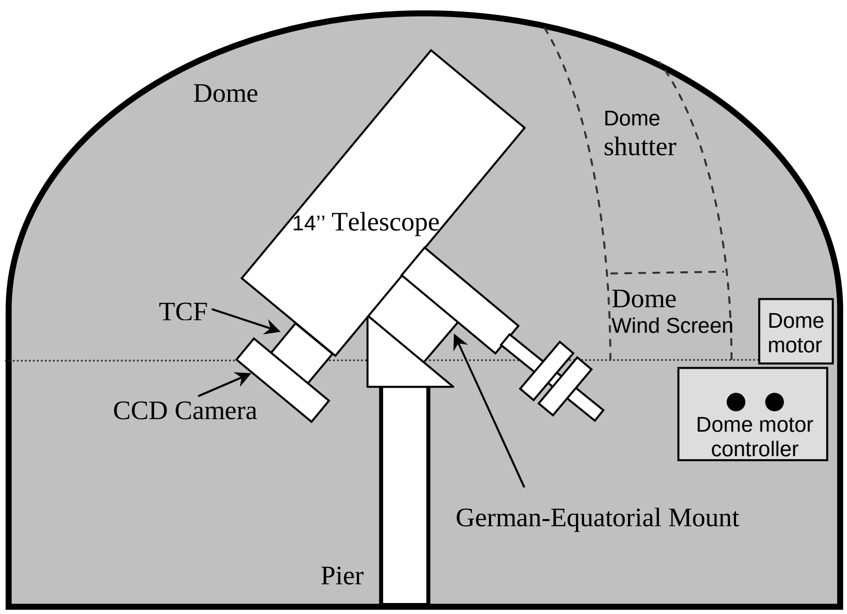


Figure 5. CASTOR-V schematic representation

3.1.1 Observatory dome

The CASTOR-V observatory dome sits on a small building (# 316), constructed expressively for CASTOR-V during winter 2001-2002. Upon the building completion, the installation of the observatory dome took place. Figure 6 shows CASTOR-V during the installation phase of the dome. The chosen dome is a 10.5-foot-diameter Ash Dome (Model REA), the same one used in the initial version of CASTOR-K. The dome size is large enough for the current combination of the chosen telescope and mount, and would have the ability to house 18'' optics and an associated mount if required. The top part of the dome, having a spherical shape, simply rolls on a circular rail, which allow its angular displacement by means of a small mechanical motor. The shutter of the observatory dome has two parts: the main shutter window located in the higher portion and the 'wind screen' (WS), a smaller window mechanically hooked to the main shutter just below the latter (Figure 5). This configuration permits to pull up, either the main shutter and the WS or only the main shutter. This dome design has the drawback of a limited observing field of view (FOV) in either the higher portion (WS up) or in the lower portion (WS down).

Figure 6. Installation of CASTOR-V's observatory dome in winter 2002

3.1.2 Dome Controller

For enabling autonomous remote sensor operation, the dome must be synchronized to track the movements of the telescope and telescope mount. The technology chosen is an automated dome controller from Meridian Controls Corporation. Tom Melsheimer, the president of Meridian, performed its installation in March 2002. The Dome controller includes the dome and shutter motors and their respective control boxes in addition to a 12 V battery charged by a solar panel. Figure 7 presents the Meridian dome motor and its controller, which allow performing dome angular displacements either clockwise (CW) or counter-clockwise (CCW). The operation is straightforward: turn it on, then each buttons must be pushed down to rotate the dome either clockwise (CW) or counter-clockwise (CCW).

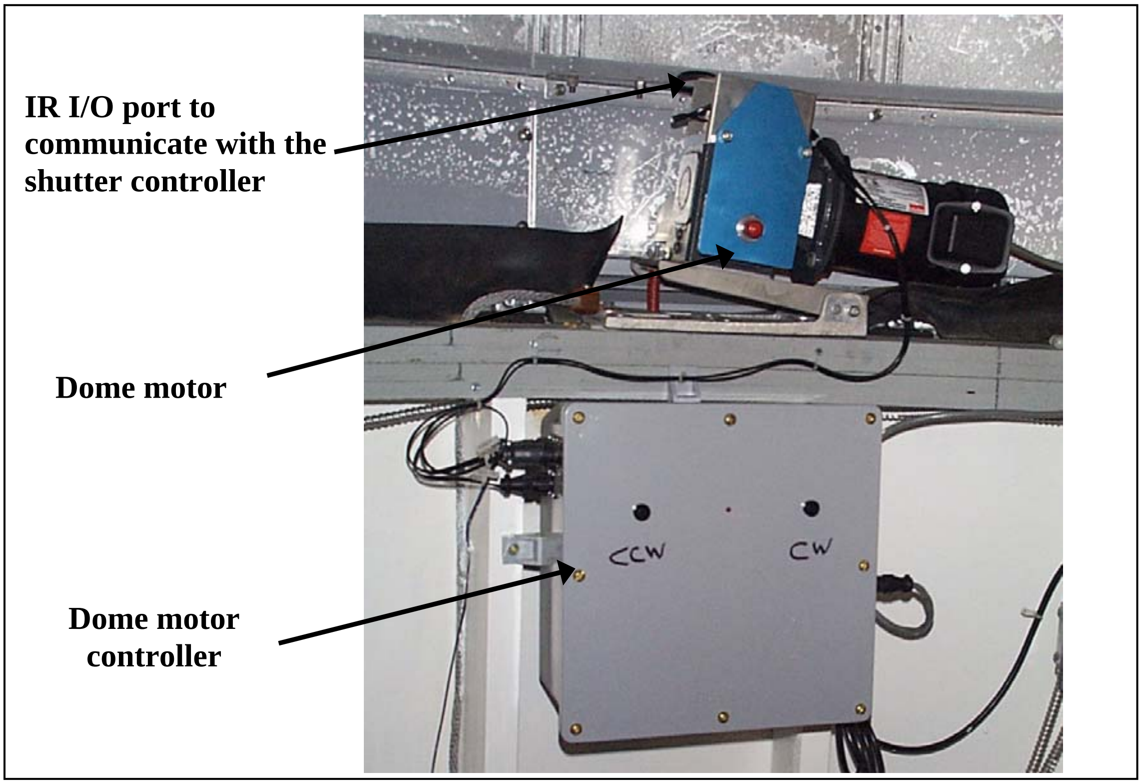


Figure 7. Dome motor and its controller used to rotate the observatory dome of CASTOR-V

Figure 8 presents the different elements needed to control the shutter opening: A) the shutter controller; B) the dome shutter motor, and C) the wind screen motor. As mentioned in section 3.1.1 and illustrated in Figure 5, the shutter includes two parts: the main shutter in the upper part and the wind screen (WS) in the lower part (Figure 8-C). Each one has a dedicated motor but a single controller is needed for operating both motors. In the default state, the WS is hooked to the shutter. The operation of the dome shutter controller, once the on/off switch is pressed, is described in Table 2. The main drawback of this dome controller originates from its requirement to be rotated in a certain position where the two parts of the IR I/O port are aligned, in order to communicate with the dome shutter controller.

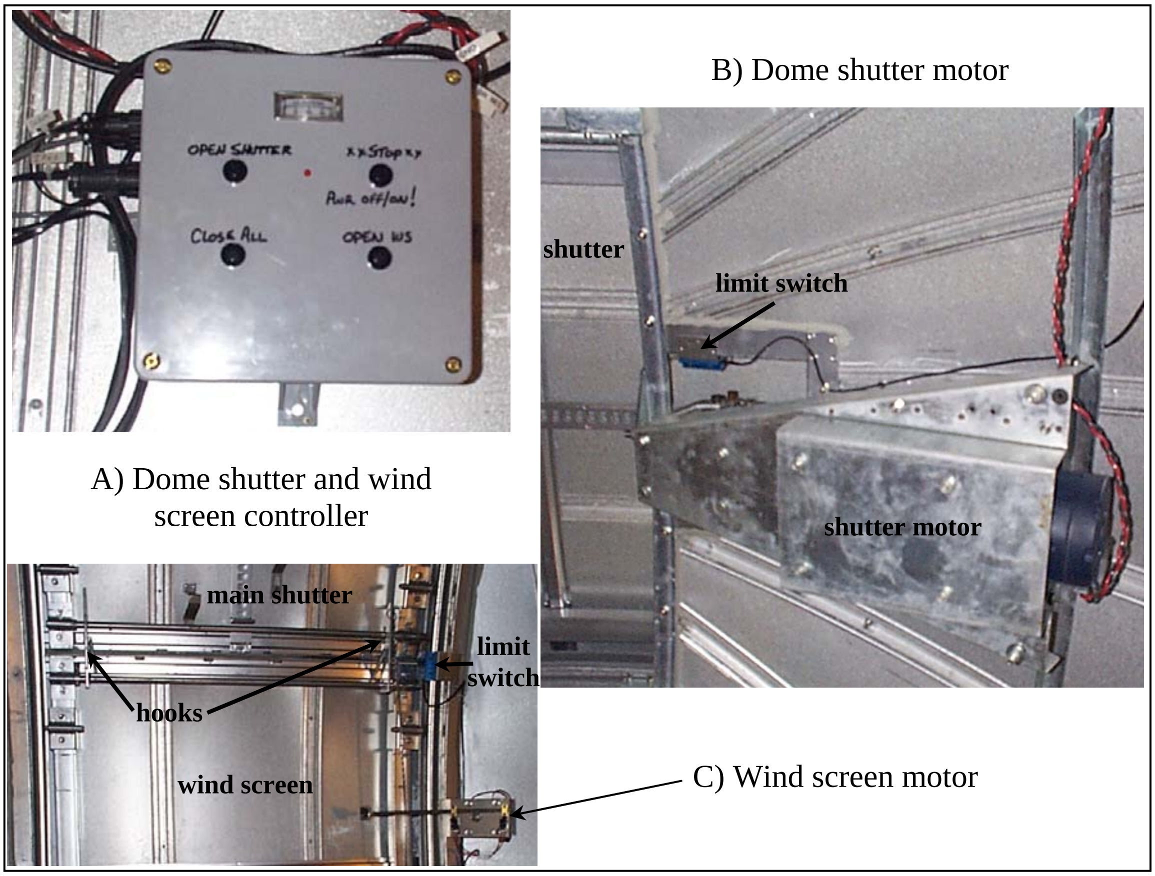


Figure 8. Dome shutter and wind screen motors and the controller used to open and close either the shutter or the shutter and the wind screen of the observatory dome in CASTOR-V

Table 2. *Operation of the dome shutter controller*

COMMAND	OPERATION
Open shutter	The WS motor pulls the chain to unhook the WS to the main shutter and the dome shutter motor pulls up the main shutter until the upper limit switch is on.
Open WS	The dome shutter motor pulls up both the main shutter and the WS.
Close all	The dome shutter motor pulls down the shutter assembly until the lower limit switch is on and the WS motor let go the chain to hook the WS to the main shutter.
STOP	Make everything stop and the on/off switch must be turned to off.

3.1.3 Telescope mount

The Paramount GT-1100 ME mount is a very accurate, cost-effective COTS mount and has a **German Equatorial configuration** (Figure 9). This type of mount was selected due to its high pointing accuracy possibilities and its lower price compared to an equivalent fork-type mount. There are two major implications of this configuration. First, the useful payload mass is only half of the total load carrying mass due to the requirement for the counterweight. The second limitation of the German Equatorial configuration is its requirement to reverse itself as it crosses the local **meridian**. This limitation must be considered for scheduling observations and it also causes extra pointing error since the reversal manoeuvre consists in a long slew. This ME mount from Software Bisque is the new generation of the GT-1100 used in the initial configuration of CASTOR-K.

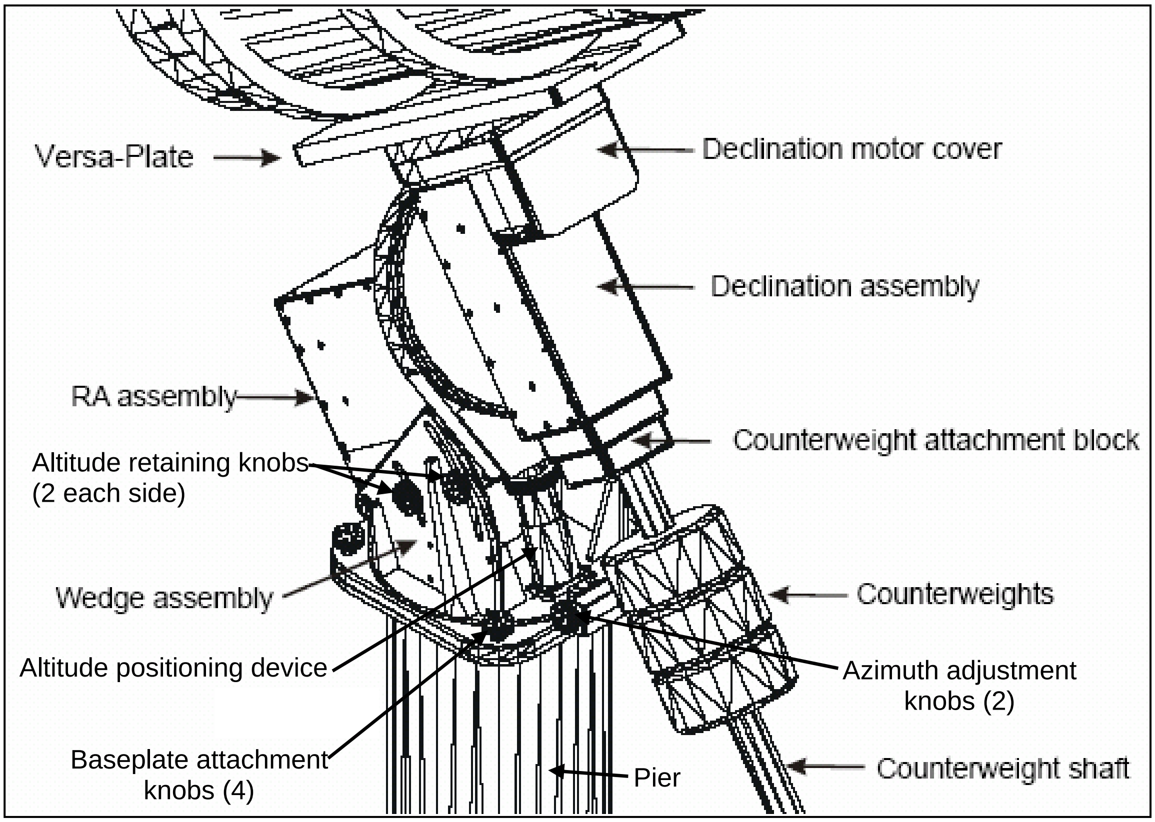


Figure 9. Sketch of the German Equatorial GT-1100 ME mount

The new mount generation (ME) has a lot of improvements: heavier payloads allowed; larger bearing surface for more stability; ultra-precision gears; more efficient mount design; periodic error correction polynomial curve-fitting; improved altitude and azimuth adjustments; improved exterior finish and quality; improved accessory control panel; AutoHome for absolute positioning; 'Protrack' integration to analyze and improve the pointing accuracy; and finally a new dual-axis motion control system (DC servo motor drive). Table 3 presents the mount specifications.

Table 3. *Paramount GT-1100 ME mount specifications.*

SPECIFICATION	DETAILS
Design	German Equatorial Mount (GEM) with all stainless-steel and anodized aluminum construction. (Worms and the Versa Plate plungers are manufactured from brass.)
Weight	29 kg (64 lbs.), including base plus Versa Plate but without optical tube assembly or counterweights.
Instrument carrying capacity	68 kg (150 lb.), not including the counterweights.
Gear specifications	All aluminum 11.45-inch (29 cm), 576 tooth right ascension gears and 7.45-inch (18.9 cm), 375 tooth declination gear each with guaranteed 5 arcsecond or less peak-to-peak periodic error before periodic error correction.
Worm blocks	Spring-loaded right ascension and declination worm block assemblies can be engaged for near zero backlash, or disengaged for adjusting payload balance.
Local operation	Joystick manual control (10-foot cable included) or PC-interface control
Cabling	Through-the-mount wiring for mount control plus auto-guider input, parallel or serial port CCD camera control and two additional devices (dew heater, video camera, etc.). A large access hole permits the addition of custom cables through the mount.
Counterweights	Two 9 kg (20 lbs.) counterweights are provided.
Latitude adjustment limits	Latitude wedge can be adjusted from 15º to 58º.
Azimuth adjustment limits	The azimuth can be adjusted plus or minus 4 degrees.
Azimuth adjustment design	The Paramount ME has a precision 11-inch azimuth adjustment "bearing" for easy polar alignment.
Power	60 watt supply (48V DC at 1.2 amps).
	During tracking, the mount draws 20 watts, and approximately 50 watts during maximum rate, dual axis slews.

3.1.4 Tube Optical assembly

The Celestron CGE-1400 is a 14'' Schmidt-Cassegrain telescope and this COTS optical tube assembly can be accommodated by the paramount ME mount. Figure 10 present a schematic representation of a Schmidt-Cassegrain telescope, which use a combination of mirrors and lenses to fold the incoming light and form an image (Catadioptric). In the Schmidt-Cassegrain the light enters through a thin aspheric Schmidt correcting lens, then strikes the spherical primary mirror and is reflected back up the tube and intercepted by a small secondary mirror, which reflects the light out an opening in the rear of the instrument where the image is formed at the eyepiece.

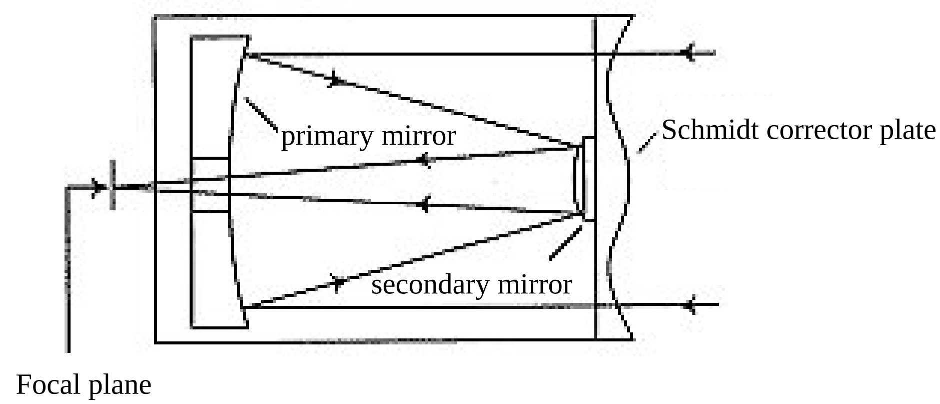


Figure 10. Schematic representation of a Schmidt-Cassegrain telescope

The most important Schmidt-Cassegrain advantages are listed below.

- Best all-around, all-purpose telescope design. Combines the optical advantages of both lenses and mirrors while canceling their disadvantages.
- Excellent optics with razor sharp images over a wide field.
- Excellent for deep sky observing or astrophotography with fast films or CCD's.
- Focal ratio generally around f/10. Avoid faster f/ratio telescopes (they yield increased aberrations).
- Closed tube design reduces image degrading air currents.
- Most are extremely compact and portable.
- Easy to use.

- Durable and virtually maintenance free.
- Large apertures at reasonable prices and less expensive than equivalent aperture refractors.
- More accessories available than with other types of telescopes.
- Best near focus capability of any telescope type.

Table 4 presents a resume of the telescope specifications. Figure 11 presents the entire optical sensor design of CASTOR-V: the Celestron telescope can be seen sitting on the reddish mount from Software Bisque.

***Table 4**. Celestron CGE-1400 specifications (model #11065).*

SPECIFICATION	DETAILS
Optical Design	Catadioptrics: Schmidt-Cassegrain
Optical diameter (Aperture)	14 inches (356 mm)
Focal length	3910 mm. (F/ratio = f/11)
Finderscope	Optical (9 x 50)
Highest useful magnification	840x
Lowest useful magnification	51x
Limiting stellar magnitude	15.3
Resolution: Raleigh	0.39 arc seconds
Dawes Limit	0.33 arc seconds
Photographic resolution	165 lines/mm
Light gathering power	2581 x unaided eye
Optical coatings	StarBright coating
Secondary mirror obstruction	4.5’’
Optical tube length	31’’
Optical tube weight	45 lbs

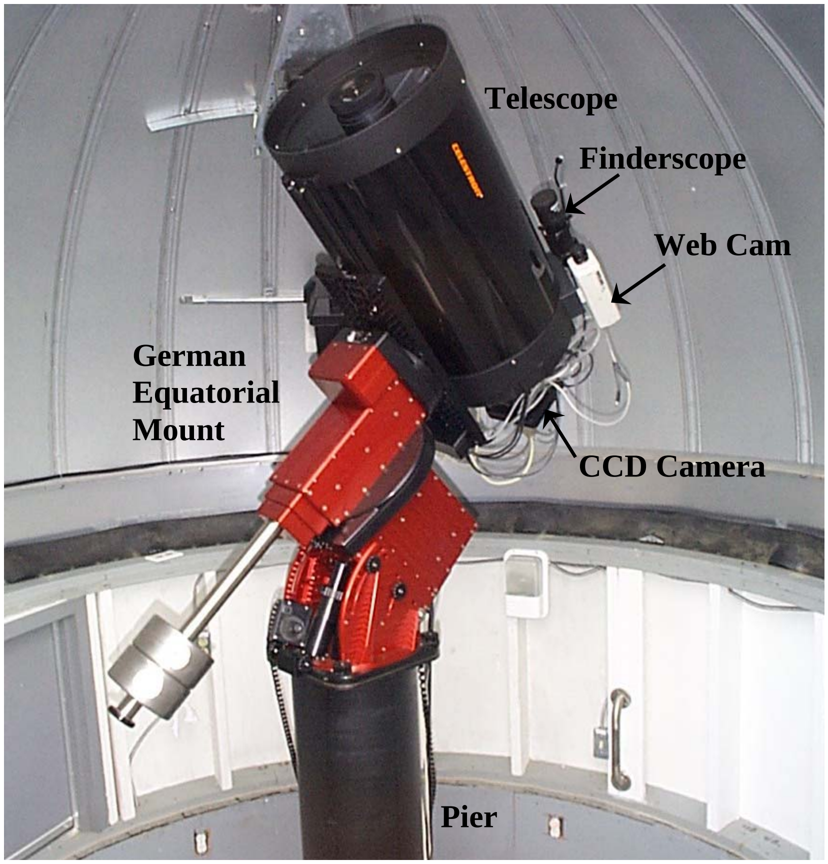


Figure 11. The optical sensor of CASTOR-V: mount, telescope and CCD

3.1.5 Temperature compensating focuser (TCF)

Optec Inc, has developed a focusing system, which compensates for temperature changes and holds the focus steady throughout the night: the TCF-S (S standing for the serial version). Indeed, an electronic controller system monitors the telescope's tube temperature and compensates the focus accordingly. A small temperature probe is attached to the side of the telescope tube and monitors temperature with a resolution of 0.1°C. A simple learning procedure is used to find the temperature coefficients specific to a certain telescope system. A manual mode allows the user to set the focus manually at any time.

The TCF-S is a robust Crayford style motorized focuser with high repeatability. The Crayford design allows for a solid friction roller focusing system with no play and very little backlash. Optec's implementation is ideal for applications, which require exact focus such as CCD imaging or film astrophotography. A geared stepper motor rotates the drive shaft with one step rotation of the motor equal to a 0.000203 cm (0.00008 inch) movement of the drawtube. A pair of pushbuttons control the direction of focus and the DRO (digital read-out) displays the current position. The TCF-S focuser can easily handle cameras and instrument packages weighing up to 10 pounds.

The digital nature of the TCF-S allows opportunities for truly intelligent focusing. Using the serial version TCF-S focuser, programmers can communicate directly with the focuser's controller (located in the hand control) via any serial port. The simple ASCII protocol is easily programmed and has been implemented in many popular imaging and camera control software packages. For example, *CCDSoft* Version offers the @Focus© routine, which communicates with the TCF-S via a serial port to provide truly automatic focus control. MaxIm DL/CCD version 3 also provides remote and automatic focus control with the TCF-S focuser.

At the end of an observing session, the TCF-S focuser remembers the last temperature and position. When the unit is turned back on for a new session, the TCF-S computes a new position using the current tube temperature and moves to that position. Assuming no changes to the optical configuration, the object will snap into sharp focus.

Figure 12. Temperature compensator focuser (TCF) from Optec

3.1.6 CCD camera

The Apogee AP8p CCD is a 1024x1024 pixel back illuminated high Quantum Efficiency (QE) Camera. It is transparently interfaced to a more practical computer parallel port rather than an internal card. The imaging area of the CCD chip, SI-003AB, consists of 1024 columns, each of which contains 1024 picture element (pixels). The columns are isolated from each other by channel-stop regions. The 1024 rows of pixels are further divided into two groups of 512 rows (upper and lower sections) for clocking flexibility and output amplifier selection. There is an output amplifier at each corner of the device, at each end of the two output serial registers. The signal charge collected in the imaging array is transferred along the columns, one row at a time, to one or both of the serial registers and from there, to the desired output amplifiers. The serial registers are also divided into two sections. Thus the array can be divided into quadrants to maximize data transfer.

Figure 13 presents the imaging section of CASTOR-V: the Optec TCF and the Apogee CCD. Table 5 presents the different specifications of the AP8p CCD.

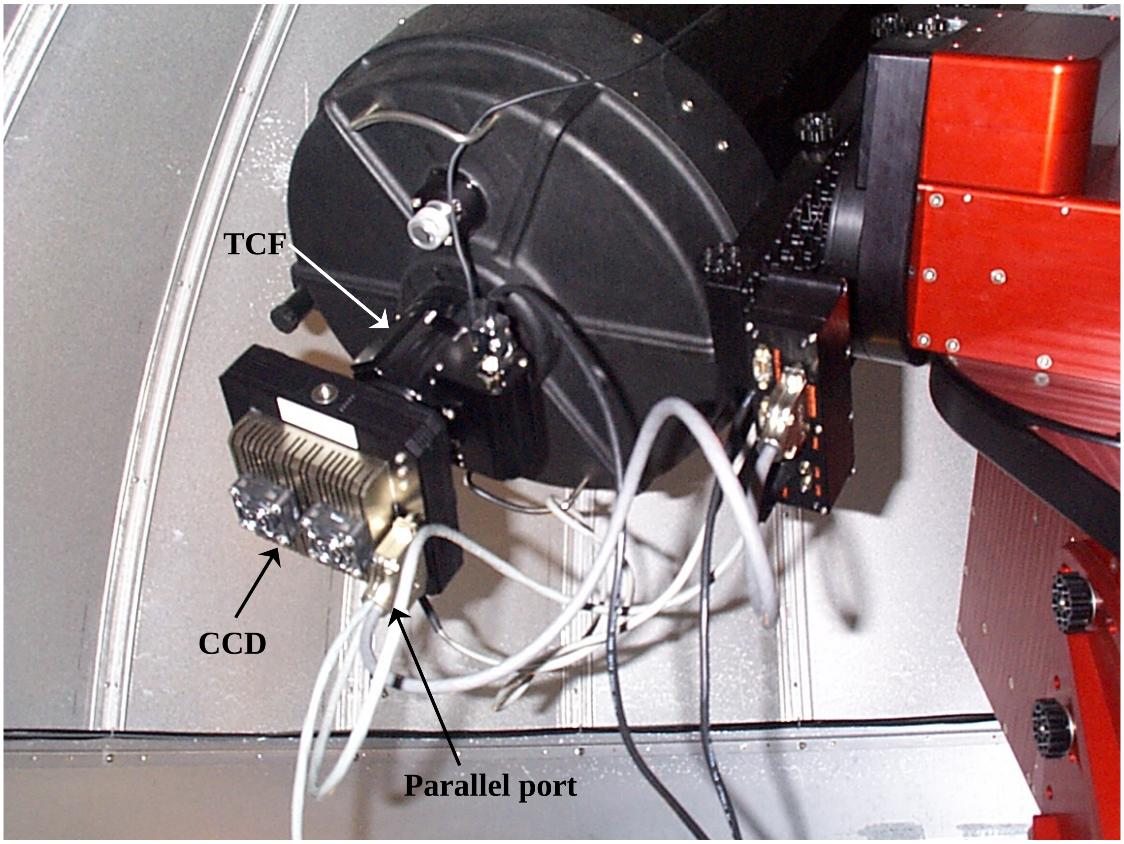


Figure 13. Imaging section of CASTOR-V: temperature compensator focuser and the CCD

Table 5*. Apogee AP8p CCD specifications (SITe SI-003AB).*

SPECIFICATION	DETAILS
Charge Couple Device (CCD)	SITe SI-003AB
Array (pixels)	1024 x 1024
Pixel size	24 µm
Area	24.6 x 24.6 mm^2
Well Depth (Binned 1:1)	> 300,000 electrons
Anti-blooming	none
Charge Transfer Efficiency (CTE)	0.99999
Read Noise (typical)	15 electrons
Dark current (20ºC)	50 pA/cm^2
Digital Resolution	16-bits, 35 kHz
Shutter	Melles Griot 42 mm iris
Exposure Time	0.02 to 10,400 seconds (2.88 heures) in 0.01 second increments
Frame Sizes	Full frame, subframe, focus mode
Cooling	Thermoelectric cooler with forced air. Standard: 40-50ºC below ambient temperature.
Temperature stability	± 0.1ºC
System Gain	4-5 electrons/ADU
Camera Head	Camera head is 6x6 inches x 1.95 inches thick, plus additional 1.2’’ for heat sinks and fans. Weight is 3 lbs.
Remote Triggering	TTL input to PC controller allows exposure start within 100 ns of trigger for applications requiring precise synchronization of exposure to external events.

The SI-003AB CCD imager is designed to efficiently image scenes at low light levels from UV to near infrared. The thinned back-illuminated version provides superior quantum efficiency (QE) (see Figure 14). They have exceptional quantum efficiency compared to front-illuminated CCDs. This is due to the way they are constructed: a front-illuminated CCD thinned to only 15µ thick and mounted upside down on a rigid substrate. The incoming light now has an effective access to the pixel wells without those pesky gate structures blocking the view.

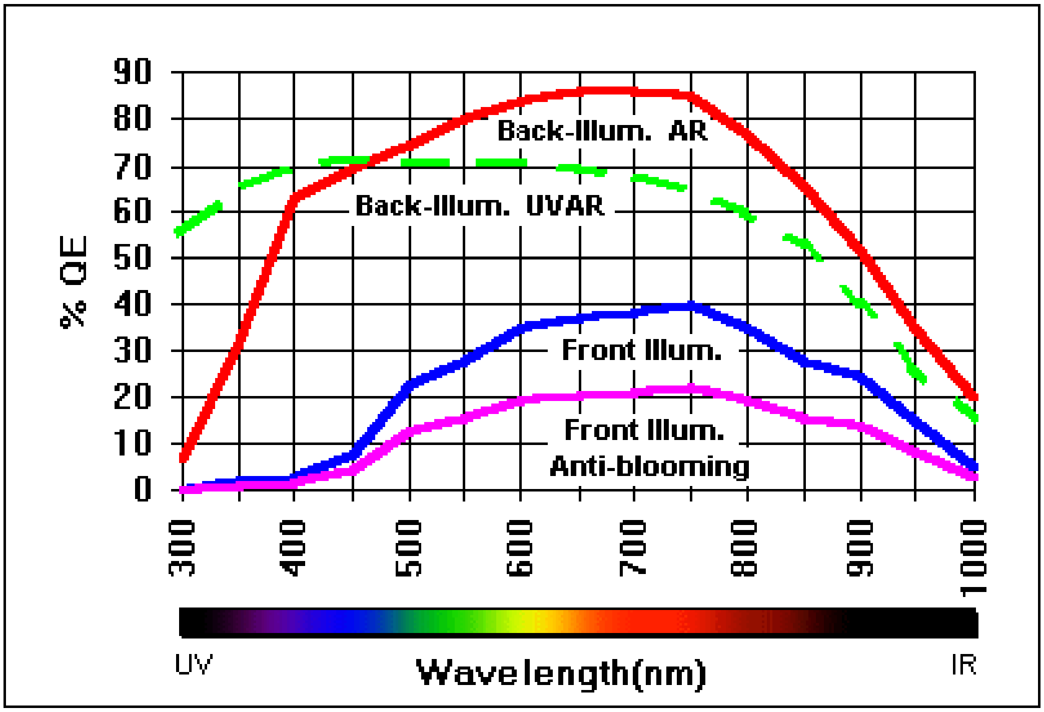


Figure 14. Typical QE curves for front and back-illuminated CCDs

Since the satellite streak detection is low light level work, the anti-blooming option is not useful. Indeed, anti-blooming gates built into the CCD occupy about 30% of the pixel area. The result is a 70% fill factor and reduced sensitivity and well depth.

The CCD power-up sequence must be carefully followed (Annex A) in order to insure a good communication between the CCD and the computer. To initialize the camera, the camera-control software (*CCDSoft*, MaxIM DL, etc.) needs a camera INI file (INI file diskette supplied by Apogee). In most case, no changes to the INI file are necessary.

To prevent interruption of the processor during image download, a "download priority" must be set in the camera-control software. Indeed, since the computer processor is usually not completely devoted to camera-control, the image download can be interrupted. When other processes are running in the background during the download of an AP8p image, bright lines may appear in the images.

In normal operation, it is intended that the thermoelectric cooler be turned on and allowed to reach a temperature as cool as possible. The typical AP8p cooler can reach between 50 and 55 degrees C. below ambient temperature; thus, if used at 25°C, a target temperature of -25° to

-30°C should be set in the software. When the cooler has reached its lowest possible temperature, the software will back it off by 2 degrees and regulate there. To prevent thermal shock to the CCD, the software ramps the temperature up and down very slowly. Allow 10 to 15 minutes for the cooler to reach its operational temperature.

3.1.7 GPS timing receiver

The original Datum GPS Timing Receiver at CASTOR-K uses the same model as the AFRL RAVEN system. The considerable difficulties initially experienced were eventually traced to a defective Datum computer card that was replaced by Datum at no cost. RDDC-O tested an alternative CNS GPS Clock that worked properly by itself but it was not hardware or software compatible with the Software Bisque software and the Apogee CCD camera. Datum has developed an improved version of their receiver at a lower price: the GPS Antenna bc637PCI. The antenna has been installed on the south/south-east corner of CASTOR-V building (Figure 15).

Figure 15. Weather station and the Datum GPS Antenna bc637PCI at CASTOR-V

3.1.8 Weather Station

Because a major design goal for the concept demonstrator is to enable autonomous remote operation, it is necessary to provide automated remote weather and sky monitoring capability. This is especially important for its impact on equipment risk such as could occur by opening a dome in inclement weather. In addition, the efficiency and effectiveness of scheduling can be greatly improved with the knowledge of local partial cloud conditions.

Figure 15 presents the installed weather station at CASTOR-V. It measures temperature, wind speed, wind direction, humidity, pressure and the amount of precipitation.

3.2 Software

Software Bisque products, which are COTS and custom software, are used to control the different hardware components: dome, mount and CCD. These products are gaining wide acceptance within the astronomy community, and are supported and used by many new software and hardware products. Table 6 presents the different software used by CASTOR-V.

Table 6. *Software used by CASTOR-V and their respective utility in the system.*

SOFTWARE	VERSION	UTILITY
AutomaDome	1.00.006	Controls robotic domes in order to keep the dome's slit synchronized with the telescope's optic.
TheSky (Level IV)	5.00.100	Controls telescope displacement and generates realistic rendition of the night sky.
CCDSoft	5.00.099	Used for CCD camera control, data reduction and image processing.
TPoint	1.00.505	Analyzes and improves the pointing accuracy of computer-driven telescopes.
Orchestrate	1.5.100	Controls astronomical devices through scripts.

3.2.1 ‘*AutomaDome*’ Dome Control Software

AutomaDome is an application that is integrated with *TheSky* Astronomy to control robotic domes to keep the dome's slit synchronized with the telescope's optic, without human intervention. *AutomaDome* computes the correct dome slit position for any type of telescope mount, placed anywhere inside the dome and the off axis position of the telescope is taken into account.

Determining the precise altitude and azimuth of the dome's slit relative to the telescope's optic is not a trivial matter. For example, in the case of a German Equatorial Mount (GEM) mounted slightly off the center of the dome. As the telescope slews to different parts of the sky (and different sides of the Meridian), the optic and slit must remain coincident. *AutomaDome* uses the geometry of your telescope and dome to compute precisely where the dome's slit should be. In order to do this, several parameters have to be measured and entered in the software’s fields in order for *AutomaDome* to perform satisfactorily for any asymmetrically mounted telescope. The parameters and their measured values are displayed in Table 7. The *AutomaDome* Help file should be consulted to understand what these parameters mean with respect to the dome geometry.

Table 7. *Measured Dome and Mount Geometry parameters for AutomaDome.*

PARAMETER	MEASURED VALUE
Elevation of Roll Axis	0.81856 radians
Radius of Dome	1600 millimeters
X_m (Mount Offset)	0.
Y_m (Mount Offset)	-25.4 millimeters
Z_m (Mount Offset)	+241 millimeters
X_t (Telescope Offset)	-457 millimeters
Y_t (Telescope Offset)	0
Y_0 (Optical center Offset)	0

3.2.2 ‘*TheSky*’ Astronomy Software

TheSky software displays a real time virtual sky and controls the robotic Software Bisque Paramount ME mount (Figure 16). A white cross hair appears in real-time on the computer screen to show exactly where the telescope is currently pointing while a red cross hair is used as a cursor to get information on particular objects and to indicate to which position the telescope should point at. Then, by clicking *TheSky's Slew To* button, the mount will begin its slew operation to bring the telescope (white cross hair) to this desired position (red cross hair). Figure 16 presents the interface of the software *TheSky*.

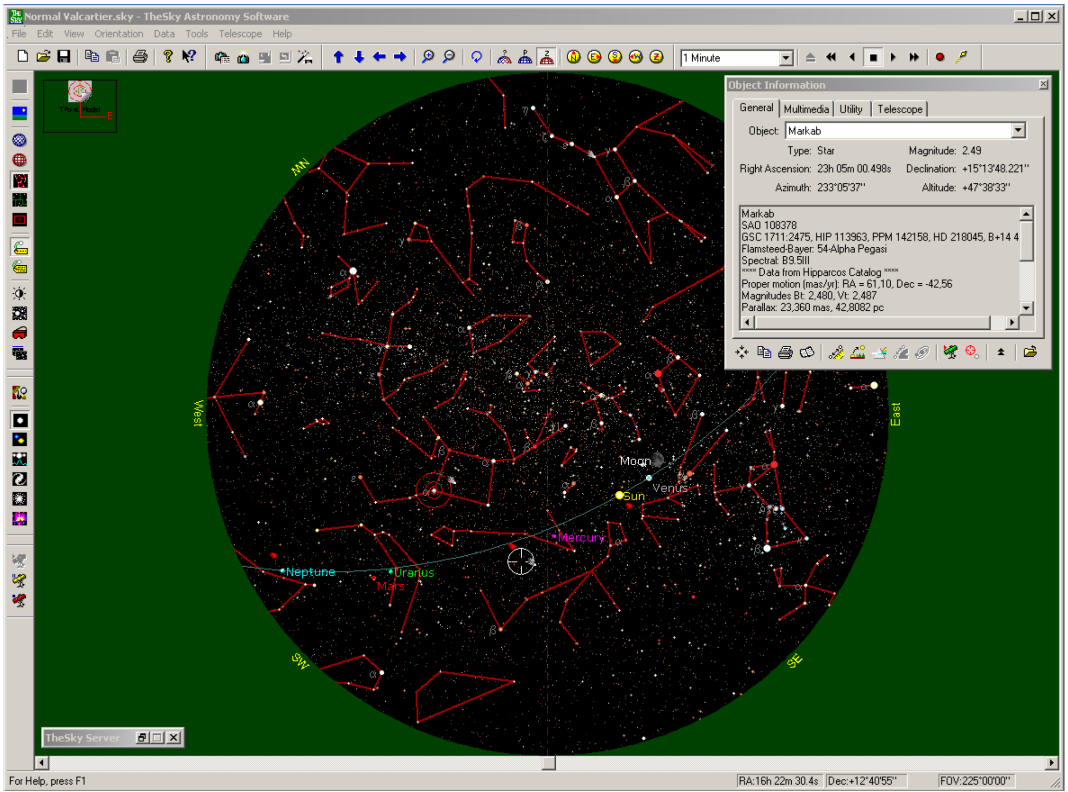


Figure 16. TheSky software interface

TheSky has a myriad of telescope functions for slewing, jogging, centering, star searching or focusing and many other versatile functions. Here are some examples:

- the Export Command can generate lists of celestial objects using a wide variety of criteria. (Ex: Man-made satellites currently above the horizon) ;
- *TheSky* Level IV can display stars from the United States Naval Observatory Catalog (USNO), which includes stars down to 21 magnitude (all 526,280,881 of them);
- the display of the "virtual" sky is flexible and fully customizable;
- the status bar can display any combination of Screen Position, Cursor Position, Earth Location, Field Width, Telescope Position, Date, and Time;
- to keep from getting lost in space, you can select any combination of object labels and reference lines for *TheSky*'s display;

- animates the motion of solar system objects;
- the Database Manager and Database Compiler give you the power to add custom data from a text file to the Object Database;
- the Image Link toolset makes it easy to identify celestial objects in CCD images or scanned photographs by means of **astrometry** computations;

3.2.3 ‘*CCDSoft*’ Astronomy Software

CCDSoft is a Microsoft Windows-based CCD camera control interface, data reduction, image processing and astronomical research application for amateur and professional astronomers. Additionally, using *CCDSoft* in conjunction with *TheSky* permits to control both CCD cameras and computer-driven telescopes, creating a powerful system for astronomical observations. Figure 17 presents the working interface of *CCDSoft*: the data acquisition tool for CASTOR-V.

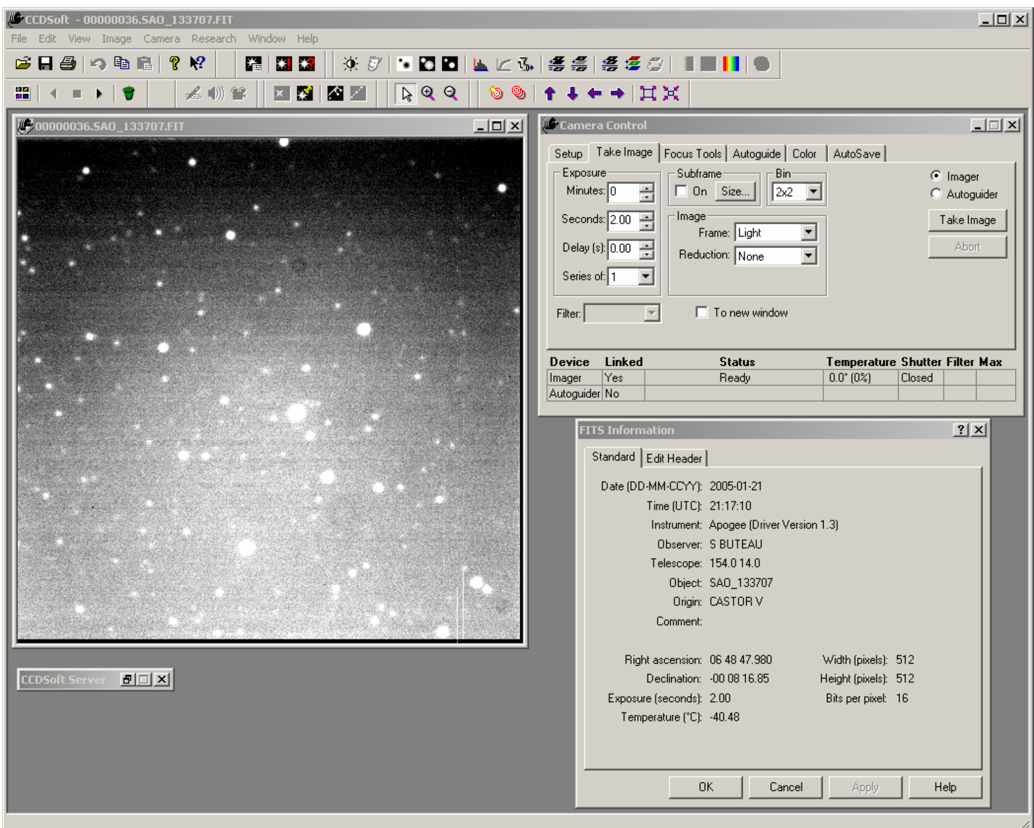
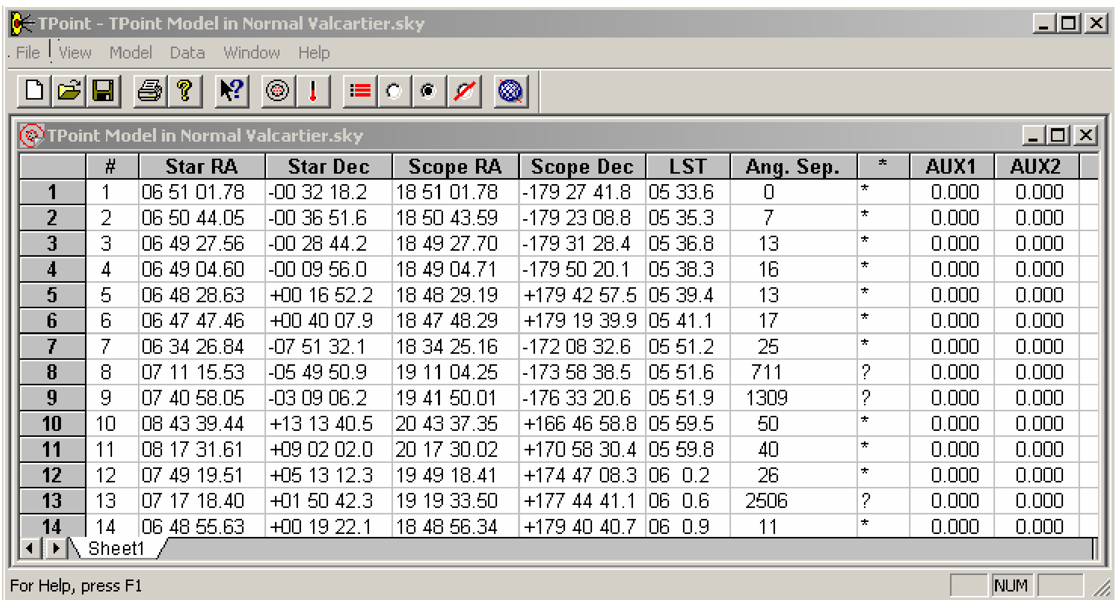


Figure 17. CCDSoft Astronomy Software working interface

3.2.4 '*Tpoint*' Telescope Pointing Analysis Software

TPoint combined with *TheSky* Astronomy Software, provides all the tools needed to efficiently analyze and improve the polar alignment and pointing performance of any computer-driven telescope. The use of *TheSky* and *TPoint* software allows one to rapidly select, target, and record telescope pointing data. *TPoint* can graphically display data in different formats and quickly reveal important characteristics of a given telescope assembly. After learning the inherent quirks and idiosyncrasies of the telescope, mount and optics (constructing the model), *TPoint* can automatically compensate for them, thus improving the telescope's pointing performance.

Figure 18 shows sample pointing data acquired by pointing at known objects in *TheSky*, slewing to these objects, performing astrometry by means of the image link function in *TheSky* and finally adding those points to the *TPoint* model. This entire process can be performed autonomously, necessitating an intervention only in the case of an image link failure.



	#	Star RA	Star Dec	Scope RA	Scope Dec	LST	Ang. Sep.	*	AUX1	AUX2
1	1	06 51 01.78	-00 32 18.2	18 51 01.78	-179 27 41.8	05 33.6	0	*	0.000	0.000
2	2	06 50 44.05	-00 36 51.6	18 50 43.59	-179 23 08.8	05 35.3	7	*	0.000	0.000
3	3	06 49 27.56	-00 28 44.2	18 49 27.70	-179 31 28.4	05 36.8	13	*	0.000	0.000
4	4	06 49 04.60	-00 09 56.0	18 49 04.71	-179 50 20.1	05 38.3	16	*	0.000	0.000
5	5	06 48 28.63	+00 16 52.2	18 48 29.19	+179 42 57.5	05 39.4	13	*	0.000	0.000
6	6	06 47 47.46	+00 40 07.9	18 47 48.29	+179 19 39.9	05 41.1	17	*	0.000	0.000
7	7	06 34 26.84	-07 51 32.1	18 34 25.16	-172 08 32.6	05 51.2	25	*	0.000	0.000
8	8	07 11 15.53	-05 49 50.9	19 11 04.25	-173 58 38.5	05 51.6	711	?	0.000	0.000
9	9	07 40 58.05	-03 09 06.2	19 41 50.01	-176 33 20.6	05 51.9	1309	?	0.000	0.000
10	10	08 43 39.44	+13 13 40.5	20 43 37.35	+166 46 58.8	05 59.5	50	*	0.000	0.000
11	11	08 17 31.61	+09 02 02.0	20 17 30.02	+170 58 30.4	05 59.8	40	*	0.000	0.000
12	12	07 49 19.51	+05 13 12.3	19 49 18.41	+174 47 08.3	06 0.2	26	*	0.000	0.000
13	13	07 17 18.40	+01 50 42.3	19 19 33.50	+177 44 41.1	06 0.6	2506	?	0.000	0.000
14	14	06 48 55.63	+00 19 22.1	18 48 56.34	+179 40 40.7	06 0.9	11	*	0.000	0.000

Figure 18. TPoint working interface

Figure 19 shows the *TPoint* Fit Data dialog box in the case of a *TPoint* model active (A) and inactive (B). This dialog box allows you to specify which "terms" (left side) will be included in the model and its relative impact by means of the graphical RMS pointing results (right side) representing the model efficiency. *TPoint* even has an advanced analysis capability that enables one to determine axis misalignments, gear errors, and more. Indeed, after sufficient pointing data is acquired (30 or more points), *TPoint* will tell how to adjust the mount to achieve the best polar alignment (Figure 20).

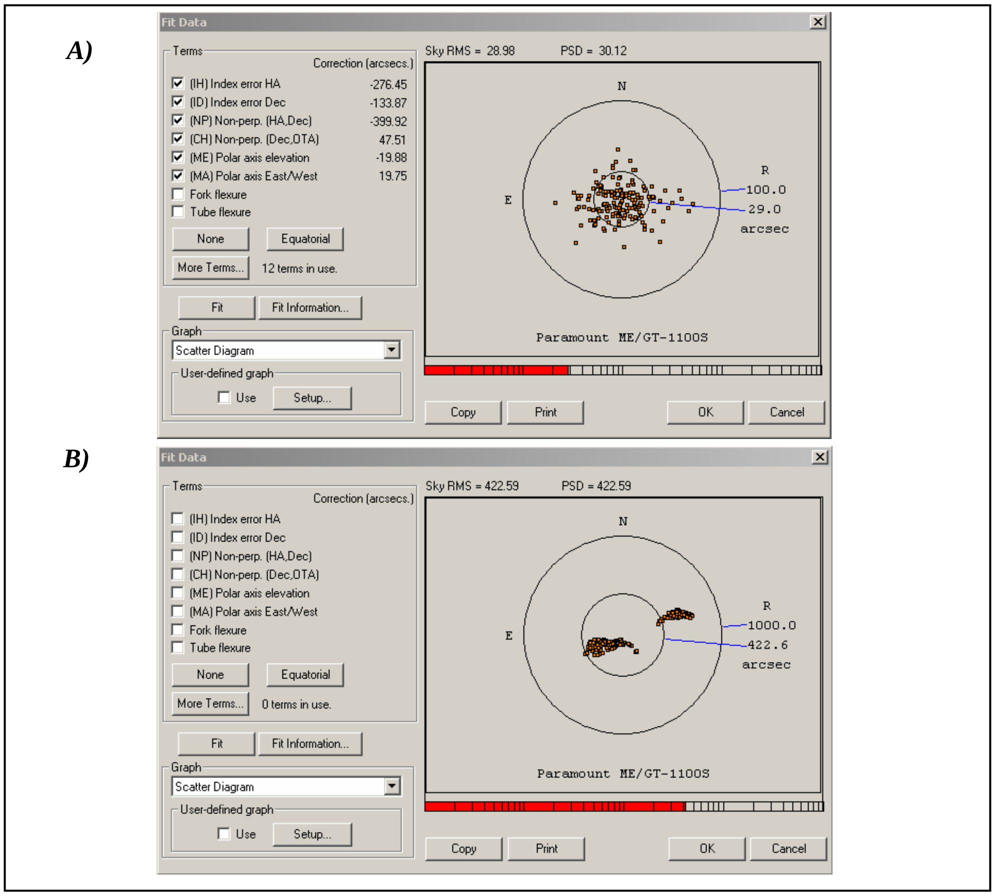


Figure 19. Fit Data dialogue box with the TPoint model activated(A) and deactivated (B)

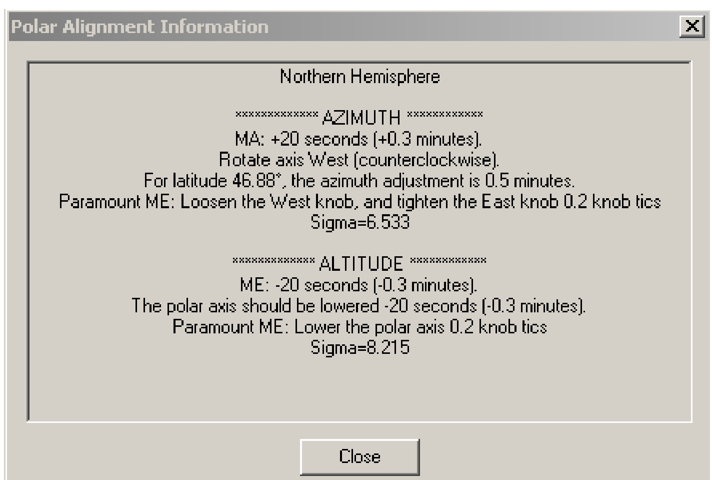


Figure 20. Polar Alignment information window from TPoint software

3.2.5 *Orchestrate*

Orchestrate allows one to control astronomical devices through scripts using a simple and efficient graphical user interface (GUI). *Orchestrate* leverages the capabilities of *TheSky* astronomy software, *CCDSoft* CCD astronomy software, *TPoint* telescope pointing analysis software and *AutomaDome* dome control software to tightly integrate precise control of the telescope, CCD camera, dome and other devices.

Figure 21 presents the *Orchestrate* working interface. Its operation is simple: enter commands into a "spreadsheet-like" interface, then click 'Run' to begin the script and these commands are executed, without any human intervention. No programming experience is necessary. *TheSky* astronomy software contains powerful data export feature and capabilities for generating *Orchestrate* script.

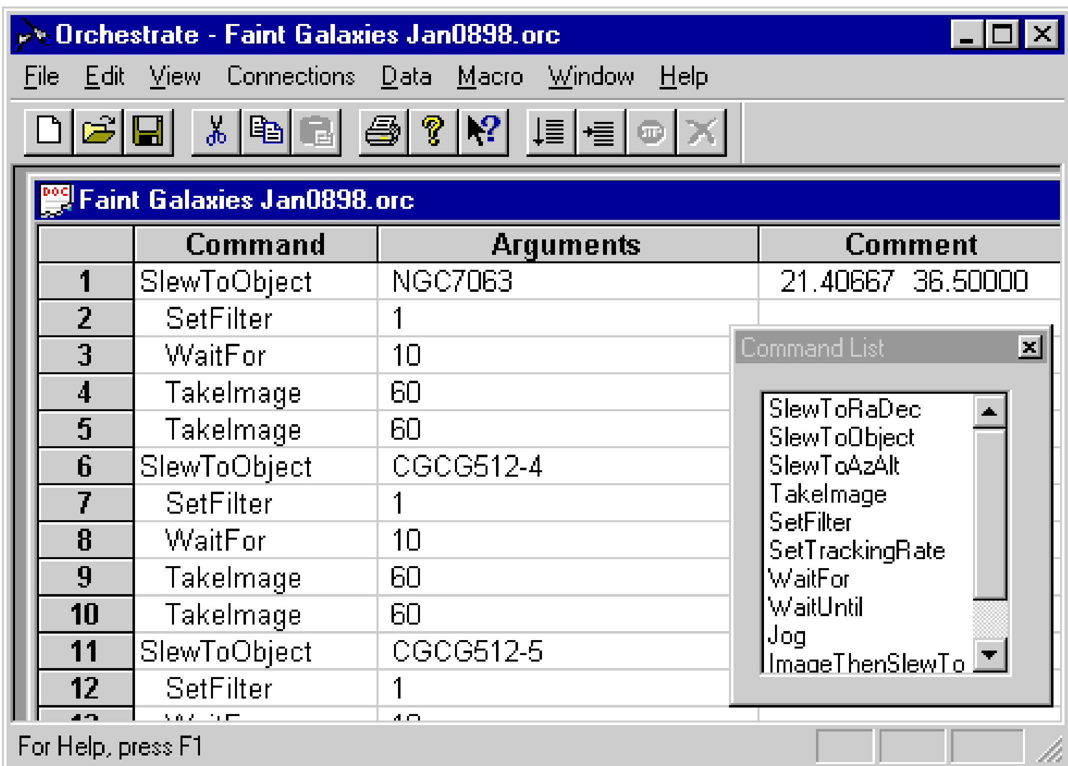


Figure 21. Orchestrate working interface and the command list window

4. System characterization

This section presents results from different testing procedures in order to characterize the system. Before any testing shall be performed, procedures required to properly start and shut down the system are presented in Annex B and C respectively.

4.1 Minimum Elevation

One aspect to consider, when performing observation, is the local horizon delimited by the surrounding environment. Indeed, any buildings, trees or telephone poles close to the observatory might obstruct the field of view (FOV). It is hence important to perform a minimum elevation assessment, determining the minimum elevation that the telescope can see through the dome's shutter opening when the dome's windscreen is not obstructing the view. In order to assess the minimum elevation at CASTOR-V, limited mainly by the surrounding forest, the calibrated telescope (tracking turned off) was pointed to the treetops corresponding to specific azimuths. By this means, it was possible to measure the minimum elevations as seen from the telescope. When a specific treetop was centered within the telescope's field of view (FOV), its azimuth and elevation angles were read off the *TheSky* software. Figure 22 presents the minimum elevation results obtained in June 2002 (blue diamonds) and in November 2003 (pink dots). The difference between the tree lines is due to the felling of some trees in fall 2003 in order to maximize the possible FOV of CASTOR-V.

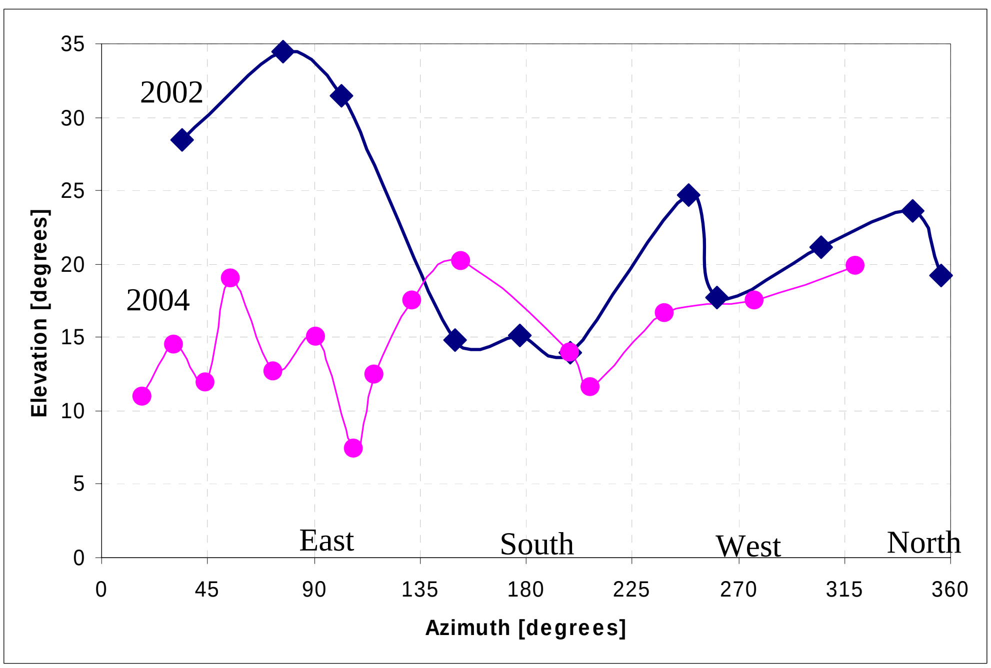


Figure 22. Minimum elevation as seen by the telescope (windscreen up), June 2002

These minimum elevation data can be included in the *TheSky* software (View/Reference Lines/Horizon-based lines/Edit Local) in order to limit the virtual sky display to the possible telescope FOV.

However, following certain trouble with the shutter-windscreen assembly, the windscreen was permanently unhooked from the main shutter (Figure 8-C). Since the top of the windscreen has an elevation of about 14 degrees referenced to the telescope, the minimum elevation is hence the maximum of either the windscreen top (14º) or the tree elevation (Figure 22). This FOV limitation does not introduce significant loss since the area of the sky below 15º (even 20º) is characterized by fairly poor observation conditions due mainly to the propagation through the atmosphere.

4.2 Dome and mount slew time

The time needed to accomplish a certain displacement of the entire system is of importance since a minimum of one satellite acquisition every 5 minutes is a requirement for the CD. The time needed to perform mount displacement on either the Right Ascension (RA) or the Declination (Dec) axis, and dome azimuth displacement was assessed. Figure 23 presents the results of this slew time test.

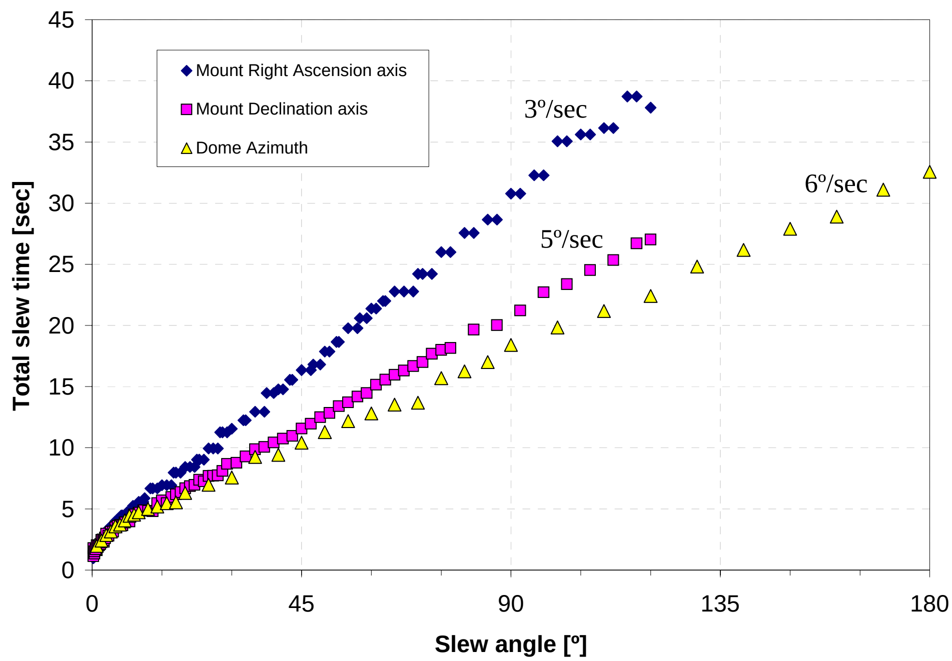


Figure 23. Total slew times for various RA and Dec slew angles for the Paramount GT-1100 ME mount and azimuth slew angles for the Ash Dome

All the mount and dome displacements were operated from the software *TheSky* and the different mount slew angles were all performed on one side of the meridian. These results were obtained with a maximum slew rate setting of 85% (in *TheSky*). During a real '*slew to*' command, the three different types of displacement, mount RA, mount Dec, Dome azimuth, are executed simultaneously, so the time related to a certain slew angle is actually the maximum time (speed x displacement) and not the sum of the three values. From the fitted (linear regression) data, we can approximate the three different displacement speeds:

- Mount Right Ascension = 3.2 degrees/sec,
- Mount declination = 4.7 degrees/sec,
- Dome azimuth = 6.0 degrees/sec.

In this test, the measurement of the needed time to cross the meridian is missing. Compared to all other angular displacement, this time parameter can be fairly long due to the German equatorial mount used in the system. However, this result depends not only on the angular displacement over the meridian but much more on the start and finish location of the slew (declination delta), which is much more difficult to characterize. The time needed to cross the meridian can range from a few seconds to around one minute depending on the start and end declination position. The fastest meridian-crossing slew is performed when the scope is initially pointing toward the celestial pole.

4.3 CCD

Three different types of tests were performed to characterize the Apogee CCD camera: dark count, downloading time and evaluation of the delay effect on the dark count level.

4.3.1 Dark current (dark count)

The dark current may be the most important CCD specification next to the quantum efficiency, resolution (number of bits) and noise figure. Dark current refers to that property of all CCD sensors to spontaneously generate charges in each pixel, depending on the acquisition time and temperature. It represent the thermal agitation of frees electrons in the silicon substrate of the CCD. The lower the sensor temperature, the lower the dark current. It is usually expressed in electrons count per unit of time at a given temperature or as a current per sensor area at a given temperature. The main reason that CCDs are cooled is to minimize the dark current.

Dark images of 20 seconds were taken at different temperature from –10 down to –50 °C in order to evaluate the dark current of the CASTOR-V Apogee CCD. Figure 24 presents the results where the dark counts are recorded by the Analog to Digital Unit (ADU). The blue squares and green triangles correspond to the average dark count in a Region Of Interest (ROI) having a 10 pixel radius and located at the bottom left (35,980) and the top right (1010,10) respectively. The orange diamonds correspond to a global average of the entire array of CCD pixels. The dark count represented in Figure 24 includes the bias contribution originating from the system electrical offset. Those results present two different system characteristics: 1) the expected CCD dark count dependency to the temperature and 2) the important dark count performance degradation from the top to bottom axis which is also dependent on the CCD temperature. This latter aspect is related to the temperature difference on the CCD chip and most of all to the extremely long downloading time (section 4.3.2) of the parallel port AP8p CCD. Indeed, the dark count continues to build during the download time and the readout (digitalization in ADU). The dark count performance degradation along the top to bottom axis, is directly related to the transfer time (first paragraph in section 3.1.6).

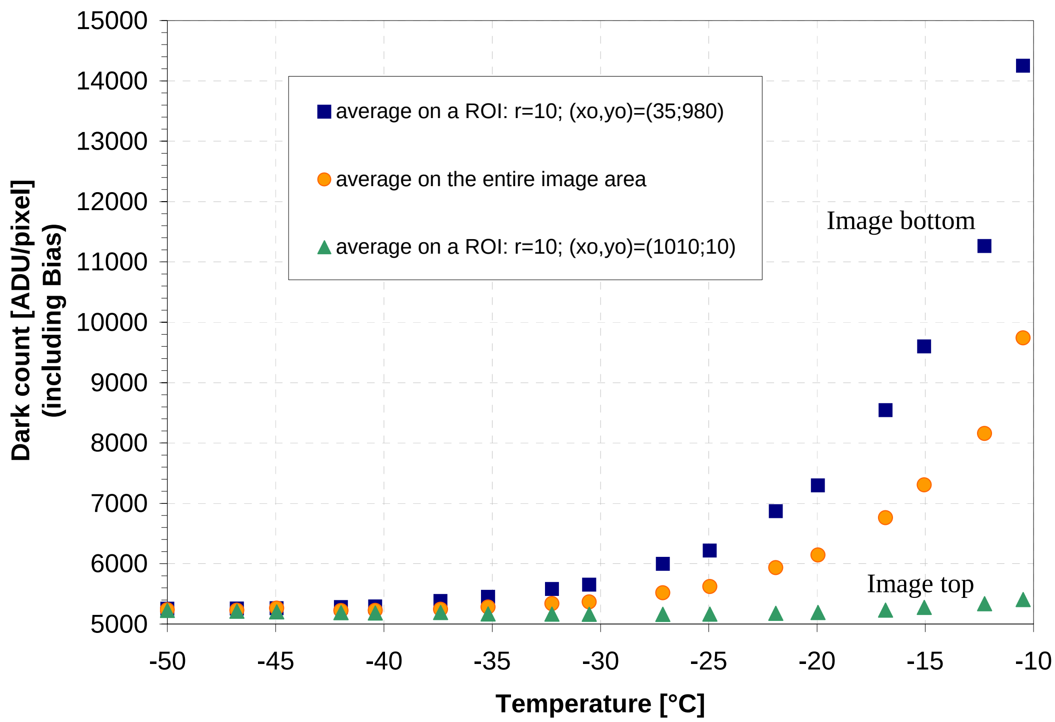


Figure 24. Dark current dependence on temperature for a 20 seconds exposure

The necessity to cool the sensor is obvious from these results (Figure 24). Although corrections can be made for dark contribution in the finished image by subtraction, the error in this process increases with increasing dark count, given some degree of temperature instability and dark noise present in every system. It is hence always advantageous to minimize the amount of dark count in the imaging system. The chosen operating temperature of the AP8p CCD is -30°C in order to diminish sufficiently the top to bottom gradient and to assure that this operating temperature will be reached even during the warm season. The SITe (CCD chip) back-illuminated sensors generate a lot of dark count. These sensors require greater cooling to achieve the same dark count range as the usual front illuminated CCD. Apogee AP series systems employ a sealed soft-vacuum chamber with Argon back-fill as a no-maintenance compromise in cost and performance for cooling the CCD chip.

At any given temperature, the rate at which electrons are freed is supposed to be constant. In order to verify this and also to evaluate the bias (dark count for a zero exposure frame), a series of dark images all taken at an operating temperature of –30 °C were taken for different exposure times from 0.02 to 180 seconds. Figure 25 shows these results: the dark count in ADU for two ROIs located at the top(blue squares) and the bottom (green triangles) of the image and the global average (orange circle) of the entire dark frame and these, for different exposure time.

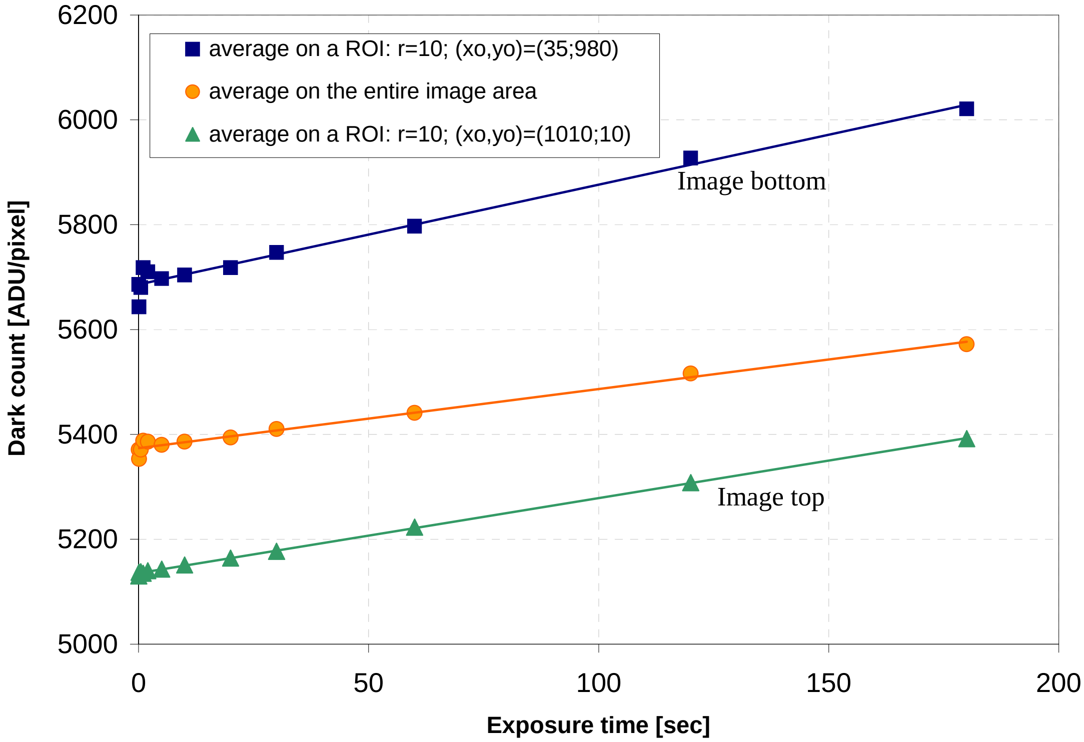


Figure 25. Dark count dependence on exposure time at –30 °C

From these results, the linearity of the dark count build-up within the CCD chip is clear for exposure time larger than one to two seconds. Lower than this, the signal is fairly noisy. The bias, represented by the intercept evaluated from the linear regression, is dependent on the ROI following the charge build-up during the delay and readout of the frame. The lowest bias level is obtained from the first pixels transferred and hence corresponding to the amount of count of a real 0 second dark frame. The dark count in electrons per pixel per second (e/p/s) can be evaluated from these results with the following formulae:

$$\text{Dark count [e}^{-}\text{/pixel/s]} = \left(\frac{\text{Dark count - Bias}}{\text{t}_{\text{exposure}}}\right)\left[\frac{ADU}{pixel \cdot s}\right] \bullet \text{gain}\left[\frac{\text{e}^{-}}{ADU}\right], \qquad (1)$$

where $t_{exposure}$ is the exposure time and the gain in electrons/ADU is expressing how many electrons of charge are represented by each count (ADU). The measured gain can be determined from the test data sheet of the CCD or can be roughly evaluated by dividing the well depth by the digital resolution (16-bits = 2^{16} count). The dark count characteristic of the CASTOR-V Apogee CCD was calculated with Equation 1 and ranged from 4 to 7 (e/p/s) at -30 °C, which is close to the 4.4 e/p/s @ -27 °C specified in the test data sheet and the 8 e/p/s @ -30 °C of the SI-003AB CCD specification sheet.

4.3.2 CCD downloading time

After many dark frames have been collected at different temperatures and exposure times, the downloading time measurements have only shown a dependence in the binning mode, as shown in Table 8. Most CCDs have the ability to clock multiple pixel charges in both the horizontal and vertical direction into a single larger charge or "super pixel." This super pixel represents the area of all the individual pixels contributing to the charge. This is referred to as binning. Binning of 1x1 means that the individual pixel is used as is. A binning of 2x2 means that, an area of 4 adjacent pixels have been combined into one larger pixel, and so on. In this instance the sensitivity to light has been increased by 4 times (the four pixel contributions), but the resolution of the image has been cut in half. Figure 26 illustrates the binning effect.

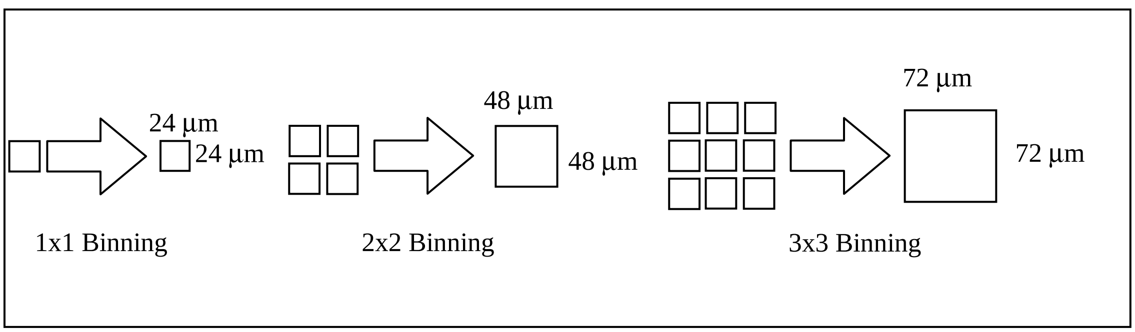


Figure 26. Pixel binning effect

Table 8. *Downloading time for the AP8p CCD for different binning mode.*

BINNING MODE	CCD MATRIX [PIXELS]	DOWNLOADING TIME [SEC]
1 x 1	1024 x 1024	34.0 – 36.5
2 x 2	512 x 512	10.1 – 11.5
3 x 3	341 x 341	5.3 – 6.0

4.3.3 Time delay effect on dark noise

A varying dark count level was observed from the numerous dark frames taken and it was suspected that the dark current was accumulating even during the delay between the shots and the CCD reading would reset it to zero. In order to evaluate the effect of time delay between two downloads on the dark current, a specific testing procedure was performed. That consisted initially, in taking two 30-second consecutive dark frames at -30 °C (1x1 binning mode) and after a certain time delay, to take another two dark frames with the same characteristics. The time delay between each two frames series is longer each time. The results presented in Figure 27 uses the same legend as Figure 24 and 25 but with one particularity: the clear and full symbols represent the dark count of the first and second dark frame respectively after the time delay elapse.

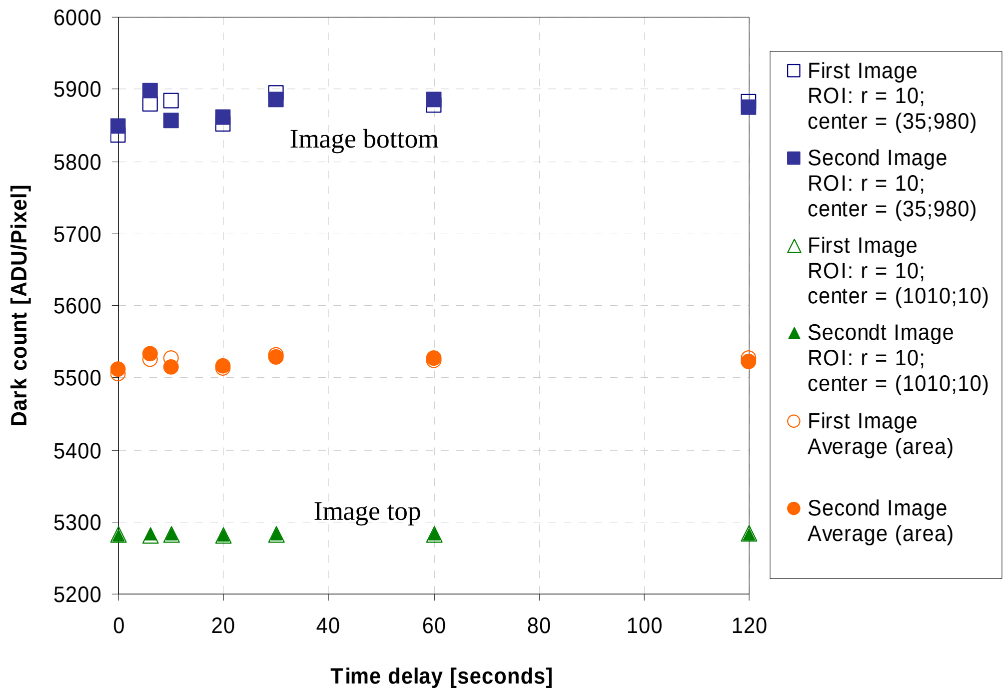


Figure 27. Dark count comparison between 30 seconds images taken either rapidly (second) or after a certain time delay (first) once an image has been taken

The results show absolutely no effect of time delay between two images on the dark count background level of the AP8p CCD. Indeed, the small discrepancy between first and second image, are only related to the dark count fluctuation. The cause of the variation of the dark count level (to be distinguish from dark noise) must reside in either the CCD chip cooling system efficiency stability or in the bias level fluctuation.

5. Particularities and Issues

During the first year of operation, 2002-2003, several issues came up while operating locally the system. Hardware and software problems were resolved as they appeared. This section resumes the different issues and how they were handle in addition to different particularities of the hardware components that must be considered to operate CASTOR-V in an optimum manner.

5.1 Dome

The Ash Dome controlled by a Meridian controller and operated from *AutomaDome* Control Software (Software Bisque) had exhibited various problems during the first six months.

5.1.1 Dome particularity: the snow

The accumulation of snow on the dome, as seen on Figure 28, has two direct impacts on CASTOR-V operation: 1) blocking the sunlight to the solar panel used to recharge the 12 volt battery powering the dome shutter controller and 2) putting extra-weight on the shutter and creating the possibility of snow falling on the telescope. Usually the snow on the dome will regularly fall off on its own, but depending on the weather condition sequences, this was not always the case. It is hence important during winter, to verify periodically, especially after an important snowfall, the accumulation of snow on the Dome and solar panel. In addition, the telescope park position should be selected to avoid any contact between incoming snow or water from the small shutter gaps that may be present and the telescope corrector plate.

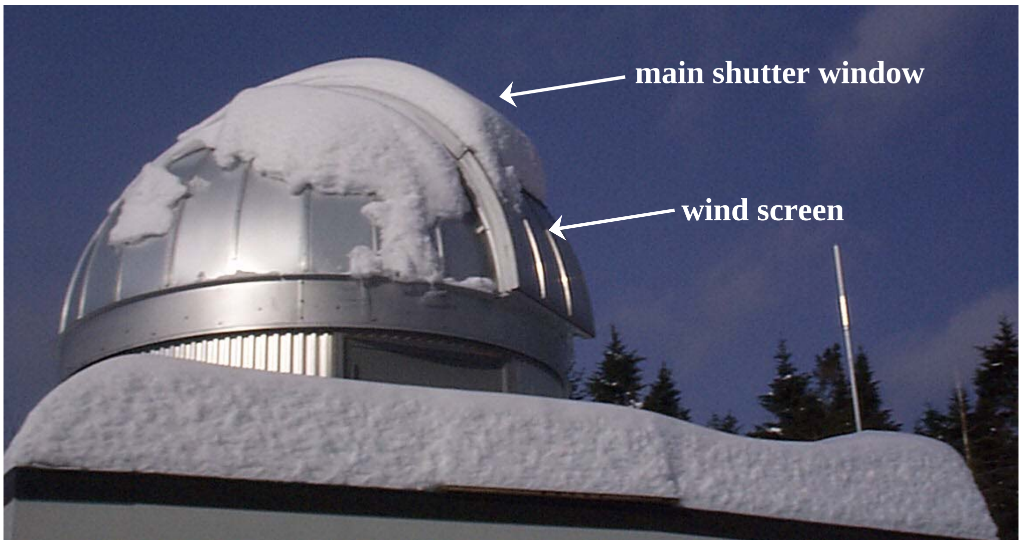


Figure 28. Snow on the dome and shutter window

5.1.2 Dome issue 1: Control from the software

Following the installation of the dome controller, the close shutter command from the *AutomaDome* Dome Control Software was far from being reliable. Indeed, the close shutter command responded properly only once every five times in average. The command thus had to be entered many times before the shutter could be effectively close down. This particular operation state is incompatible with the remote operation requirement.

Meridian Control Inc. sent a new integrated circuit chip (Figure 29) for the dome controller printed circuit board (PCB). Once the old PCB chip was replaced, the close shutter command started to respond adequately. But meanwhile, the open shutter command from the software, was not opening the main shutter anymore but rather the wind screen (WS) and the main shutter. Indeed, from the software, there was only one possible 'open shutter' command and not a 'WS open' and a 'shutter open' as on the Meridian dome controller box. When the WS and the main shutter opens, the possible FOV for the telescope is limited overhead because the shutter assembly stops as soon as the main shutter clears up the shutter opening completely. This command hence leaves the WS on the zenith portion of the shutter opening, creating an obstruction to the telescope possible FOV. The wind screen was then unhooked permanently from the main shutter, by taking off the springs holding the two hooks.

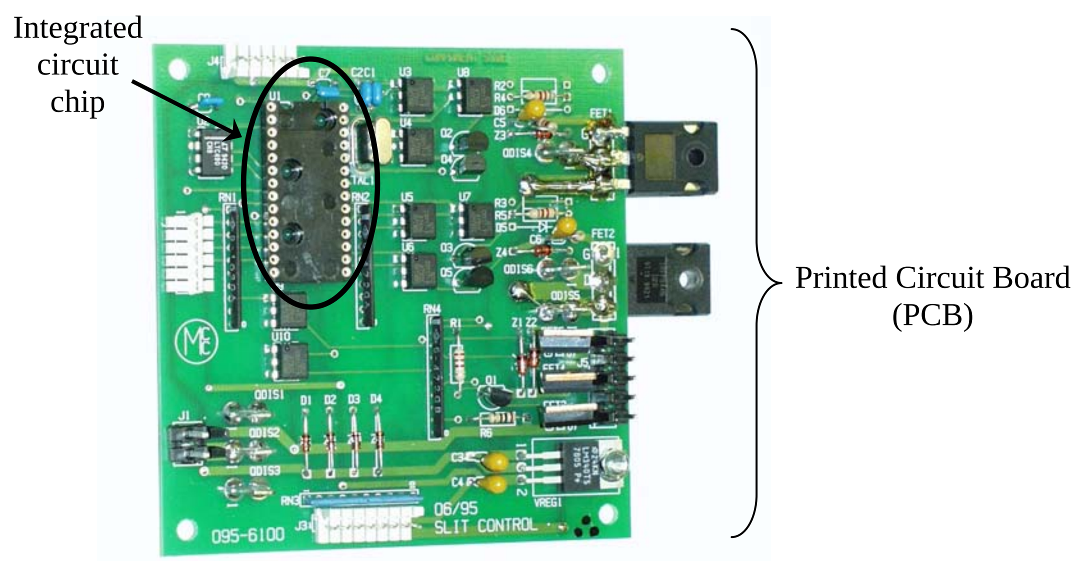


Figure 29. Integrated circuit chip on the PCB of the dome controller

5.1.3 Dome issue 2: PCB damage

During winter 2002-2003, CASTOR-V was operated pretty often without any consideration on the ambient temperature. The system was hence sometimes tested at temperatures as low as -20 °C. After one particularly cold observing night in February 2003, the shutter motor stopped while closing the main shutter. From the software, there was no evidence of any kind of problem with the shutter. The shutter had to be closed using a direct connection to the battery, hence bypassing the controller, which was not responding anymore. This shutter breakdown originated from damage on the controller PCB (one burned line).

The origin of the problem was the shutter motor heavy grease, which was not suitable for low temperature as experienced by CASTOR-V. *Meridian Control Inc*. (California) did advise to change the grease of the motors for one designed for cold climate, like the one in Quebec, Canada. This suggestion was not implemented but should have been. On the other hand, the circuit security (fuse) on the PCB failed to protect it since it did not avoid the burning of a track. The damaged PCB was rapidly repaired in-house as shown in Figure 30, and the two motors were brought down, cleaned and new oil/grease (-45 F) was used. In January 2005, on another cold night, the shutter motor required so much power that the fuse and its holder blew up. The fuse holder was replaced by a similar one. In order to eliminate these potential issues, it is advised to use CASTOR-V only at temperatures higher than -20 °C.

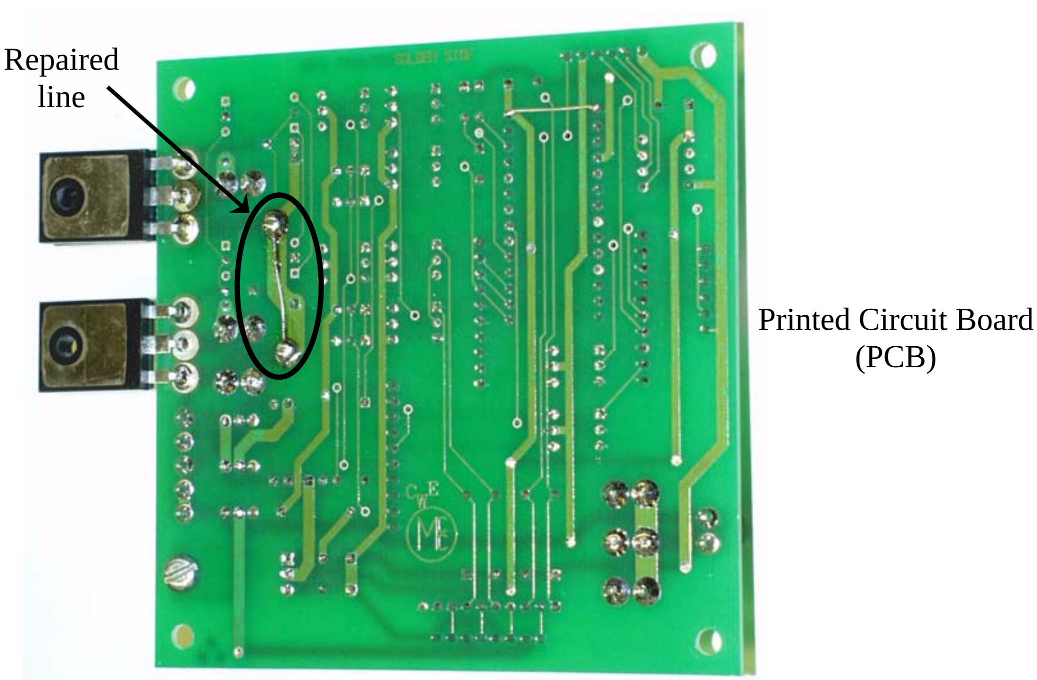


Figure 30. In-house repaired PCB line of the dome controller

5.1.4 Dome issue 3: Shutter malfunctioning

Once the motors had appropriate grease and the PCB was repaired, it was time to test the dome controller operation. All the commands were working fine except for the ‘open WS’, in which case, the main shutter was now pushing down the WS instead of pulling it up. Annex D details the status of the dome controller manual operation. *Meridian control Inc.* sent a new PCB with a new chip to resolve the problem. But the new PCB with the new chip had the same limitations as the in-house repaired one (Annex D).

Three solutions were then proposed: 1) return the entire shutter controller including the enclosure to repair the unit as a whole; 2) a field service repair of the unit but not until the first week of May; and 3) replace the entire system, shutter and dome control, with the hardware and software upgraded version. Option 2 was selected but when M. Melsheimer from *Meridian Control Inc*. arrived at the USA/Canada border, his access was refused related to non-adequate working papers. From his point of view this was the last tentative to come in Canada. After additional tests, it was decided to simply disconnect the wind screen motor from the dome controller (Figure 31). In this configuration, the WS is permanently down with no possibility to rise it up. This solution did not introduce a significant limitation because the FOV was already limited by the tree line surrounding CASTOR-V.

Figure 31. WS motor disconnected from the dome controller box

5.2 Mount

The Paramount GT-1100 ME controlled by *TheSky* Astronomy Software, both from *Software Bisque Inc*. also had its share of problems, in most cases related to cold temperature.

5.2.1 Mount particularity: Pointing accuracy

The pointing accuracy of the mount is required for efficient satellite tracking purposes. The pointing accuracy must be compared to the field of view, FOV_{CCD}, produced by the Apogee CCD camera used on the Celestron CGE-1400, which is given by:

$$FOV_{CCD} \cong 57.3 \cdot \left(\frac{d_{CCD}}{F} \right) [\text{deg}] = 3439 \cdot \left(\frac{d_{CCD}}{F} \right) [\text{minutes of arc}], \quad (2)$$

where d_{CCD} is the width of the CCD chip and F is the telescope focal length. For CASTOR-V, d_{CCD} is 24.6 mm and F is 3910 mm, which gives a FOV of 21.6 arc-minutes. The long and more precise T-Point run (172 map points) performed in January 2005 allowed reaching a pointing accuracy of 29 arc-seconds (Figure 19), representing about 2.2% of CASTOR-V field of view.

Figure 32. Satellite streak (23536U) obtained with CASTOR-V while having a bad pointing accuracy

In order to keep this level of pointing accuracy, a short mapping run facilitates re-establishing the relationship between the telescope and an existing *TPoint* pointing model once the telescope is "synchronized" from *TheSky*. An entirely new *T-Point* run should be carried out when the pointing accuracy degrades above one quarter of the FOV (5.4 arc-minutes in the present case). Else any given satellite streak risks to be just partly in the FOV (Figure 32) or even outside of it.

5.2.2 Mount issue 1: Type-a failure

During winter 2002, the mount had its first failure (type-a failure). When *TheSky* software issued a command to the telescope to point to a given spot in *TheSky* software. After a normal start, the telescope mount stops slewing suddenly in one axis (declination). From the software interface, the 'telescope slewing' window was still in action since the telescope has not reach its target position because the mount has stopped slewing. No error notification was issued by the software when the declination axis stops responding. On the adapter panel of the telescope mount, the led related to the problematic axis, was blinking. In order to regain control of the mount, a complete mount shutdown was required and a 'find home' command was used to reset the software.

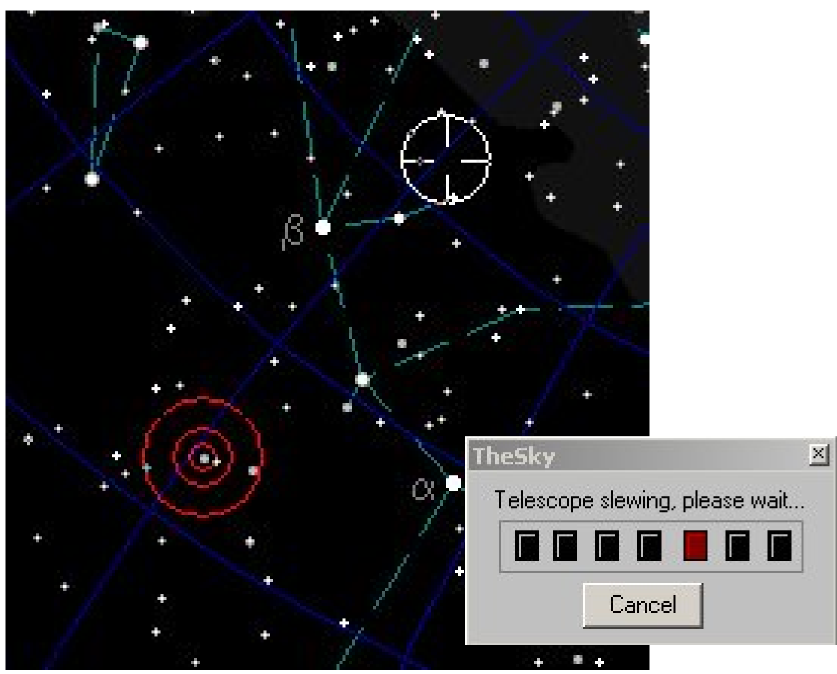


Figure 33. TheSky interface during a-type mount failure

This random failure was reported to Software Bisque and they suggested different verifications. The problem origin seemed to be related to potential cross-talk between the motor wires (three leads departing from the motor) and the 5 encoder wires bundled near the 3 motor wires (Figure 34). Once the declination motor cover (5 screws) on the declination housing was removed, it was insured that the capacitor and 5 encoder leads were separated from the 3 motor wires departing from the motor, as much as possible. Figure 34 shows wires in the original manufacturer position. For the CASTOR-V mount, the attempts to provide additional space was made and achieved. After this simple manipulation was performed, this type of mount failure has never reappeared.

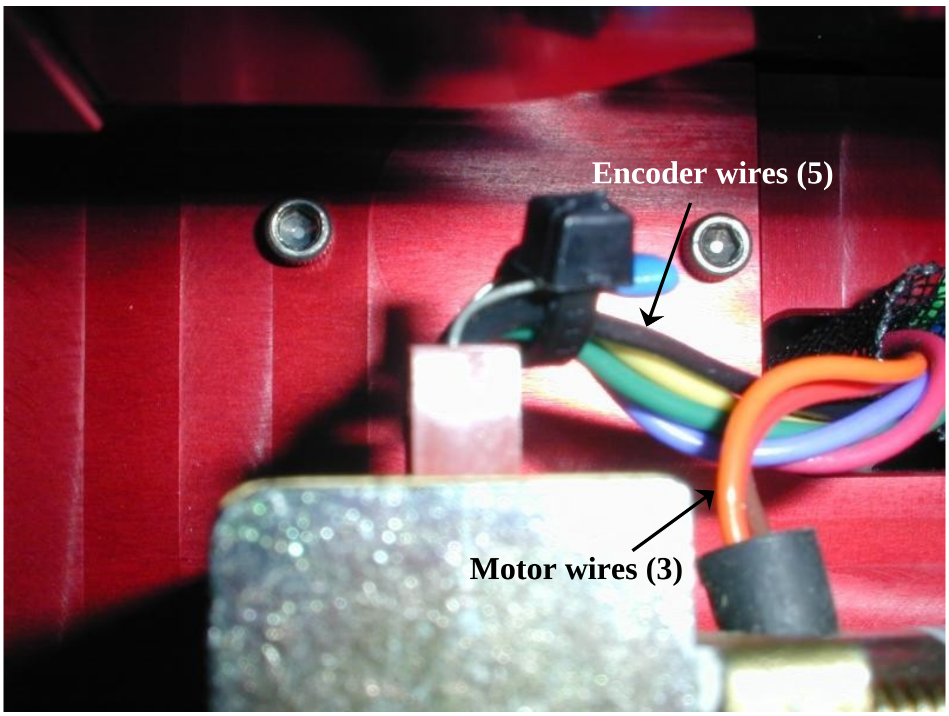


Figure 34. Motor wires (3) and encoder wires (5) in the telescope mount

5.2.3 Mount issue 2: Type-b failure

The mount had a second failure (type-b) also during winter 2002. When *TheSky* software issued a command to the telescope to point to a given location in the sky, after a normal start, the telescope mount stops slewing suddenly in both axes. The ‘slew command’ window shuts off and the actual telescope position was different than the one reported in *TheSky* virtual sky. There was no blinking led on the telescope mount adapter panel. Up to this point, there was no indication of any problem from the software. Once a new slew command was issued to the telescope mount, a message from *TheSky* software, indicating that the mount was not homed, appeared (Figure 35). This state prohibited any new displacement until a home command was send to the mount.

The problem was related to cold weather. In fact, the mount simply lost power because the current required by the motor was too high due to cold temperature. At –20 °C, the mount motors require about twice the power required at +20 °C and the power supply was simply failing in delivering the necessary power.

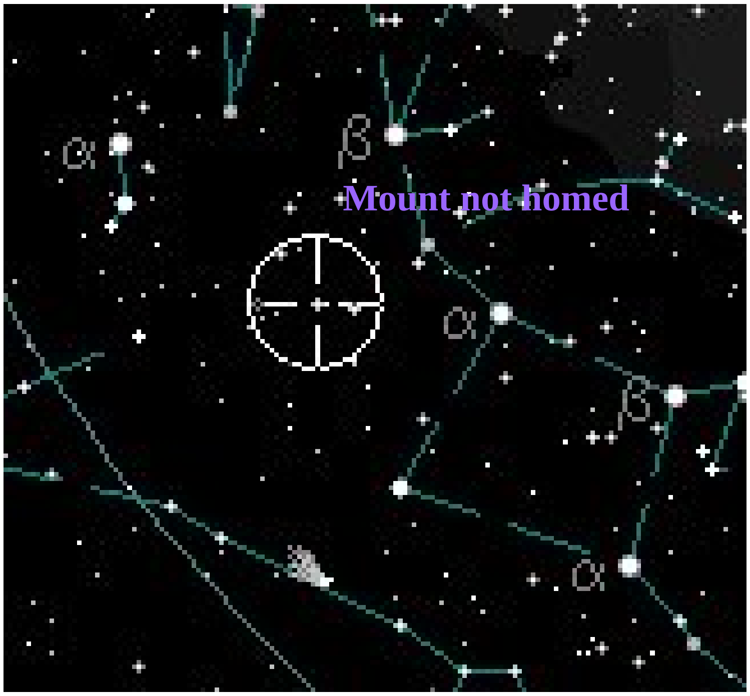


Figure 35. TheSky interface during b-type mount failure

To overcome this type-b failure, *Software Bisque* suggested to 1) unscrew the declination and RA knobs (Figure 36) to loose up the gears, 2) add about 5 drops of normal 3-in-1 oil on the RA worm (Figure 37) to eliminate a potential worm-gear resonance issue, and 3) reducing the maximum speed for the colder months to about 65%. This last option should help the motors overcome the additional torque required when the bearing grease has become more viscous. But this solution would have a major impact on the number of observations that can be performed over night.

Notwithstanding the three above suggestions, the mount type-b failures were still occasionally observed, even though much less frequent. To resolve definitely the problem related to this additional power requirement, a 80-watt power supply was purchased to replaced the original unit limited to 60W. This ultimate action resolved this particular issue and did not require the maximum mount speed to be reduced.

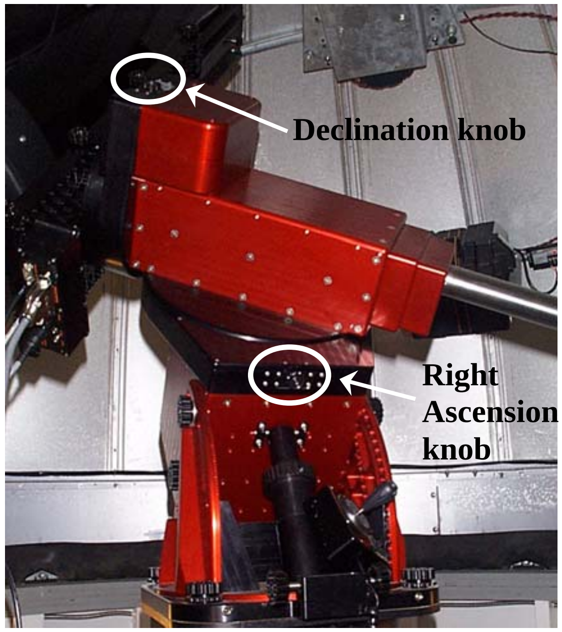


Figure 36. Declination and Right Ascension knobs of the Bisques ME telescope mount

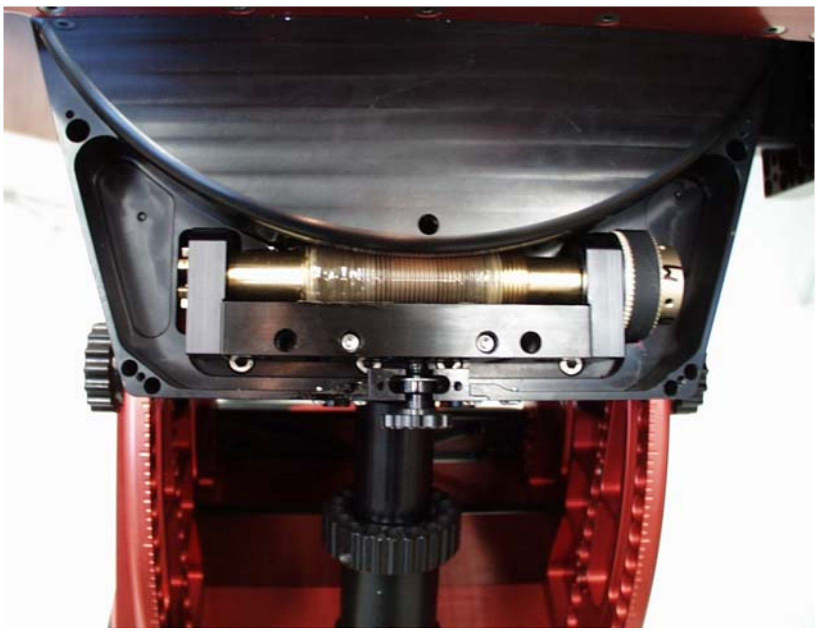


Figure 37. Right Ascension worm gear of the Bisques ME telescope mount

5.3 CCD

The Apogee AP8p CCD camera controlled by *CCD Soft* Astronomy Software was the hardware component, which has suffered the most from diverse types of problems. The different issues with the CCD are presented chronologically.

5.3.1 CCD issue 1:Top image artefact

The first images taken with CASTOR-V met the expectation but presented a washed out region at the top of the CCD frames. This top image artefact, as shown in Figure 38, was systematically present. The CCD had to be sent back to Apogee in order to be diagnosed and properly fixed. Apogee traced the problem to the positive lead on the cooler that had an almost undetectable short. This short to the CCD chamber caused the cooler malfunction. Apogee was confident that it was the cause of the problem and they repaired it. Indeed, after its reparation, the top image artefact has never reappeared.

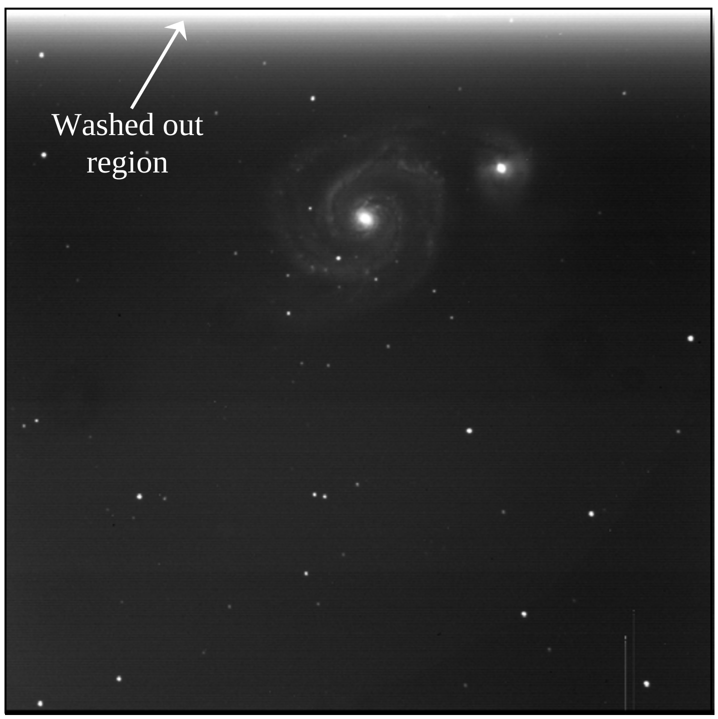


Figure 38. Example of an image with the top image artefact taken in June 2002 with CASTOR-V (Whirlpool nebula)

5.3.2 CCD issue 2: Fringes artefact

As soon as the CCD camera came back from its repair at Apogee, it was reinstalled on CASTOR-V setup and tested. A new issue was now perceptible. Fringes were now polluting the CCD dark frames and light images. The power supply was suspected and Apogee sent a new one. After some testing, it was found that 1) the fringes artifact issue was not related to the power supply in any way, 2) the problem was intermittent and 3) the CCD cables or the mount pass through were suspected. Finally, an intermittent connection was found in a cable and the CCD cable set was entirely replaced. This fringes artifact issue never manifested itself again.

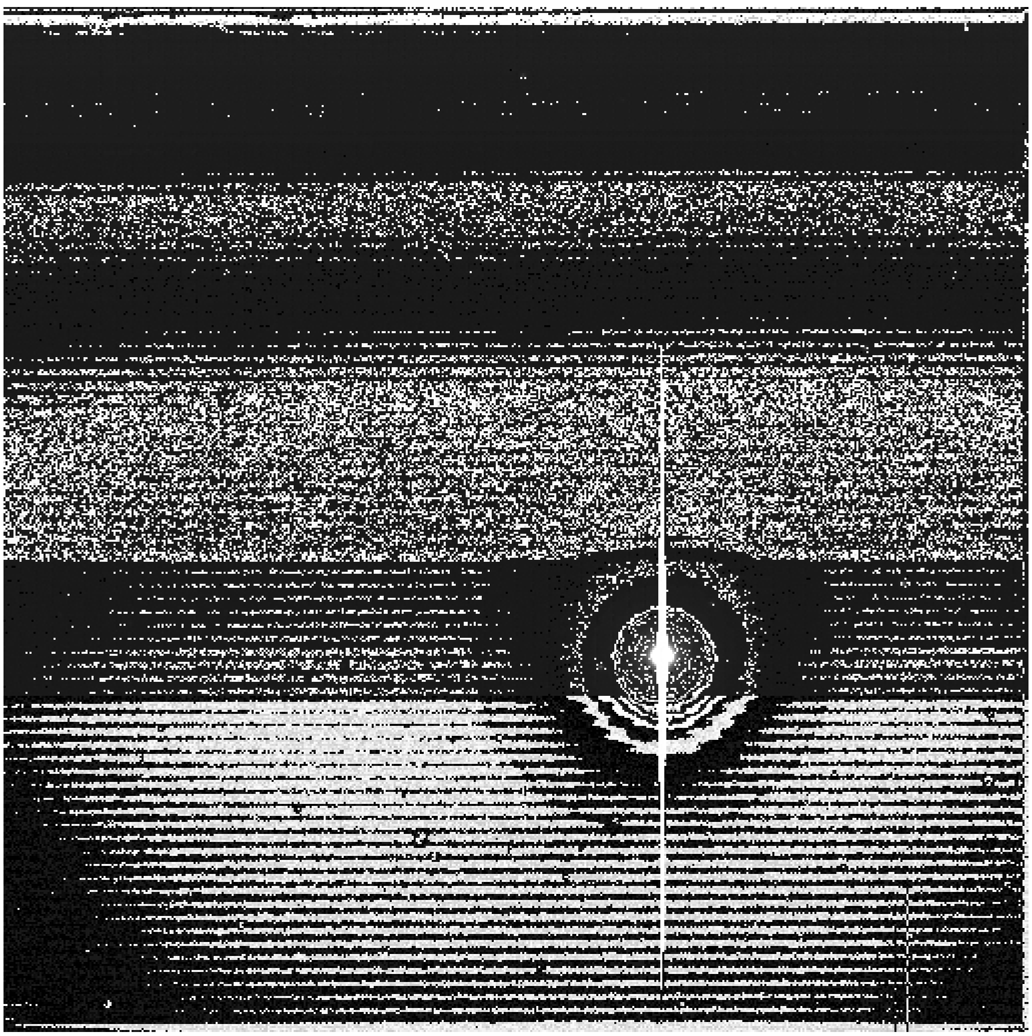


Figure 39. Example of an image with the fringes artefact taken in August 2002 with CASTOR-V (Vega)

5.3.3 CCD issue 3: Dark ring and halo effect

In the middle of an observing session on December 18th 2002, a dark ring accompanied by a hallo effect suddenly appeared on the CCD image (Figure 40). This feature originated from a ring of moisture in the CCD chamber of the camera. Before changing the desiccant, it was suggested (from the Apogee instruction for desiccant swap) that the camera fan should be run for about an hour before cooling starts to drive out any moisture and prevent the halo caused by fogging on one of the various pieces of glass of the camera head. This moisture ring never reappeared and the CCD fan is usually always running for a given period of time before cooling (less than an hour).

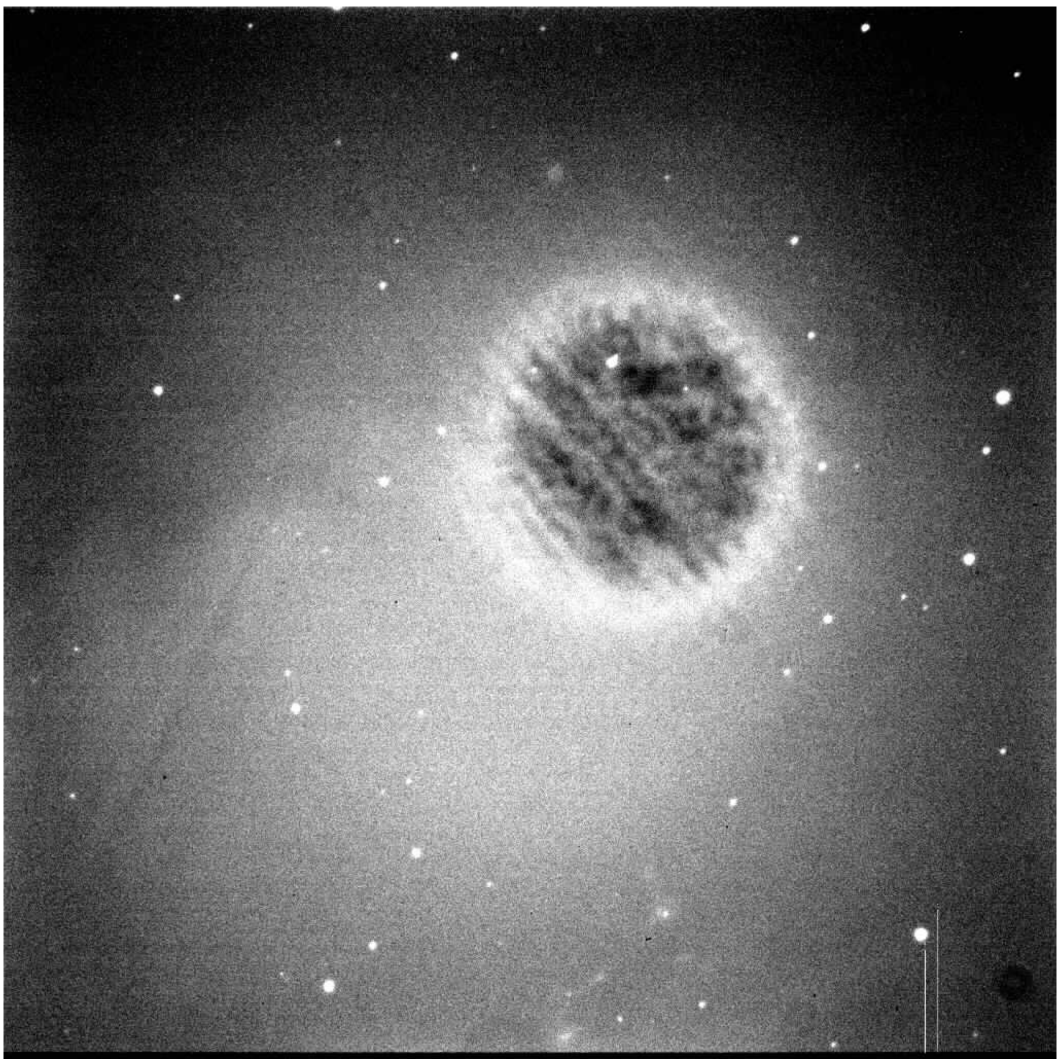


Figure 40. Example of an image with the dark ring and halo artefact taken in December 2002 with CASTOR-V

5.4 Telescope

The Celestron Model CGE-1400 has experience only one problem: dew.

5.4.1 Telescope issue: Dew problem

In October 2002, in the middle of an observing session, the system suddenly seemed to have a focus problem. But after some quick checks, it was determined that the focus was still optimum and the sky was still clear. In fact the problem came from the presence of dew on the corrector plate of the Schmidt-Cassegrain telescope (SCT). Indeed, depending on the humidity level and ambient temperature, dew can appear on the correcting plate.

This kind of problem is very frequent with a SCT. From a thermodynamic point of view, a clear sky is about 60 ºC colder than the ambient temperature. The correcting plate of the SCT, sandwiched between a clear sky and a reflecting mirror, becomes colder than the ambient temperature favoring the formation of dew. Fortunately, this issue is well known and can be solve with heating elements that maintain the temperature of the optical element.

A dew heater and a Baader TurboFilm™ were added to the optical tube assembly of CASTOR-V. The TurboFilm™, based on a diffraction limited high-transparency monopolymer, was already used at CASTOR-K to protect the optics of the SCT. It can be easily replaced once it gets dusty or scratched. Its thinness provides minimal heat capacity that allows quick setting to the ambient temperature.

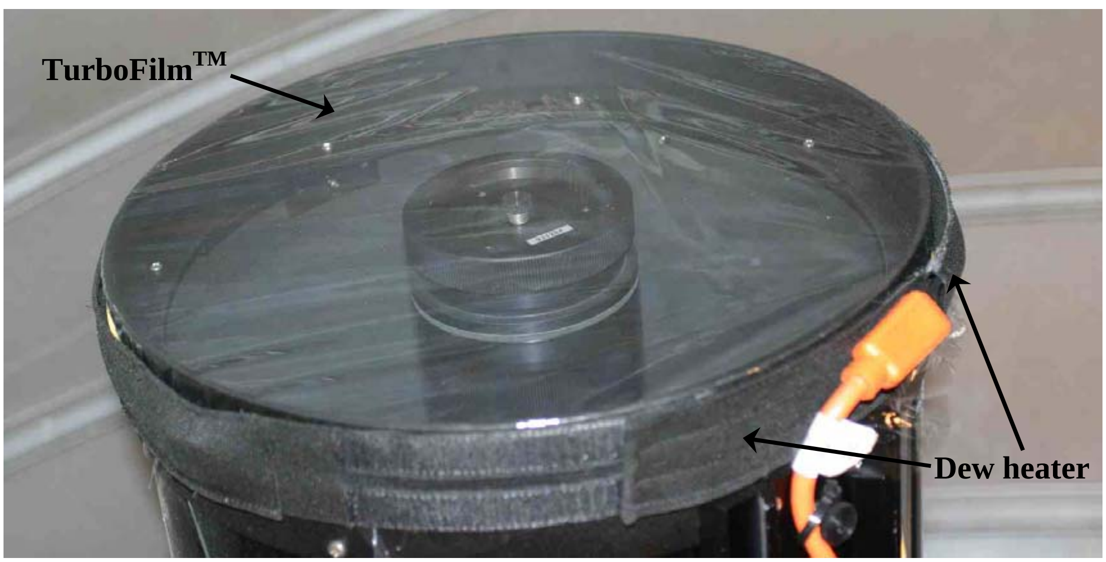


Figure 40. Dew heater and the Baader TurboFilm on the telescope corrector plate

6. Results

Among the thousands of images collected by CASTOR-V since June 2002, only a few will be presented in this report. This section is aimed at showing typical satellite streaks and tracking images. From these pictures, the reader will be aware of the different issues in the satellite detection field. The first section will present the overall outcome for a particular tasking, the last two will present images acquired in the sideral and satellite tracking mode respectively. The two white vertical lines at the lower right corner of all images are due to two dead pixels.

6.1 Satellites task

At the end of June 2003, exactly one year after the optical assembly of CASTOR-V, a request to acquire a series of 20 satellites were sent by SoSP to task the CD. However, at that time, CASTOR-V was the only system in operation since CASTOR-K was in the process to be upgrated and CASTOR-S was not installed yet. Table 9 presents some details on the satellites of the tasking list.

On June 26th and July 6th 2003, 6 and 8 others satellites from the tasking list were respectively observed. From the 20-satellite task, 14 were tracked and their respective streak images were collected. From the non-observed 6 satellites, LAGEOS 1 (08820), COSMOS 2024(20026) and a PAM-D debris (27765) were not accessible at night during this period of the year. Indeed, they were only observable more than half an hour after sunrise (Satellite Tool Kit results). Three other satellites, COSMOS 1490 (14258), COSMOS 1989 (19751) and Molniya 3-39 (20813) were simply too low in altitude, between 7 and 12 degrees, to be observed by CASTOR-V, considering the trees all around the observatory (section 4.1). Accordingly, CASTOR-V was able to track all the satellites that could be effectively observed at this particular time of year and from its position considering its local horizon.

Table 9. *20 satellites task from SoSP to the CD.*

INTERNATIONAL DESIGNATOR	NORAD CATALOG NUMBER	NAME	SOURCE	LAUNCH DATE	LAUNCH SITE
1976-039A	8820	LAGEOS 1	US	1976-05-04	AFWTR
1976-004A	8585	CTS	CA	1976-01-17	AFETR
1983-084A	14258	COSMOS 1490 (GLONASS)	CIS	1983-08-10	TYMSC
1988-112A	19713	MOLNIYA 3-34	CIS	1988-12-22	PLMSC
1989-001C	19751	COSMOS 1989 (ETALON 1)	CIS	1989-01-10	TYMSC
1989-014A	19807	MOLNIYA 1-75	CIS	1989-02-15	TYMSC
1989-039C	20026	COSMOS 2024 (ETALON 2)	CIS	1989-05-31	TYMSC
1990-084A	20813	MOLNIYA 3-39	CIS	1990-09-20	PLMSC
1991-067A	21726	ANIK E1	CA	1991-09-26	FRGUI
1992-070B	22195	LAGEOS 2	IT	1992-10-22	AFETR
1992-085A	22255	MOLNIYA 3-43	CIS	1992-12-02	PLMSC
1993-079A	22949	MOLNIYA 1-87	CIS	1993-12-22	PLMSC
1995-016A	23536	BRAZILSAT B2	BRAZ	1995-03-28	FRGUI
1996-019A	23833	NAVSTAR 37 (USA 117)	US	1996-03-28	AFETR
1999-036D	25850	4th Stage	CIS		
1999-005A	25626	TELSTAR 6	US	1999-02-15	TYMSC
2001-031A	26871	GOES 12	US	2001-07-23	AFETR
2002-027A	27438	INTELSAT 905	ITSO	2002-06-05	FRGUI
2003-005A	27663	NAVSTAR 51 (USA 166)	US	2003-01-29	AFETR
2000-040D	27765	PAM-D Debris	US	2000-07-16	

6.2 Satellite streak images

Figure 41 presents an example of an image with an easy to detect satellite streak. This streak was obtained from TELSTAR 6 (NORAD #25626) on June 27th at 3h24 local time. TELSTAR 6 is an American geostationary communications spacecraft that was launched by a Proton-class booster from Baikonur on February 15, 1999. The 3.8-ton spacecraft carries 24 C-band and 28 Ku-band transponders to provide voice and video communications to the US and Canada, after parking over 93 deg W longitude.

Satellite/image specifications : Height = 35 791 km

Phase angle = 22 degrees

Exposition time = 30 seconds

Figure 41. Satellite streak easy to detect with CASTOR-V

Figure 42 presents an example of an image with a faint satellite streak, hard to detect. This streak was obtained from the satellite MOLNIYA 3-43 (NORAD #22255) on June 26th 2003 at 22h30 local time. A Molniya carrier rocket launched the MOLNIYA 3-43, a CIS communications spacecraft from Plesetsk Cosmodrome on December 1992. Initial orbital parameters are: period 701.2 min, apogee 39,103 km, perigee 466 km, and inclination 62.5 deg.

Satellite/image specifications : Height = 38 677 km

Phase angle = 98.5 degrees

Exposition time = 30 seconds

Figure 42. Very faint satellite streak imaged by CASTOR-V

Figure 43 presents an example of an image with a tumbling satellite, which produces a streak with an irregular intensity. This streak was obtained from the satellite MOLNIYA 3-42 (NORAD #22178) on June 12th 2003 at 23h06.

Satellite/image specifications : Height = 32 352 km

Phase angle = 101.8 degrees

Exposition time = 50 seconds

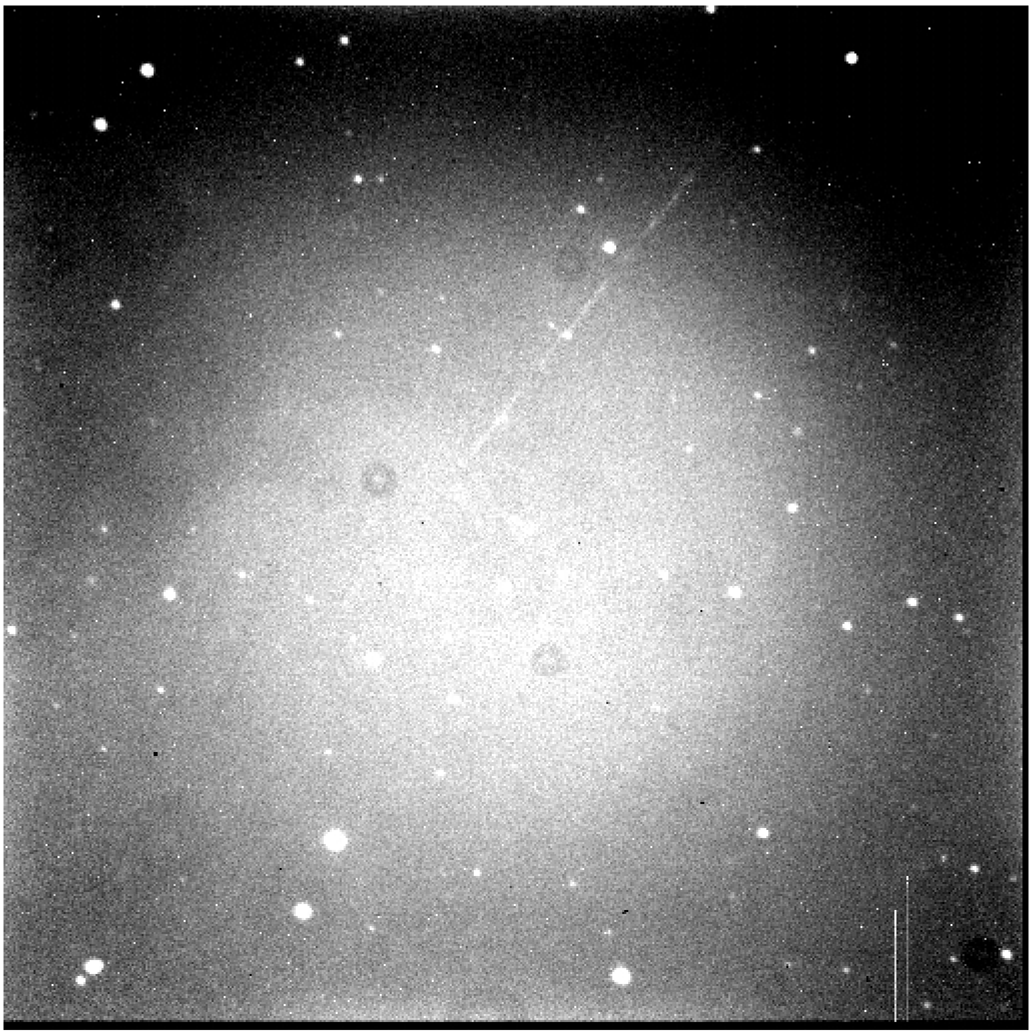


Figure 43. Irregular streak produced by a tumbling satellite

Figure 44 presents an example of an image with a strobed acquisition, which consists in a sequence of the CCD shutter opening and closing during the exposition time. This streak was obtained from the satellite GEOS 12 (NORAD #26871) on July 7th 2003 at 1h55 local time. The strobing presented in Figure 44 is based on a 10-3-2 acquisition mode, in which the shutter first opens for 10 sec and then for 3 sec for a certain number of times, each one spaced by a 2 sec delay. For a 50 seconds exposure time, the shutter hence opens 8 times for 3 sec. This type of sequence permits to obtain the orientation of the satellite propagation. GOES 12 is an American geosynchronous weather satellite that was launched by an Atlas 2A rocket from Cape Canaveral on July 23, 2001. The 980-kg, 973-W spacecraft carries an IR imager, a sounder, and an X-ray imager.

Satellite/image specifications : Height = 35 785 km

Phase angle = 19.6 degrees

Exposition time = 50 seconds with strobing 10-3-2

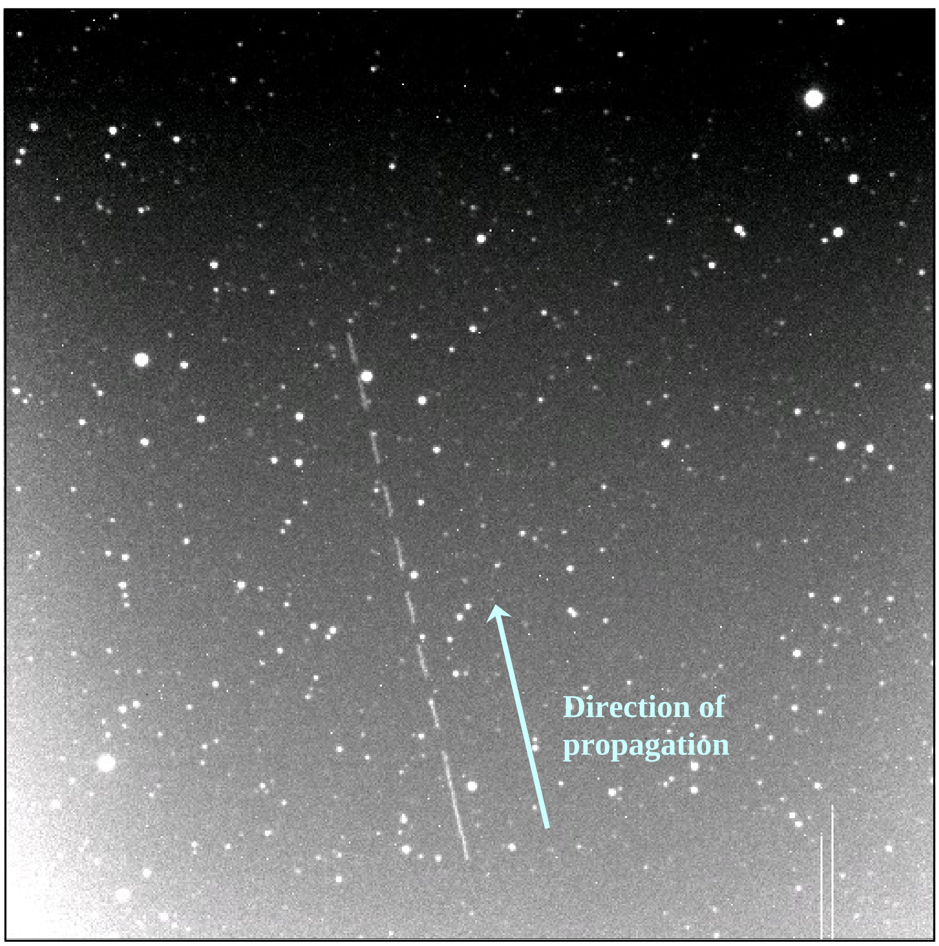


Figure 44. Strobed acquisition 10-3-2 for an exposition of 50 seconds

Figure 45 presents an example of an image with a multi streak image. This streak was obtained from the satellite ANIK E1 (NORAD #21726) on June 27th 2003 at 0h50 local time. These multi-streak images are typical of **geostationary** satellites. Indeed, all these satellites lie on a orbit over the equator, close to the same "magic" altitude of 35,786 km at which a satellite's orbital speed exactly matches the rate at which the earth rotates: once every sideral day, 23 hours 56 minutes (see the geostationary arc over the equator in Figure 1). This orbit is mainly used by the telecommunication and meteorological satellites. Following these particular conditions, all the satellites are practically side by side and remain stationary relative to the Earth's surface. For a certain exposition time, these satellites still produce a streak on the CCD considering the telescope mount is used in the sideral tracking mode. This particular mode continually moves the telescope in right ascension to compensate for the earth rotation, which permits keeping the observed objects in the FOV and having point-like stars in the image.

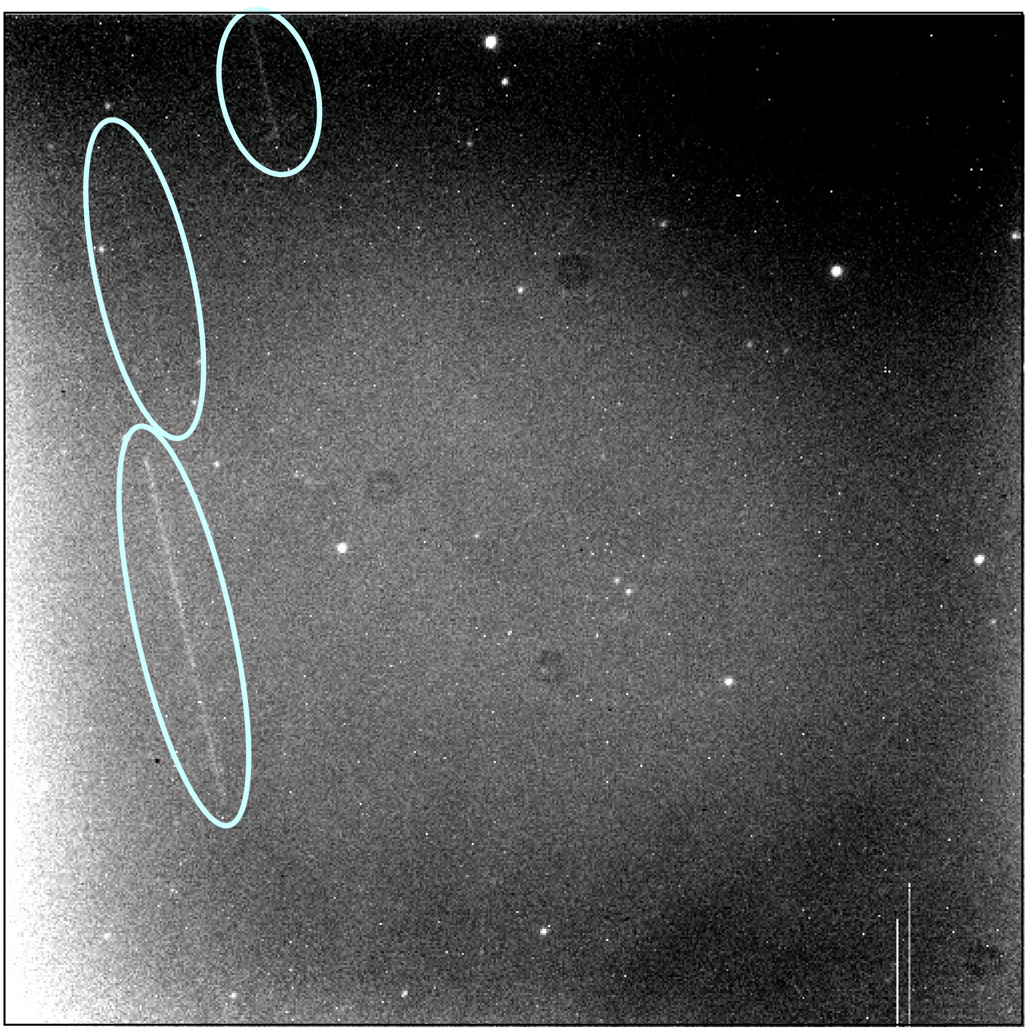


Figure 45.Multi-streaks image from the geostationary belt

Satellite/image specifications : Height = 35 794 km

Phase angle = 52.2 degrees

Exposition time = 30 seconds

ANIK-E1 is a Canadian geostationary communications satellite, launched on September 26, 1991 from the Kourou Space Center, French Guiana, using the Ariane booster rocket. The spacecraft was placed in a transfer orbit of 35,952 km apogee, and 268 km perigee, with an inclination of 4 deg., and immediately placed in a geostationary orbit at 111.1 deg W over the eastern part of the Pacific Ocean.

6.3 Satellite tracking mode

In order to detect a satellite, one can either search a satellite streak in an image tcollected in the sideral tracking mode or a point-like satellite in an image obtained in the satellite tracking mode. Indeed, the Paramount GT-1100 ME from *Software Bisque Inc.* has the capacity to track satellite with an efficiency depending on the speed of the tracked satellite. Once the orbital parameters, commonly called **TLE** standing for **Two Lines Element set**, of a given satellite are imported in *TheSky* Astronomy Software, this latter can calculate and guide the telescope mount in the same trajectory as the satellite of interest. This allows keeping the object constantly at the same position relatively to the CCD FOV.

For a given exposition time, the resulting image includes streak-like stars and a point-like satellite when the tracking is efficient. Figure 46 and 47 presents examples of a very and a less efficient tracking respectively, while the mount is set in the satellite tracking mode.

This particular capacity of CASTOR-V has led to the investigation of spectral acquisition of satellites. In addition to satellite detection, the possibility to obtain a certain amount of information from their spectral signature is attractive. The SBIG Self-Guiding Spectrograph and the ST-8XE camera were purchased for this latter purpose. The spectrometer and ST-8XE are coupled and mounted as a unit on the telescope. The system is known to be handy for collecting spectral data since both the object of interest and the spectrometer entrance slit are simultaneously imaged on the tracking CCD, allowing the object to be viewed and accurately placed onto the slit. Once the object is maneuvered onto the slit, self-guiding will then hold the object on the slit. This work will be presented in a subsequent report.

The photometric and spectral research field were not part of the CD initial definition but these capabilities are of great interest for the clients.

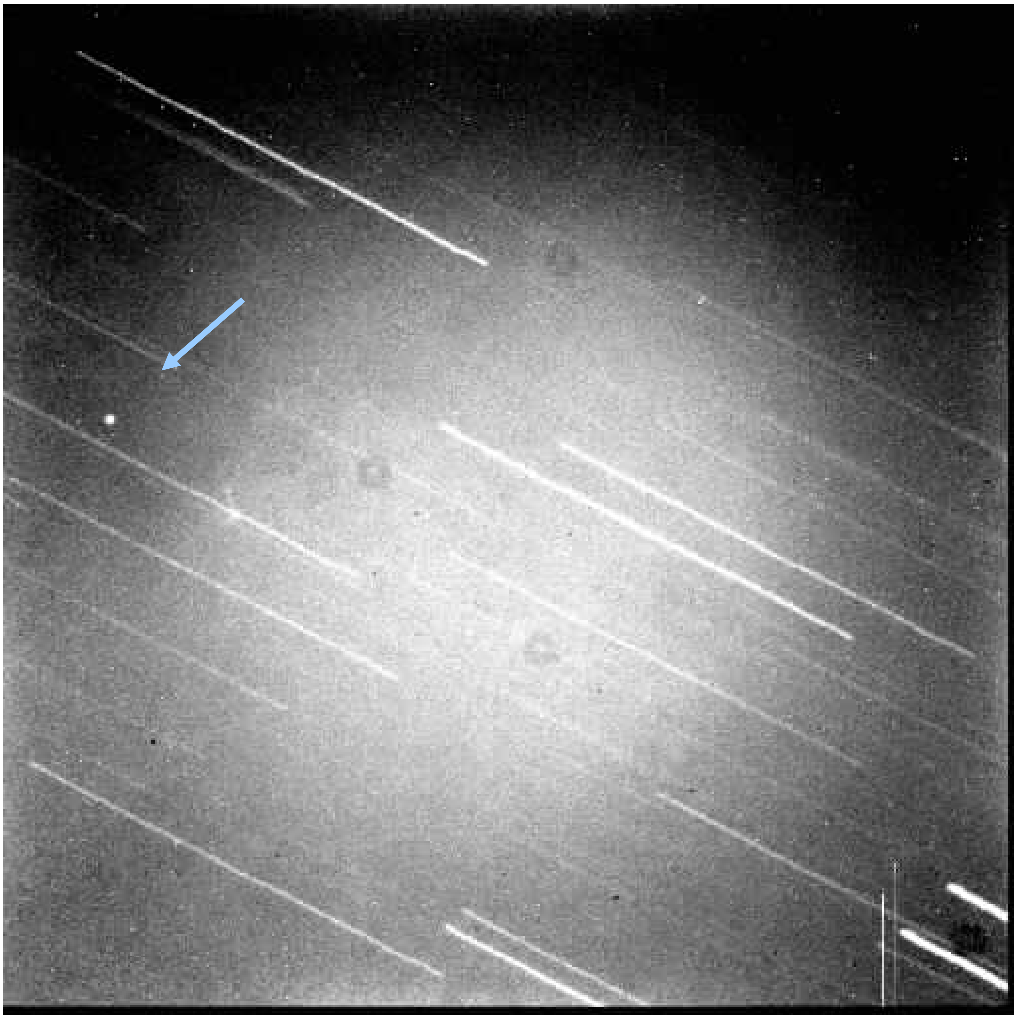


Figure 46. MOLNIYA 1-91 (#25485) imaged for 60 seconds with the mount in the satellite tracking mode (efficient satellite tracking)

Figure 47. MOLNIYA 3-46 (#23211) imaged for 20 seconds with the mount in the satellite tracking mode (not efficient satellite tracking)

7. Conclusion

CASTOR-V was characterized and tested to optimize operation and identify problematic issues associated with this particular sensor. The knowledge acquired will also be applicable to the other two sensors included in the Concept Demonstrator owing to their near-identical design. The system characterization included the following measurements: 1) minimum elevation around CASTOR-V, 2) dome and mount slew time, 3) CCD dark current, including the time delay effect, and 4) downloading time.

An efficient operating procedure was developed to eliminate system malfunctions on start-up and shut-down. The minimum elevation assessment takes into account the local horizon, hence eliminating time losses incurred while searching for satellites obscured by the trees near CASTOR-V. The slew time results showed that the mount right ascension, mount declination and dome azimuth have a displacement speed of about 3.2, 4.7 and 6.0 degrees/sec, respectively. Based on this information, the maximum delay to perform a slew command for any displacement on the same side of the meridian was determined. This maximum delay is less than one minute. This value is reasonable, since the current requirement is one observation every 5 minutes. The dark current of the Apogee AP8p CCD is fairly high, since it is a back-illuminated CCD, but it does provide higher sensitivity via its high quantum efficiency. Cooling the CCD to around –30ºC can minimize the dark current, which otherwise causes a significant performance degradation along the top-to-bottom axis of the CCD. The fairly long download time for the CCD images has an impact on this noise performance, and must hence be reduced as much as possible by use of the maximum binning mode that will not cause any loss of resolution. Experimentation confirmed that the dark current is not affected by delays between exposures.

Troubleshooting yielded several significant findings. The CASTOR-V dome behaviour is reliable with the appropriate PCB chip and the wind screen motor off. The telescope mount is fairly sensitive to cold, which can cause various malfunctions, and its pointing accuracy must be verified periodically, and in any event must be updated at least once a year. The CCD camera should be turned on for about one hour prior to cooling to expel humidity from the CCD chamber. If a fringe artifact appears in the CCD images, conductors and connections must be checked. The issue of dew on the corrector plate of the Schmidt-Cassegrain telescope was solved by the addition of a dew heater and a turbo film in front of the corrector plate.

CASTOR-V had a 100% success rate on a 20-satellite observation tasking, allowing for location constraints and surrounding elevation limitations. By the end of summer 2003, CASTOR-V was deemed ready for remote operation through the SSOC, with allowance made for the different particularities and issues highlighted by extensive testing at DRDC – Valcartier.

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Annex A: CCD Power-up sequence

Figure A-1 presents the connection diagram for the Apogee CCD to the controlling computer. When connecting the camera to the computer, first connect the 37-pin connector of the cable to the camera then, connect the camera's pigtail (round 5-pin connector) to the DC side of the power supply. Plug in the AC side of the power supply to a wall outlet (camera fans should come on). Lastly, plug the 25-pin connector into the parallel port of your computer. It is not necessary for the computer to be powered off when plugging in the camera.

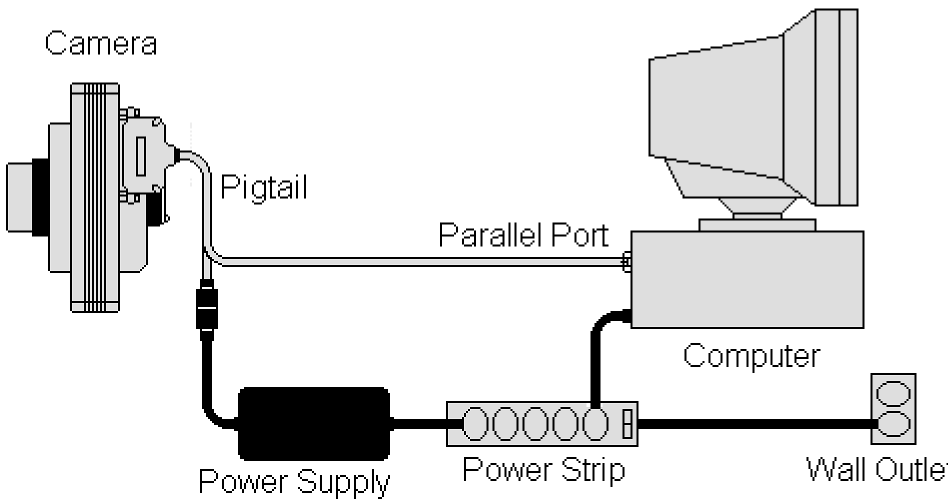

Figure A-1. CCD camera plug-in scheme

Some computers must have the camera powered on before connecting it to the parallel port or else the camera-control software will not interface with the CCD. The camera must be powered on before the computer in order for its OS (windows) to detect and configure the device at start-up. Unplug the camera from the parallel port and unplug the power supply from the AC power source. Plug the power supply back in (camera fans come on), then plug the camera cable back into the computer's parallel port. Reinitialize the camera in the software. NOTE: This sequence is only necessary when plugging in the camera. If the camera stays connected to the parallel port, you do not have to unplug and plug the cable in again when powering up the computer.

Annex B: CASTOR-V start-up procedure

Legend :

⇒ Software: open this software
- ♦ Main menu bar → menu item → sub-menu item
  - ➢ Click window button

❖ CCD CAMERA

⇒Open *CCDSoft*
- ♦ Camera → setup → connect
- ♦ Camera → setup → temperature
  - ➢ Temperature set point: -30 °C
  - ➢ check: temperature regulation
  - ➢ check: fan on
- ♦ Camera → server settings → check what is needed

❖ DOME

⇒Open *AutomaDome*
- ♦ Dome → link → establish
- ♦ Home find
- ♦ Open
- ♦ Minimize

❖ THE SKY

⇒Open *TheSky*
- ♦ Telescope → link → establish
- ♦ Telescope → option → find home
- ♦ Ctr + shift + D (simultaneously): the Dome Controller window appears
- ♦ Dome → link → establish (in the Dome Controller window)
- ♦ Minimize the Dome Controller window
- ♦ Telescope → server settings → check::
  - ➢ allow remote connections
  - ➢ allow map
  - ➢ remote clients use *Orchestrate*'s "ImageThenSlewTo" command
- ♦ Minimize

❖ ORCHESTRATE

⇒Open *Orchestrate*
- ♦ Open or create a new data file
- ♦ Connections → check:
  - ➢ *TheSky*
  - ➢ Telescope
  - ➢ Camera

Annex C: CASTOR-V shut-down procedure

- CCD CAMERA
  - ⇒ In *CCDSoft*
    - Camera → setup → temperature
      - Temperature set point: ambient temperature
      - check: temperature regulation
      - check: fan on
    - Wait 10 minutes after the CCD temperature has reached the ambient
    - Camera → setup → disconnect
    - Close *CCDSoft*

- DOME
  - ⇒ In *TheSky*
    - Position the dome slit to the North-West position
    - Maximize the Dome Controller window
    - Dome → Park
    - OK (park complete)
    - Dome → Find home
    - OK (Find complete)
    - Dome → Close slit
    - Dome → Link → Terminate
    - Close the Dome Controller window
  - ⇒ In *AutomaDome*
    - Dome → link → terminate
    - Close *AutomaDome*

- MOUNT
  - ⇒ In *TheSky*
    - Telescope → options → Park
    - To set the park position:
      - Telescope → options → find home
      - Ctr T (telescope field of view)
      - Move to → Declination 15° North
      - Slew
      - Telescope → set park → OK
      - park

- Software
    - Close *TheSky*
    - Close *Orchestrate*

Annex D: Dome controller operation (repaired PCB)

Table D-1. *Dome controller mal functioning behaviour*

INITIAL STATE	COMMAND	BEHAVIOUR
Left LS of WS motor: on Lower LS of shutter motor: on	Open Shutter button	• Shutter motor = +12V (pull-up) • WS motor cl • Once Upper LS of Shutter motor on, everything stops.
Left LS of WS motor: on Lower LS of Shutter motor: on	Open WS button	• Shutter motor = -12V (**pushes-down !)** • WS motor ccl • Right LS of WS on • Shutter motor = +12V (pull-up) • WS motor cl • Once Upper LS on, everything stops.
Right LS of WS motor: on Lower LS of Shutter motor: on	Open Shutter button	• Shutter motor = -12V (**pushes-down !)** • WS motor cl • Left LS of WS on • Shutter motor = +12V (pull-up) • WS motor cl • Once Upper LS on, everything stops.
Right LS of WS motor: on Lower LS of Shutter motor: on	Open WS button	• Shutter motor = +12V (pull-up) • WS motor cl • Once Upper LS of Shutter motor on, everything stops

WS motor	= Wind Screen motor
Shutter motor	= Shutter motor (big motor used to open or close the shutter)
LS	= Limit Switch
LS on	= Limit switch pushed down
cl	= Clockwise
ccl	= Counter-clockwise

List of symbols/abbreviations/acronyms/initialisms

ADU	Analog to Digital Unit
AFETR	Air Force Eastern Test Range, Florida, USA
AFWTR	Air Force Western Test Range, California, USA
CA	Canada
CASTOR	Canadian Automated Small Telescope for Orbital Research
CASTOR-V, K, S	Denotes a particular sensor – Valcartier, Kingston, Suffield
CCD	Charged Couple Device
CCW	Counter-clockwise
CD	Concept Demonstrator
CF	Canadian Forces
CIS	Commonwealth of Independent States (former USSR)
COTS	Commercial off-the-shelf
CW	Clockwise
Dec	Declination
DND	Department of National Defence
DRO	Digital read-out
FOV	Field of view
FRGUI	French Guiana
GEO	Geosynchronous satellite
GPS	Global Positioning System
GUI	Graphical user interface
IT	Italy
ITSO	International Telecommunications Satellite Organization (INTELSAT)

NIR	Near Infra-red
NORAD	North American Aerospace Defence Command
NORAD	North American Aerospace Defense
PCB	Printed circuit board
PLMSC	Plesetsk Missile and Space Complex, Russia
QE	Quantum Efficiency
RA	Right Ascension
RMC	Royal Military Colledge
ROI	Region Of Interest
SBO	Space-based optical
SCC	Space Control Center
SCT	Schmidt-Cassegrain Telescope
SOI	Space Object Identification
SoSP	Surveillance of Space Project
SSN	Space Surveillance Network
SSOC	Sensor System Operations Center
TCF	Temperature Compensating Focuser
TLE	Two Lines Element
TYMSC	Tyuratam Missile and Space Center, Kazakhstan
US	United States
USSPACECOM	United States Space Command
UTC	Universal Time Coordinate
UV	Ultra violet
WS	Wind screen

Glossary

Astrometry	The measurement of angular distances between objects in the sky. By studying the parallax of stars, their absolute distances can be measured, and by measuring small angular changes over a long period of time, proper motion can be determined. Performing the astrometry on an image resumes to identify the coordinates of the different stars.
Visual magnitude	A scale used by astronomers to measure the brightness of a star. The scale upon which magnitude is measured has its origin in the Hellenistic practice of dividing those stars visible to the naked eye into six *magnitudes*. The brightest stars were said to be of first magnitude (m = 1), while the faintest were of sixth magnitude (m = 6), the limit of human visual perception (without the aid of a telescope). Each grade of magnitude was considered to be twice the brightness of the following grade. The modern system is no longer limited to 6 magnitudes or only to visible light. Really bright objects have *negative* magnitudes.
German equatorial mount	A German Equatorial mount uses a counterweight on a long shaft opposite the telescope to counterbalance the weight of the telescope. The telescope is able to track the sky about a polar axis to compensate for the Earth's rotation.
Meridian	A great circle passing over the zenith and through the celestial poles.
Two line element (TLE)	A group of numbers provided in two lines and separated by spaces that specify the orbital parameters (elements) for a satellite, spent booster rocket, or other man-made satellites.
Geostationary orbit	An orbit in which a satellite appears to remain in the same spot in the sky all the time. When a satellite is in geostationary orbit, it travels at exactly the same speed as the Earth is rotating below it. Geostationary satellites are always located directly above the equator. It is a special case of the geosynchronous orbit with a zero inclination and circular.
Geosynchronous orbit	Orbit in which the period of the spacecraft is the time taken for the Earth to complete 360° rotation. T_{orb} = 23 h 56 min which is 1 sidereal day.

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Defence R&D Canada (DRDC) is developing a Surveillance of Space Concept Demonstrator (CD) consisting in three geographically dispersed, ground-based, small optical sensors for satellite observation. These three sensors will be operated remotely via the Sensor System Operations Center (SSOC). Before the remote operation was undertake, CASTOR-V, the sensor located at Valcartier, has been characterise and tested in order to optimise its operation and to do the trouble shooting of this particular sensor. The present report first describes the sensor hardware and software, it then presents some results of the sensor characterisation such as the dome and mount slew time, the CCD dark current and other important features. Two significant findings following the testing results are first that any displacement on one side of the meridian necessitates less than one minute and second, the CCD must be cooled down to about –30 ºC to minimise the important top to bottom dark count gradient. Finally, for the benefit of future users and system designers, particularities and issues that occurred with CASTOR-V, related to hardware, software or operation, are described along with their respective solutions or recommendations. CASTOR-V is now ready for remote operation through the SSOC.

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Surveillance of Space, CASTOR, Concept Demonstrator, CCD carachterisation, slew time, minimum elevation, satellite streak.

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