Solaris: a global network of autonomous observatories in the southern hemisphere

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ABSTRACT

We present Project Solaris, a network of four autonomous observatories in the Southern Hemisphere. The Project's primary goal is to detect and characterize circumbinary planets using the eclipse timing approach. This method requires high-cadence and long time-span photometric coverage of the binaries' eclipses, hence the observatories are located at sites having similar separation in longitude and nearly identical latitudes: South African Astronomical Observatory, Republic of South Africa (Solaris-1 and -2), Siding Spring Observatory, Australia (Solaris-3) and Complejo Astronómico El Leoncito, Argentina (Solaris-4). The headquarters coordinating and monitoring the network is based in Toruń, Poland. All four sites are operational as of December 2013. The instrument and hardware configurations are nearly identical. Each site is equipped with a 0.5-m Ritchey-Chrétien or Schmidt-Cassegrain optical tube assembly mounted on a direct-drive modified German equatorial mount along with a set of instruments. Computer, power and networking components are installed in rack cabinets. Everything is housed in sandwiched fiberglass clamshell 3.5-m diameter robotized domes. The Argentinian site is additionally equipped with a 20-ft office container. We discuss the design requirements of robotic observatories aimed to operate autonomously as a global network with concentration on efficiency, robustness and modularity. We also present a newly introduced spectroscopic mode of operation commissioned on the Solaris-1 telescope. Using a compact échelle spectrograph (20 000 resolution) mounted directly on the imaging train of the telescope, we are able to remotely acquire spectra. A fully robotic spectroscopic mode is planned for 2015.

Keywords: robotic telescopes, telescope network, autonomous observatory, photometry, eclipsing binaries, exoplanets, systems enginnering.

1. INTRODUCTION

Observing the stars can be a truly inspiring and romantic experience. In the era of CCD, spectrographs and sophisticated data acquisition equipment, however, observing has become a task that is associated with hard work, long sleepless nights in remote locations, strong dependance on weather conditions, repetitive tasks, and a financial effort. It is natural for human to avoid tiresome and recurring work. The first Automated Photoelectric Telescopes have been constructed in the mid 1960's and since fewer and fewer astronomers actually observe at the telescope.[1] In this paper we describe Project Solaris that operates a global network of autonomous telescopes.

1.1 Nomenclature

In the astronomical community telescopes that are able to observe automatically are referred to as robotic telescopes. Ref. 2 gives definitions of remote, unmanned, robotic and fully autonomous observatories as seen from the observer's perspective. The author defines modes of operation based on how advanced are the algorithms that schedule and reschedule the observing queue depending on the conditions. From the mechanical point of view a telescope mount is a kinematic system with two degrees of freedom consisting of two rotary joints. In general, it can be considered as a robot that works in three-dimensional space. The telescope mount, of course,

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is just the platform that supports the actual telescope and instruments attached to it. These, depending on the complexity of the instrumentation, can introduce many more degrees of freedom with corresponding actuators to the configuration. Assuming that all subsystems are computer controlled and do not require human actuation to operate, the definition of a **robotic system** seems to be appropriate.

The telescope and instrumentation are usually housed in a dome or in some kind of specialized building that serves as a shelter. If the observer can leave the dome and operate the telescope from a different place, we would call this setup a **remotely-operated** observatory. This system requires that the telescope and dome are fully robotic and that the observer can remotely access and control all the necessary features of the system using some kind of user interface that is accessible via the internet or local network. Depending on the advancement of the system, signals from weather stations, surveillance cameras, sensors, etc. can be either analyzed by the observer in raw form or processed by the computer and selectively presented to the observer whenever human intervention is required.

An observatory that can operate without human intervention during long periods of time (days, weeks, months) interrupted only by hardware failures and major software problems should be called an **autonomous observatory**. In such observatories, all subsystems are fully integrated and are programmed in such a way to cope with all predictable problems (avoid damage and return to normal operation after the problem) and robust enough to secure the equipment by all means in case of unpredictable problems. This approach requires complex systems engineering design, some level of redundancy and multiple levels of security procedures, as well as intelligent diagnostics capabilities.

Going one step further brings us to networks of autonomous observatories, where two or more standalone observatories operate as one system that is managed centrally and allows one to carry out projects that require more than one telescope. The Solaris Global Telescope Network is such a project.

1.2 Existing Telescope Networks

The concept of robotic telescopes and telescope networks is not new. Currently more and more telescopes are operated remotely and many are being integrated into networks operating in various modes depending on the available equipment and software. Below we present a very short overview of some networks currently operating or under construction. **HAT South**[3] is a network of automated homogenous telescopes that are capable of continuous monitoring of the Suthern Hemisphere site. It has been established to detect transiting exoplanets. It uses six telescope units located at three sites. Each unit consists of four 0.18-m f/2.8 optical telescopes installed on a common mount that have a combined field of view of 8.5°x 8.5°. Las Cumbres Observatory Global Telescope Network (**LCOGT**[4]) is an organization that is building and running a world-wide network of autonomous telescopes, including the the 2-m Faulkes telescopes, 17 1-m telescopes and nearly two dozen 0.4-m telescopes. The telescopes will be equipped with imaging and spectroscopy instruments. **Master-II**[5] is a network of telescopes dedicated to observe and study optical counterparts of gamma-ray bursts (GRBs). It consists of four telescopes installed in observatories in the Russian Federation covering six time zones. The network is operational since 2010. The Telescope ALert Operations Network (**TALON**[6]) is a network server that allows communication of alert triggers from various sources and directs them to appropriate telescopes on the network. The network, or RAPid Telescope for Optical Response (RAPTOR), consists of three telescopes located in three observatories separated by approximately 38 km in New Mexico. **SuperWASP**[7] (Wide Angle Search for Planets) is a network of two observatories (La Palma, Canary Islands and the South African Astronomical Observatory) each consisting of an equatorial mount and eight wide-field cameras having a total field of view 482 square degrees. The MOnitoring NEtwork of Telescopes (**MONET**[8]) is a network of two 1.2-m telescopes located at the McDonald Obserbatory in Texas and the Saouth African Astronomical Observatory. Pi of the Sky[9, 10] is a project running a network of two observatories located at San Pedro de Atacama Observatory and El Arenosillo Test Centre in Spain. Every node consists of multiple telephoto lens and custom CCD cameras.

Apart from telescope networks, a large amount of single autonomous telescopes operate all around the globe - both professional and amateur. In this paper, however, we focus on the challenges associated with designing and deploying a network of autonomous observatories around the globe.

1.3 Scientific Rationale

The primary goal of Project Solaris is to detect and characterize circumbinary planets using the eclipse timing method. This approach requires high cadence and high precision photometry of selected binary stars. To date, 12 planetary system (15 planets, 2 multi planetary systems) have been detected using the eclipse timing method (exoplanet.eu). The ASAS* Catalogue of Variable Stars contains 50122 variable stars, including 11062 eclipsing binaries. 5374 of these are contact binaries, 2939 are semi-detached binaries and 2749 are detached binaries. 60 stars have been selected from the last group based on eclipse width, eclipse depth, maximum magnitude, orbital period the availability of nearby reference stars and the expected timing precision. As shown in[11] using numerical simulations, it is possible to detect exoplanets orbiting eclipsing binary systems using a network of 0.5-m telescopes achieving 0.1-1.0 s precision in timing. A global network of identical 0.5-m telescopes has been proposed to accomplish this task. Apart from photometry aimed at eclipse timing, the network can be used for other stellar astrophysics projects, including spectroscopy.

2. NETWORK DESCRIPTION

2.1 Design Prerequisites

The goal of the Solaris Project determines the conditions that must be satisfied by the proposed network of autonomous telescopes. These assumptions are listed below.

1. Global coverage. The network must be designed in such a way that a selected target can be observed continuously or nearly continuously assuming favorable weather conditions over a period of more than 24 hours. This implies even longitudinal spacing and close latitudes of the sites.
2. Fully autonomous system. Due to the global coverage of the network and limited human resources, it is crucial that the observatories operate autonomously. This also guarantees compatibility across the network.
3. Emphasis on photometry and timing precision.
4. Standardization and modularity. From the systems engineering point of view, all components of the network should be identical across all sites and allow easy replacement and/or upgrade.

2.2 Remote sites

Three sites have been chosen for the Solaris network: Republic of South Africa, Australia and Argentina. Table 1 summarizes the geographical locations of the sites, Fig. 1 gives an graphical overview. All of them lie within less than 1° difference in latitude. In terms of construction work, commissioning and other installation-related tasks, each site has been challenging in some area. Details are provided in the following subsections.

Table 1: Solaris Network site summary.

Node	Solaris-1 and Solaris-2	Solaris-3	Solaris-4
Observatory	South African Astronomical Observatory	Siding Spring Observatory	Complejo Astronómico El Leoncito
Country	Republic of South Africa	Australia	Argentina
Latitude	32°22'50" S	31°16'24" S	31°47'57" S
Longitude	20°48'39" E	149°03'52" E	69°18'12" W
Elevation (m AMSL)	1842	1165	2552

*All Sky Automated Survey

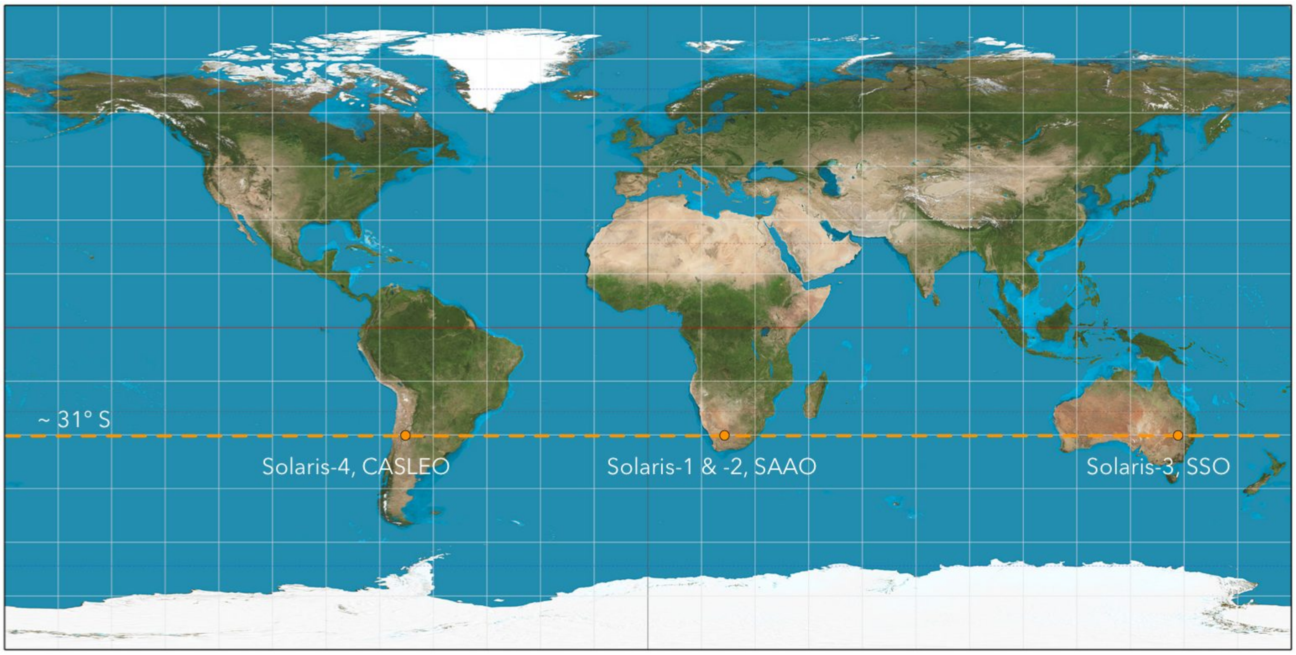

Figure 1: World map with Solaris sites. Longitudinal separations between the sites, counting from Solaris-1 towards the east are: 128°15', 141°38' and 90°7'. Original source Wikimedia Commons.

2.2.1 Solaris-1 and Solaris-2, South African Astronomical Observatory, Republic of South Africa

The South African Astronomical Observatory is located in the Northern Cape, near the town Sutherland in the Hantam Karoo, a semidesert area. It is the home of the Southern African Large Telescope, six smaller telescopes ranging from 0.5 to 1.9-m and six international research facilities, including BiSON, KELT-South, LCOGT, Monet, SuperWasp and, since 2011, Solaris. All telescopes are located on a plateau. The vicinity of SALT, the largest telescope on the Southern Hemisphere, makes SAAO an attractive location for a small autonomous observatory due to the availability of technical support staff, a well established workshop and a reasonable and helpful administration office. Rapidly changing weather conditions and severe winds are common.

2.2.2 Solaris-3, Siding Spring Observatory, Australia

The Siding Spring Observatory is located near the town Coonabarabran in New South Wales, on the border of the Warrumbungle National Park. The observatory is situated on the remnants of a large, heavily eroded shield volcano. The base rock is hard dolerite that has poor electrical conductivity and is difficult to drill in making this site particularly challenging in terms of construction. Due to the rich fauna, mainly gum tree, bushfires are a realistic threat to the observatory. A severe bushfire passed through the observatory in 2012 destroying a few buildings. Astronomical equipment and domes have not been damaged. SSO is home to the 3.9-m AAT and several other telescopes operated by the Australian National University and international institutions: Faulkes South, HAT-South, ROTSE, UKST, APT and, since 2012, Solaris.

2.2.3 Solaris-4, Complejo Astronómico El Leoncito, Argentina

Complejo Astronómico El Leoncito is located in the San Juan Province near the town Barreal. It is situated in the Leoncito National Park, a popular tourist attraction in that area. Nevertheless, CASLEO is the most remote of the Solaris sites. The main nearby highway, Routa National 149, is partly unpaved (but in good condition). All roads in the National Park and in the observatory are narrow unpaved roads, vulnerable to flooding during severe rainfall. Contrary to SSO and SAAO, observatory facilities are not concentrated in one place. The observatory's main buildings, including the Jorge Sahade 2.15-m telescope, Solar Submilimiter-wave Telescope (SST), workshop and dormitories are located in a small valley. Other facilities, such as HSH, ASH and THG are located on a nearby mountaintop called Burek, 7 km away. The Solaris-4 observatory occupies a similar mountaintop, 700 m from Burek and was the first telescope to be installed in that place. Earthquakes are not uncommon in the area.

The Project's headquarters is located in Toruń, Poland in the Department of Astrophysics of the Nicolaus Copernicus Astronomical Centre of the Polish Academy of Sciences. All remote databases are synchronized with the central database in Toruń.

3. SYSTEM COMPONENTS

Every Solaris observatory consists of numerous types of components that have been chosen in such a way to enable autonomous operation. Below we describe the most important elements of the system. The low-level architecture of the system is presented on the diagram in Fig. 2.

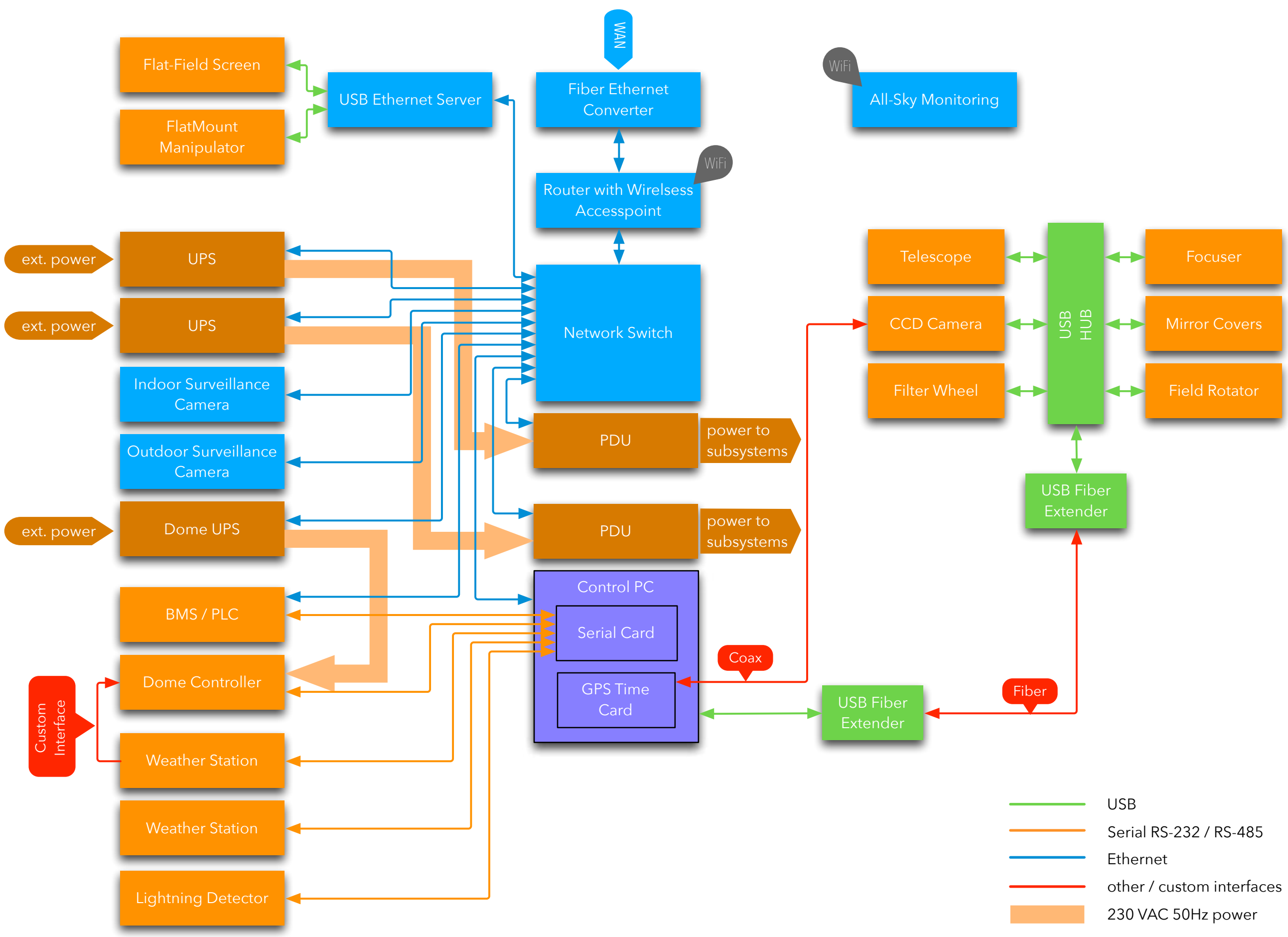

Figure 2: Low-level architecture of a Solaris node. The diagram presents an overview of all components used in the observatory along with the most important communication channels that interconnect the elements of the system. A single PC is used to control and integrate all subsystems (Tab. 4).

3.1 Dome

Clamshell domes manufactured by Baader Planetarium GmbH are used in Project Solaris. The dome consists of a stationary dome base and four rotating segments. The segments are motorized and allow the top half of the dome sphere to open. The dome is a self sustained structure made of fibre-reinforced plastic supported by a heavy steel ring. It is a double skin, rigid sandwich design with intermediate thermal insulation of hardened polyurethane foam. The outer layer of the dome is pure white with a titanium-oxide pigmented gelcoat that protects the dome from infrared radiation. The inner surface is surrounded with stiffening flanges and durable sealing. Four heavy duty motors drive the segments via toothed sections comprising hardened steel rollers. The motors are controlled by frequency inverters and a dedicated microcontroller. The microcontroller accepts commands from a PC via a serial link or from a infrared remote control for local manual operation. When open,the AllSky Dome enables a full 180°view of the sky. The dome features an entrance door that is accessible at any time and a computer cabinet bay that gives extra space for hardware. Thanks to the self sustained structure the footing construction is simplified to a nearly cylindrical base. This reduces construction and material costs. The dome can be assembled and placed on the concrete base in two days without a crane. According to the manufacturer, a properly assembled dome can withstand winds exceeding 200 km/h.

The concrete footing consists of two parts: the dome footing and the telescope footing. They are mechanically separated from each other to limit wind-induced vibration propagation from the dome to the telescope. The physical gap is filled with foam. Both parts of the footing are made from reinforced concrete. In case of Solaris-4, which is situated in a seismic region, the design has been modified to comply with the local construction standards that are more robust in case of earthquakes.

3.2 Astronomical equipment

Astronomical equipment is the core of every observatory. In the following sections we present the astronomical components used in the Solaris observatories.

3.2.1 Telescope

The telescope consists of three main components: the Optical Tube Assembly (OTA), the telescope mount and the pier.

The OTA houses the optics of the telescope. All four Solaris telescopes are 0.5-m diameter reflecting telescopes. Solaris-1, -2 and -4 have f/15 Ritchey–Chrètien optics, Solaris-3 is a standard Schmidt-Cassegrain f/9 design equipped with a field corrector. Focusing is accomplished with a movable secondary mirror that is driven by a stepper motor coupled to a screw drive. The optical configuration can be collimated using calibration screws. Both mirrors allow manual adjustments and have six degrees of freedom. The OTA is a truss design consisting of a steel mirror cage that is connected to the secondary mirror support via eight carbon fiber bars. The usage of carbon fiber limits the effect of thermal expansion and lowers the overall weight of the structure. The primary mirror cage features motorized mirror covers that protect the optics from dust and accidental damage when the telescope is not observing. The covers are controlled with a dedicated controller that communicates with the PC through a USB interface. A similar controller is responsible for controlling the focuser's stepper motor.

High performance of the mount and its robustness are very important factors that have direct impact on the overall efficiency of the observatory. Project Solaris utilizes Astrosysteme Austria DDM160 mounts. Each mount has two degrees of freedom which correspond to the Right Ascension (RA) and Declination (DEC) that are driven by high torque direct drive motors. The motors are controlled with a dedicated controller based on a digital signal processor. The motors have user-tunable PID[†] controllers that utilize high accuracy incremental encoders. The mount controller is connected to the PC via a serial USB interface.

The mount is attached to a steel pier, which in turn is bolted to the concrete floor of the observatory. The imaging train, described below, is attached to the telescope and allows the observer to capture data. The field of view of Solaris-1, -2 and -4 telescopes is 13 arc minutes, Solaris-3 – 21 arc minutes and the camera has a square chip with 2048x2048 pixels, each pixel in the focal plane corresponds to 0.38 (0.62 for Solaris-3) arc minutes on the sky. Depending on the weather conditions, the image of a star will take roughly a few square pixels on the CCD chip. This illustrates the level of precision that must be met by the control system in order to track the sky during exposures that may last from seconds to tens of minutes. The DDM160 mount and its control software utilize sophisticated models and filters that introduce correction factors that compensate for mechanical flexure,

[†]Proportional-integral-derivative controller.

Table 2: DDM160 manufacturer's specifications

property	value
axis diameter	160 mm hollow axle
bearings	taper roller bearings 240/160mm
weight	220kg
loading capacity	300 kg
operating voltage	24 VDC
pointing accuracy	better than 8 arc sec. RMS
tracking precision	better than 0.25 arc sec. RMS in 5 min.
encoder resolution	0.007 arc sec.
slewing speed	13 deg./s

thermal expansion, misalignment and other effects. Moreover the system's PID controllers allow the telescope to operate in windy conditions correcting errors caused by turbulence.

3.2.2 Imaging train

The imaging train consist of a CCD camera, field rotator and filter wheel along with the necessary adapters that couple the instrument with the OTA.

Project Solaris utilizes Andor iKon-L 936 **CCD cameras** in all four observatories. Their main features are high sensitivity, low readout noise, very low dark current, fast readout speeds and three stage thermoelectric-only cooling to -70° Celsius. The camera also supports shutter timing signals, i.e. it generates a TTL-level output signal that can be used to capture the moment of the opening and closure of the camera's shutter yielding very high precision in the determination of the moment of exposure. This signal is connected directly to the GPS time card in the PC. Every exposure is then recorded by the GPS card as two timestamps that are then ascribed to the FITS' header. Technical parameters of the camera have been presented in Tab. 3.

Table 3: Andor iKon-L 936 CCD Camera Specifications

parameter	value	
active pixels	2048x2048	
pixel size (μm)	13.5 x 13.5	
image area (mm)	27.6 x 27.6	
max frame rate (fps)	0.92	
active area pixel well depth (e^-, typ./min)	100,000/60,000	
readout noise (e^-, typ./max)	@50kHz	3/4
	@1MHz	7/10
	@3MHz	12.5/14
	@5MHz	25/35
digitization	16 bit	
dark current (e^-/pix/sec., typ./max)	@-100°C	0.00008/0.0003
	@-90°C	0.00013/0.0008
	@-70°C	0.001/0.007

3.2.3 Spectroscopic mode

Although the main goal of the Solaris Project is precise photometry of eclipsing binary stars, one of the telescopes (Solaris-1) has been equipped with an échelle spectrograph – BACHES. BACHES[‡] is a compact, lightweight, and

[‡]BAsic éCHElle Spectrograph, *baches* means pothole in Spanish.

inexpensive medium resolution ($R \sim 20,000$) échelle spectrograph manufactured by Baader Planetarium GmbH in accordance with a technology transfer license deal with the Max-Planck-Institut für Extraterrestrische Physik in Garching. The spectrograph has been designed by the Club of Amateurs in Optical Spectroscopy (CAOS) group that has conducted many successful instrumental projects in the past, e.g. DADOS, FIASCO, LECHES.[12]

The spectrograph body is 290x100x52 mm in size and weighs less than 1.5 kg. BACHES' head houses the actual slit, flip-mirror mechanism with control cable connector, calibration fibre input port, a 2-inch cylinder that connects to the telescope and a slit-view/guider camera interface. All interfaces have standard dimensions and are mechanically compatible with amateur telescopes' components. BACHES' head allows one to acquire spectra of the actual object of interest as well as calibration spectra. In case of the latter, light is fed to the instrument via a calibration fiber. The remotely controlled flip-mirror is used to direct the proper light beam onto the slit. We have tested the spectrograph working with the 25x100 μm slit. It is engraved in a reflective nickel plate and mounted in BACHES' head. Internally, the instrument consists of a doublet lens that collimates the light beam on to a 63 l/mm 73°échelle grating. Then a diffraction grating cross-disperses the beam that is projected on the CCD chip using an objective. The instrument is optimized for f/10 input beams and cameras with 1530x1020 9 μm pixels.[13]

A Guide and Acquisition Module (GAM) has been designed specifically for BACHES. It is a modular construction that has one optical input port and two optical output ports. Switching between the output ports is accomplished with a motorized flip-mirror. This setup allows remote or autonomous use of the photometric camera or the spectrograph without the need of manual instrument change.

The spectrograph is provided with a calibration device called Baader Spectroscopy Remote Calibration Unit (RCU). The RCU consists of a power supply, a Thorium-Argon lamp, a halogen lamp and a web-enabled remote control interface. Light from the calibration lamps is directed to a 2.5-m 50 μm fibre that is connected the spectrograph.

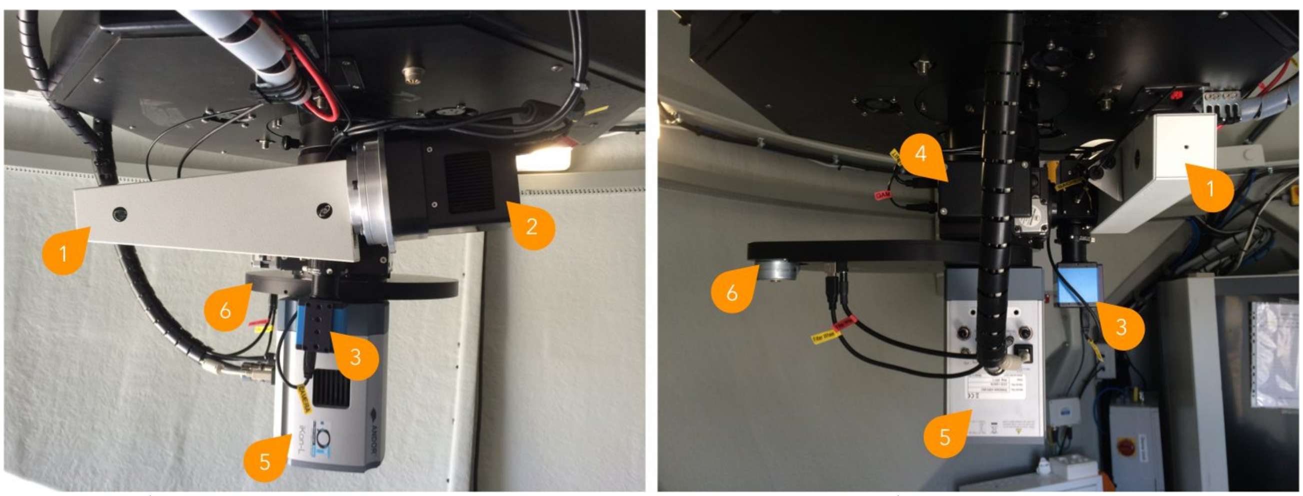

Figure 3: BACHES spectrograph installed on the Solaris-1 telescope: 1 – BACHES, 2 – FLI CCD camera, 3 – DMK slit-view camera, 4 – GAM, 5 – Andor CCD camera, 6 – FLI filter wheel.

3.3 Computer hardware

The main computer is responsible for controlling all aspects of regular operation of the observatory. We use a single desktop computer equipped with expansion boards that provide the necessary functionality: GPS card and high speed multi-port serial card. Where necessary, we use fiber optic extenders/converters (Fig. 2).

3.4 Environment monitoring

Perhaps one of the most challenging parts of establishing an autonomous observatory is proper environment monitoring that permits automatic and optimal operation of the entire system. Observatories are located in areas

Table 4: Computer Hardware

component	description
PC	Intel i7 with 12GB RAM, Nvidia GTX580 GPU with 1536 MB, 12 TB storage
computer access	KVM with integrated LCD monitor and keyboard
time source	high precision PCI Express GPS receiver with a dedicated antenna and external hardware time event capture
internet access	1Gbit fiber to ethernet converter, 1Gbit router and 24-port 100Mbit ethernet switch
power backup	two on-line UPS units: 3000VA and 1500VA
power distribution	two power distribution units, network enabled
power supplies	astronomical equipment, incl. telescope with focuser and mirror covers, CCD camera and imaging train components, flat field screen and FlatMount, IP surveillance cameras, weather monitoring devices, emergency lighting

where weather conditions can change rapidly. Proper reaction to changing weather conditions should be appropriately balanced to optimally exploit night-time without exposing the equipment to potential damage whenever it is not safe to observe. Project Solaris utilizes several devices that supply real-time weather information.

3.4.1 Weather stations

Each node has access to two weather stations. One is installed on the dome and includes temperature, humidity, pressure, precipitation and cloud sensors. The rain signal from this device is additionally hard-wired to the dome controller. The cloud sensor measures the sky temperature using a thermopile (infrared radiation) and compares it with the ambient temperature. Based on the difference, it determines whether the sky is clear or not. The second weather station (referred to as the main weather station) is installed on a dedicated mast at some distance from the dome. This device measures temperature, humidity, pressure, precipitation, wind speed and direction. Both weather stations do not have any moving parts. Precipitation is measured using an acoustic sensor, wind speed and direction are measured using ultrasonic sensors. In South Africa, Solaris-1 and Solaris-2 share the same main weather station via an RS-485 bus that guarantees independent access to the device regardless of the status of the other node.

3.4.2 AllSky camera

The cloud sensor described above, though simple and straightforward to use, is not accurate. It measures the sky temperature locally depending on which part of the sky it is pointed at and is not sensitive to high clouds. This is a big drawback in case of high precision photometry. To overcome this problem we have developed and installed an intelligent all-sky camera cloud monitoring device. It consists of a commercially available AllSky-360 camera manufactured by SBIG and an add-on module based on a single board computer that controls the camera, acquires images, analyses them and shares the results with the main computer using a web interface. The vision system cross-references the positions and magnitudes of the stars detected on the camera image with a star catalog and determines which parts of the sky are obstructed by clouds. This is a very accurate and effective way to automatically determine cloud coverage. Example images are shown in Fig. 4. Additionally, the device has a wireless interface which simplifies installation and eliminates the risk of electrical surge propagation in data cables.

3.4.3 Video surveillance cameras

Video surveillance serves two purposes. It permits remote visual inspection of the site during manual operation, equipment testing and debugging, but also, thanks to recording capabilities, it allows us to keep track of what has been happening at the site during unattended operation. All four sites are equipped with indoor (monochromatic, fisheye, good low light performance) and outdoor (color) Mobotix cameras. An image of an external camera installed on a container in Argentina is shown in Fig. 5a.

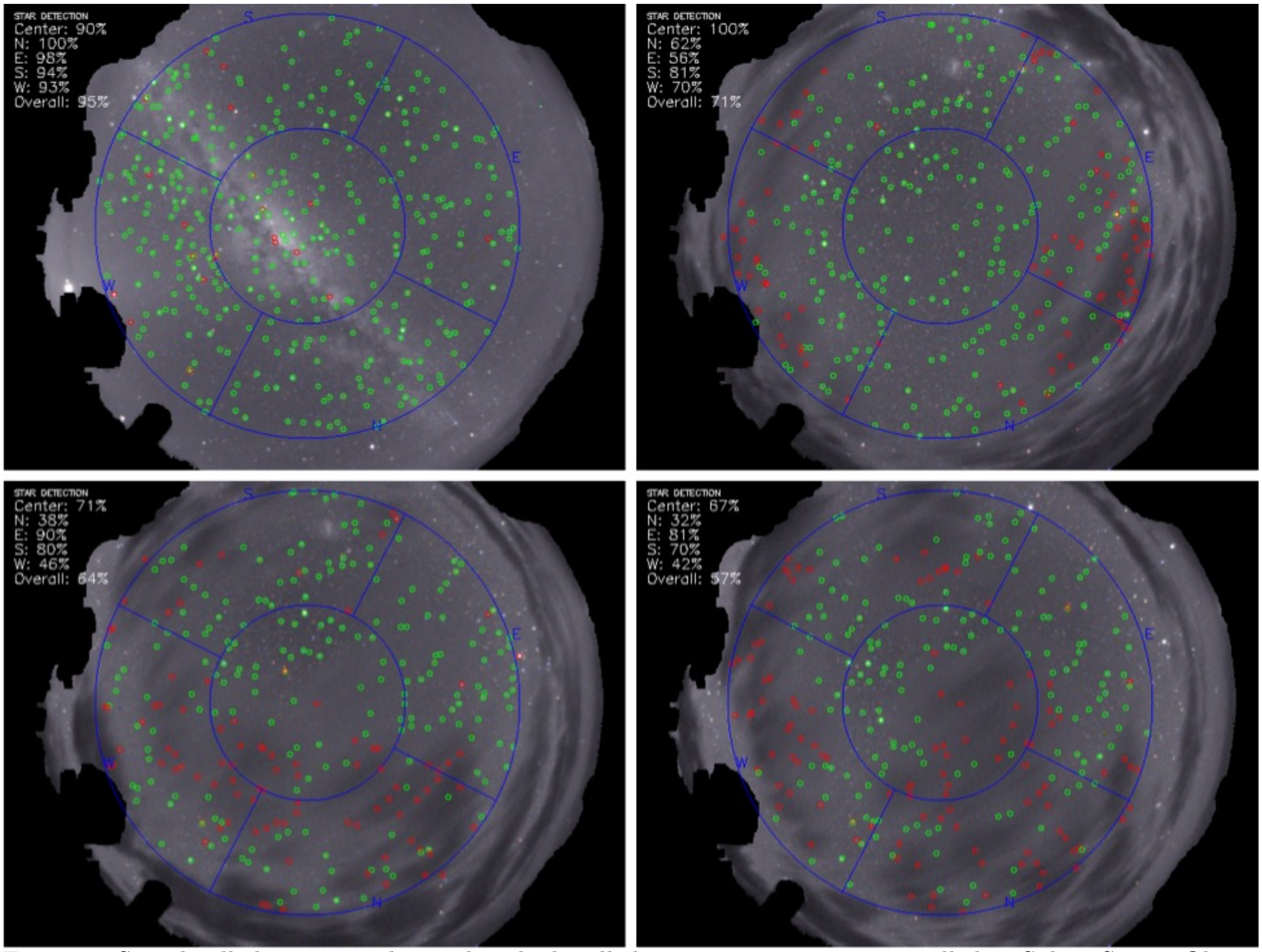

Figure 4: Sample all sky images obtained with the all-sky monitoring system installed in Siding Spring Observatory in Australia. Each of the 60 second exposures shows different cloud coverages. In all four cases, the standard could sensor reported cloudless conditions. Green circles denote stars properly detected and identified in the catalog, red circles denote stars obscured by clouds.

3.4.4 Lightning detector

Boltec lightning detectors are installed in the Solaris-3 and Solaris-4 observatories. The devices are sensitive to radio frequency electromagnetic signals emitted during a lightning discharge. The receiver's antenna is visible on the photograph in Fig. 8a.

3.4.5 Flatfield screen and FlatMount

The flatfield screen is an evenly illuminated 0.6x0.6m flat surface that permits calibration of the CCD camera and the optical system of the telescope. This calibration can also be done during twilight on the sky but due to time and weather constraints it is much more efficient to do it using a dedicated flat field device. We use the Alnitak Astrosystems FlatMan-XL screen that is mounted on a dedicated linear manipulator called FlatMount. The manipulator has been developed for the need of the Project and allows the screen to be positioned in front of the telescope during calibration and lowered to a home position during normal observing without obstructing the field of view of the telescope. FlatMount consists of a steel stationary chassis mounted on the steel ring of the dome and a movable frame. The frame is coupled to the stationary support via two linear bushings and a linear ball-screw actuator driven by a stepper motor. The stepper motor is controlled with a dedicated controller that

(a) (b)

Figure 5: (a) Mobotix camera, Solaris-4. Note the surge protector installed near the camera. The all-sky camera is visible on the adjacent side of the corner. (b) Flatfield screen and FlatMount with the control box (inset).

accepts commands from the PC via USB but also allows manual control of the FlatMount using pushbuttons. There are additional hardwired security features that protect the screen from colliding with the dome in case of emergency operation.

3.5 Security and HVAC

Building Management Systems (BMS) are well known throughout the industry. They are also getting more and more common in residential applications. Autonomous astronomical observatories, however, due to the nature of their operation, require a slightly different approach when designing a dedicated BMS. Aspects that differentiate this approach from a standard industrial one are: (1) remoteness: professional observatories are usually located in very remote areas with limited staff (if any), (2) equipment value: a single 3,5-dome can easily contain equipment worth 0,25 M Euro or more, safety is a priority, (3) exposure of sensitive equipment to external conditions, high amplitude of temperature changes, rapidly changing conditions, high wind speeds, (4)frequent blackouts and brownouts, low electrical energy quality.

In Fig. 6 we present a diagram showing an overview of the BMS system installed in all four Solaris observatories. We use an industrial PLC[§] with a rich set of peripherals that allows the use of different communication porticos and interfaces. The CPU module is responsible for the realization of the real-time data acquisition and control of components connected to the system. The PLC is responsible for air-conditioning in the dome, ventilation and temperature control of the computer cabinet and overlooks the operation of the observatory. It is authorized to close the dome in case of emergency e.g. (prolonged power failure) or abnormal operation (e.g. dome is open during daytime). It can also isolate power from the UPS units to switch off all the components e.g. in case of overheating. Apart from acquiring data from sensors and HVAC control, the BMS does not perform any regular tasks. Its triggering limits are set in such a way that the higher-level controls (PC) act first. Only if they fail, the PLC will undertake emergency actions. This way the security system does not interfere with the normal operation of the observatory. The BMS is equipped with a range of microswitches, temperature and

[§]Programmable Logic Controller.

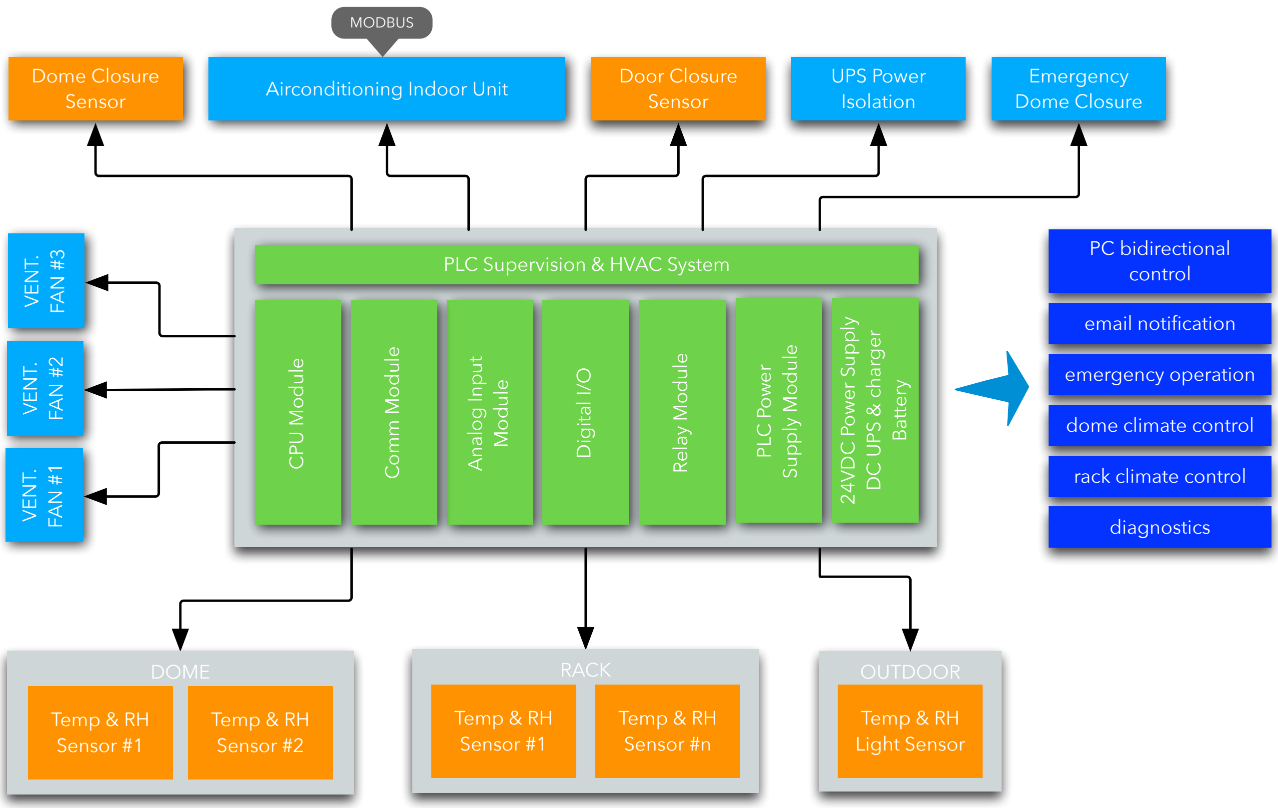

Figure 6: Building Management System design overview.

humidity sensors installed in the dome, in the rack cabinet and outdoors. The air-conditioning is controlled using a Modbus gateway.

3.6 Lightning protection, grounding and electrical system

All Solaris sites use a 3-phase TT-type electrical network with local earthing. The benefit is an interference-free earth connection especially important when using sensitive equipment. Due to the remoteness of the observatories, the long electrical grids that supply power to the sites are susceptible to interferences. This requires that the electrical installation is designed with care to avoid unnecessary equipment loss in case of power surges and noise. All three locations have local and dedicated grounding installations. In Australia the grounding system consists of six 5-m and twelve 1-m copper rods inserted into 120 mm diameter holes filled with bentonite. These rods, together with concrete reinforcement rods are interconnected using a copper wire. This copper wire also connects our grounding system to HAT-South[¶] grounding system which is nearby. In South Africa, Solaris-1 and Solaris-2 have a common grounding system that consist of two interconnected 5-m diameter copper rings, one around each footing. The electrical and grounding installations of Solaris-4 in Argentina are the most complex of the threes sites. Before Solaris' construction began, the closest place where power was accessible was the nearby mountaintop called Burek (see sec. 2.2.3). From there, a 500-m long overhead electrical grid has been installed to supply power to Solaris. The grounding system consist of a copper wire embedded into the concrete footing and extending radially outwards. Unlike other places, the Solaris-4 site is equipped with a dedicated, 10.5-m high lightning protection mast (Fig. 8a).

[¶]One of the nodes of the Hungarian Automated Telescope Network (HATNet).

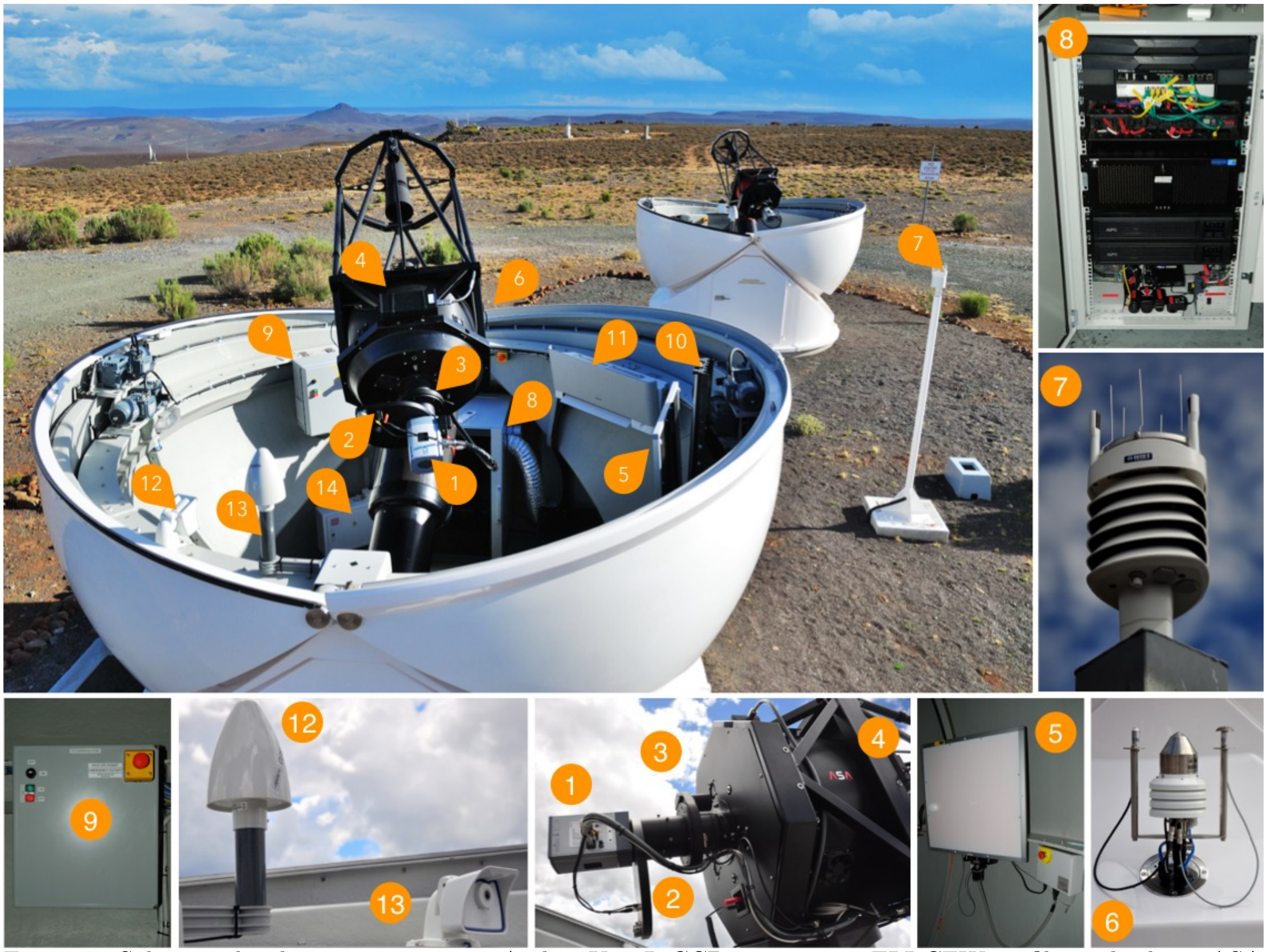

Figure 7: Solaris-2: hardware overview. 1. Andor iKon-L CCD camera. 2. FLI CFW-12 filter wheel. 3. ASA field rotator. 4. ASA mirror covers. 5. Alnitak Astrosystems FlatManXL flatfield screen. 6. Reinhardt weather station. 7. Vaisala WXT-520 weather transmitter. 8. 19-inch rack cabinet. 9. PLC Security and HVAC system. 10. FlatMount manipulator. 11. Air-conditionung indoor unit. 12. Meinberg GPS-antenna. 13. Mobotix surveillance camera. 14. Main switchboard. Solaris-1 is visible in the background.

4. HADRWARE PERFORMANCE

4.1 Telescope performance, tracking and pointing

The telescope mount, as outlined in Sec. 3.2.1, is equipped with gear-less direct drive motors. The performance of the motors can be optimized with user accessible tuning functions. Both right ascension and declination motor controllers can be configured independently with sets of PID parameters. Additionally, lowpass filters with user-tunable parameters have been implemented to dampen high frequency vibrations. The low speed operation of the motors and very small allowable position errors require that the motor controllers are appropriately tuned. It is possible to set different PID coefficients for three speeds: sidereal tracking, medium speed and maximum slewing speed.

Accurate pointing of the telescope is crucial in robotic and autonomous operation. The telescope uses a proprietary pointing model that corrects for the following errors: polar alignment, collimation, OTA mounting, OTA flexure (East and West), pier-flip. Additionally, it is possible to add n-th order Fourier series corrections to the basic model. The pointing model itself is generated automatically using a dedicated software package (Sequence by ASA) that uses third party software such as MaximDL (CCD camera control and image acquisition) and

(a) (b)

Figure 8: (a) Solaris-4: lightning protection mast as seen from the roof of the container. In the foreground: the Vaisala weather transmitter, directional WiFi antenna and Boltek lightning detector antenna. (b) Solaris-3 under bushfire threat in January 2013.

PinPoint (astrometric engine) and takes approximately 2-3 hours of nighttime to complete for a grid consisting of 150 fields evenly distributed on the sky. Figures 9a and 9b show pointing test results obtained before and after running the automatic pointing model routine, respectively. The final pointing model reduces the pointing errors by 70% though they are still larger than specified by the manufacturer.

Both pointing and tracking accuracy strongly rely on the pointing model. To achieve better tracking results, it is possible to build a *local* tracking model that probes the expected trajectory of the telescope during tracking (e.g. for the next 60 minutes) with a series of CCD images. Using the same astrometric tools as described above, appropriate corrections are computed and then applied during the actual tracking. Figures 10a and 10b show unguided tracking accuracy over a 40-minute test run in declination and right ascension, respectively (without the local tracking model). Though a clear trend is visible, the guiding errors are kept within the technical specification of the mount.

5. SUMMARY

Robotic telescopes and autonomous observatories are replacing classical observatories operated by astronomers and technicians. We have presented a global network of telescopes that is part of the Solaris Project and our systems engineering approach in designing and establishing such observatories. The network started operation in 2013.

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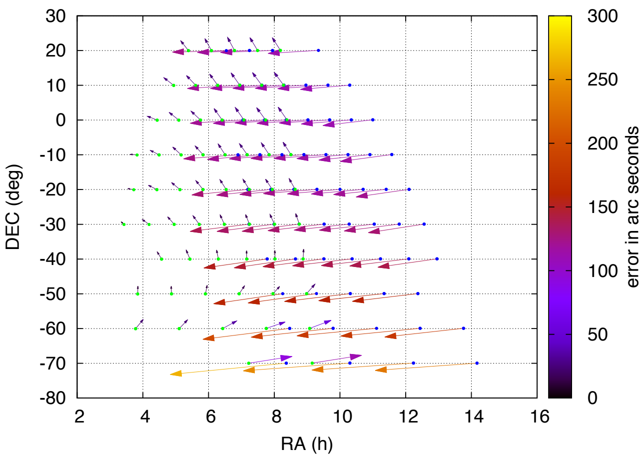
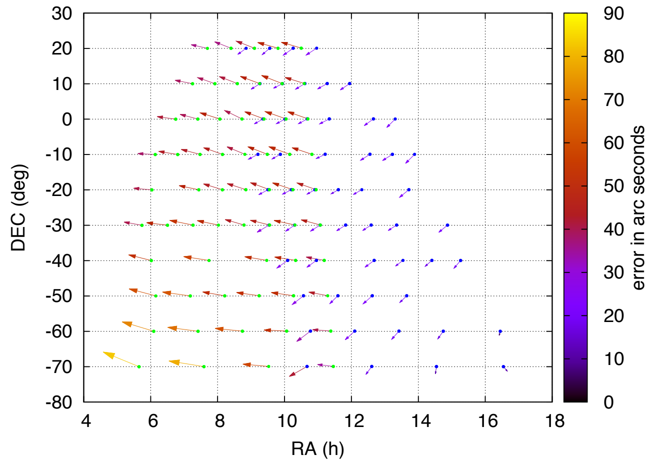
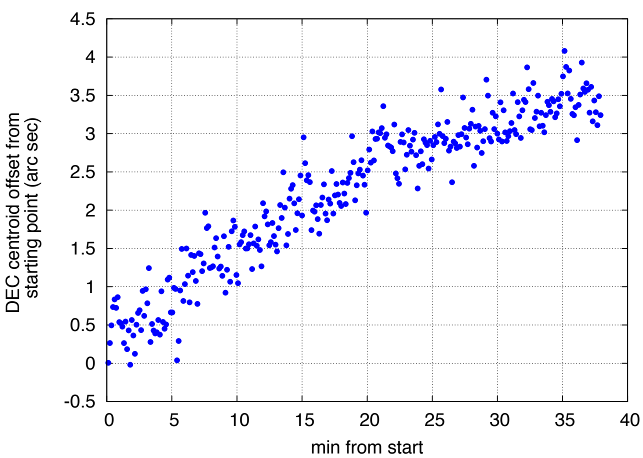


(a)

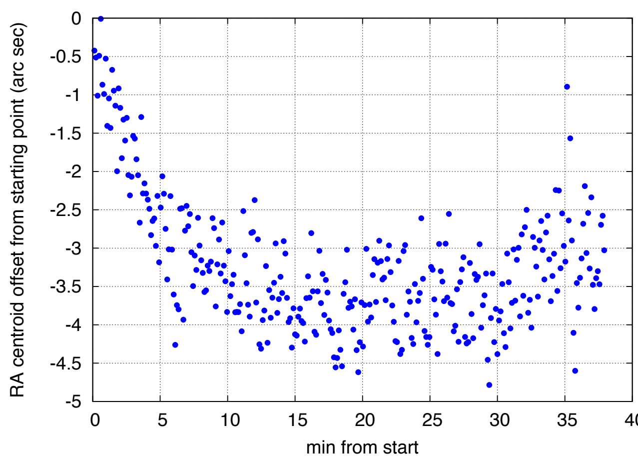


(b)

Figure 9: Solaris-3 pointing precision before (a) and after applying a pointing model (b). The maximum pointing errors are 265 arc seconds in right-ascension and 18 arc seconds in declination in the first case and 80 arc seconds for right-ascension and 20 arc seconds for declination for in the second case.



(a)



(b)

Figure 10: Solaris-3 unguided tracking test: RA = 11 20 23, Dec = -20 40 31, Az = 86.3213 Alt = 47.5619, Start = 2013-03-18T10:35:49 UT, END = 2013-03-18T11:11:35 UT, exp. time = 5s.

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