Polish and European SST Assets: the Solaris-Panoptes Global Network of Robotic Telescopes and the Borowiec Satellite Laser Ranging System

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ABSTRACT

We present the assets of the Nicolaus Copernicus Astronomical Center, Space Research Center (both of the Polish Academy of Sciences), two Polish companies Sybilla Technologies, Cillium Engineering and a non-profit research foundation Baltic Institute of Technology. These assets are enhanced by telescopes belonging to The Open University (UK), the Max Planck Institute for Extraterrestrial Physics and in the future the Radboud University. They consist of the Solaris-Panoptes global network of optical robotic telescopes and the satellite laser ranging station in Borowiec, Poland. These assets will contribute to the Polish and European Space Surveillance and Tracking (SST) program. The Solaris component is composed of four autonomous observatories in the Southern Hemisphere. Solaris nodes are located at the South African Astronomico Observatory (Solaris-1 and Solaris-2), Siding Spring Observatory, Australia (Solaris-3) and Complejo Astronomico El Leoncito, Argentina (Solaris-4). They are equipped with 0.5-m telescopes on ASA DDM-160 direct drive mounts, Andor iKon-L cameras and housed in 3.5-m Baader Planetarium (BP) clamshell domes. The Panoptes component is a network of telescopes operated by software from Sybilla Technologies. It currently consists of 4 telescopes at three locations, all on GM4000 mounts. One 0.36-m (Panoptes-COAST, STL-1001E camera, 3.5 BP clamshell dome) and one 0.43-m (Panoptes-PIRATE, FLI 16803 camera, 4.5-m BP clamshell dome, with planned exchange to 0.63-m) telescope are located at the Teide Observatory (Tenerfie, Canary Islands), one 0.6-m (Panoptes-COG, SBIG STX 16803 camera, 4.5-m BP clamshell dome) telescope in Garching, Germany and one 0.5-m (Panoptes-MAM, FLI 16803 camera, 4.5-m BP slit dome) in Mammendorf, Germany. Panoptes-COAST and Panoptes-PIRATE are owned by The Open University (UK). Panoptes-COG is owned by the Max Planck Institute

for Extraterrestrial Physics and Panoptes-MAM by Baader Planetarium. Five additional telescopes will be deployed in the near future under the umbrella of Panoptes codename. A double system 0.3-m f/1.44 TEC300VT-7DEG astrograph and a 0.5-m telescope (Panoptes-1AB) will be initially installed in Poland in mid 2017 and a 0.7-1.0-m class telescope will be installed at a yet not determined global location in 2018/2019 (Panoptes-2). They will be co-owned and/or operated by Sybilla Technologies, Cillium Engineering and Baltic Institute of Technology. These will be accompanied around 2018/2019 by three 0.6-m telescopes of the BlackGEM project (La Silla, Chile, designation Panoptes-BG-1,2,3) that will be owned by the Radboud University (Nijmegen, the Netherlands). Altogether, by 2018/2019 the network will consist of 13 telescopes. Additionally, in mid 2020 the first light of a 1.5-m f/4 telescope for SST is planned assuming that the feasibility study is approved by mid 2017. The 1.5-m telescope project is led by Nicolaus Copernicus Astronomical Center.

Borowiec Satellite Laser Ranging Station (BSLRS) belongs to the Space Research Center of the Polish Academy of Sciences (SRC PAS) and it is the only such device in Poland and one of the few ones in the world working since the mid-80's. The BSLRS entered the structures of International Laser Ranging Service (ILRS) on May 13, 1988 and represents the EUROpean LASer network (EUROLAS) consortium joining European laser stations in the frame of ILRS. The most important elements of the BSLRS system constitute two high-energy Nd:YAG pulse laser modules (50 and 450 mJ pulse energy for 532 nm), both fully operational and a transmitting-receiving Cassegrain telescope with an aperture of 0.65 m, additionally equipped with 20 cm guiding Maksutov telescope. In the long history the BSLRS has tracked 71 different satellites (52 LEO and 19 MEO), providing more than 8 million good shots (single measurements) for more than 12 400 passes of satellites over the Borowiec station. The BSLRS is currently working in the frame of Space Debris Study Group (SDSG) ILRS and European SST program. In the last few months, station has participated in several campaigns of space debris objects like ENVISAT, TOPEX/Poseidon, JASON-1 and others with good results as presented in this publication.

1. INTRODUCTION

The goal of the paper is to introduce Space Surveillance and Tracking (SST) assets, expertise and capabilities, current and those in development, of a closely collaborating group of research institutions and companies from Poland and their European academic and industrial partners. The group is composed of two public research institutions from the Polish Academy of Sciences, Nicolaus Copernicus Astronomical Center (NCAC) and Space Research Center, two Polish companies Sybilla Technologies, Cillium Engineering and a non-profit research foundation Baltic Institute of Technology (co-founded by M. Konacki, Gdynia, Poland). Their European partners include the company Baader Planetarium GmbH (Mammendorf, Germany), and scientists from The Open University (UK), the Max Planck Institute for Extraterrestrial Physics (Garching, Germany) and the Radboud University (Nijmegen, the Netherlands).

The collaboration currently encompasses 8 robotic optical telescopes in both hemispheres (Fig. 1,2) under the name Solaris-Panoptes network (see Tab. 1) and the Borowiec Laser Ranging Station of the Space Research Center. The Solaris component (NCAC [1,2]) is composed of four autonomous observatories in the Southern Hemisphere. Solaris nodes are located at the South African Astronomical Observatory (Solaris-1 and Solaris-2), Siding Spring Observatory, Australia (Solaris-3) and Complejo Astronomico El Leoncito, Argentina (Solaris-4). The Panoptes component utilizes available observing time in observatories owned by The Open University, Max-Planck-Institut für Extraterrestrische Physik, Baader Planetarium on the base of separate agreements on providing SST observations. Recently installed and commissioned by Baader Planetarium and Sybilla Technologies observatories are presented in Fig. 3.

Sybilla Technologies is a software provider (Abot software suite, see Fig. 4 and §4) and support operator of the Solaris-Panoptes network. At least six more telescopes will run under the supervision of Abot in the next three years: three observatories for BlackGEM Project, one for MeerLICHT and two new Panoptes nodes (1AB and 2) that will be fully dedicated to SST. Cillium Engineering will provide tailored systems engineering solutions for all 6 telescope installations (see §3).

BlackGEM and MeerLICHT projects are based on custom build hardware and adapted Abot software for the control of observatories [3]. First phase of BlacGEM project will bring 3 observatories in 2018/2019 (La Silla, Chile) and MeerLICHT observatory (SAAO) will be ready in 2017. Their primary goal is to provide optical counterpart observations for gravitational events detected by Advanced LIGO and Virgo in the case of BlackGEM and for MeerKAT radio telescope in the case of MeerLICHT. Both projects will produce immense amounts of optical data due to a 2.7 square degree field-of-view and STA1600 based, 10560 x 10560 pixels CCD camera. The acquired data will

be analyzed on-site by Sybilla Technologies to survey the sky for space debris and satellites. BlackGEM project will be able to dedicate up to 30% of observing time to SST tasks. If necessary, both projects can quickly deploy additional sensors to provide more SST observing time.
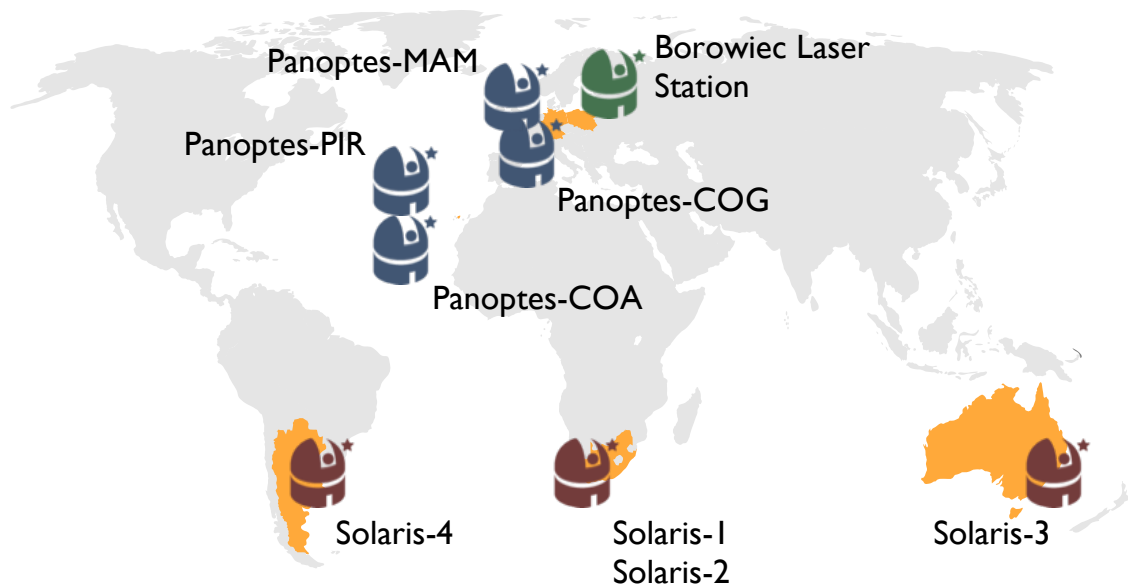

Fig. 1 The Solaris-Panoptes network and the Borowiec Laser Ranging Station as of September 2016.
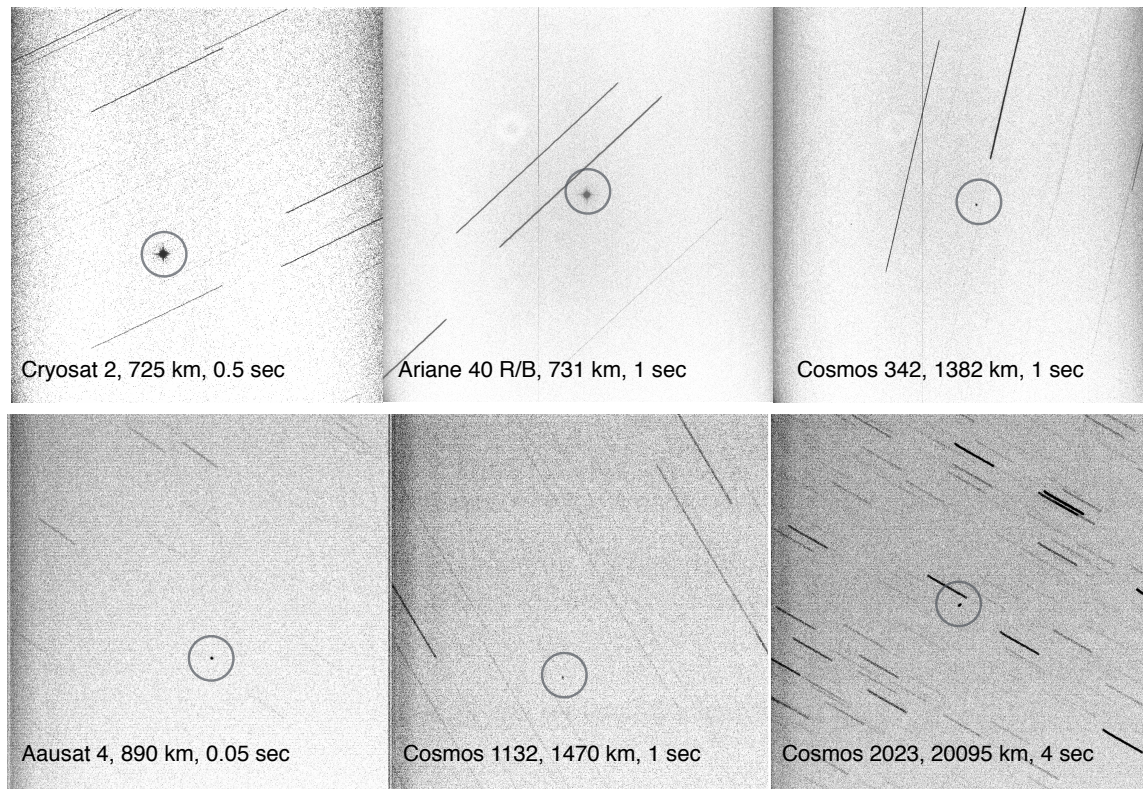

Fig. 2 Raw frames of various objects observed with Panoptes (top row) and Solaris (bottom row) components of our network.

Fig. 3 Panoptes-PIRATE and Panoptes-COAST (The Open University, UK) installed in August 2016 at the Teide Observatory by Baader Planetarium Gmbh and Sybilla Technologies.

	Sensor Location Clear nights	Main mirror, focal ratio, optical system	Mount, camera	Field of view, diagonal, pixel size	Time available for SST in %, clear hours/year
1	**Solaris-1,2** South African Astronomical Observatory, South Africa 220 clear nights	0.5 m, f/15 Ritchey-Chretien	ASA DDM-160 Andor iKon-L e2v 4240 2k x 2k, 13.5um	13' x 13', 18', 0.37"/pixel	50% 2200 hours
2	**Solaris-3** Siding Spring Observatory, Australia 220 clear nights	0.5 m, f/9 Cassegrain	ASA DDM-160 Andor iKon-L e2v 4240 2k x 2k, 13.5um	21' x 21', 30', 0.62"/pixel	50% 1100 hours
3	**Solaris-4** Complejo Astronomico El Leoncito, Argentina 300 clear nights	0.5 m, f/15 Ritchey-Chretien	ASA DDM-160 Andor iKon-L e2v 4240 2k x 2k, 13.5um	13' x 13', 18', 0.37"/pixel	50% 1500 hours
4	**Panoptes-COAST** Teide Observatory, Tenerife, Canary Islands 290 clear nights	0.36 m, f/11 Schmidt-Cassegrain	10micron GM4000 SBIG STL-1001E KAF-1001E 1k x 1k, 24 um	21' x 21', 30', 1.26"/pixel	30% 870 hours
5	**Panoptes-PIRATE** Teide Observatory, Tenerife, Canary Islands 290 clear nights	0.43 m, f/6.8 Corrected Dall-Kirkham	10micron GM4000 FLI 16803 KAF-16803 4k x 4k, 9 um	43' x 43', 61', 0.63"/pixel	30% 870 hours
6	**Panoptes-COG** Garching, Bavaria, Germany	0.6 m, f/6.5 Corrected Dall-Kirkham	10micron GM4000	32' x 32', 45', 0.47"/pixel	30% 270 hours

	90 clear nights		SBIG STX 16803 KAF-16803 4k x 4k, 9 um		
7	**Panoptes-MAM** Mammendorf, Bavaria, Germany 90 clear nights	0.5 m, f/6.8 Corrected Dall-Kirkham	10micron GM4000 FLI 16803 KAF-16803 4k x 4k, 9 um	37' x 37', 52', 0.54"/pixel	80% 720 hours
8	**Panoptes-1AB** Poland, mid 2017, later relocated, final location tbd 290 clear nights (La Palma, Canary Islands)	0.3 m, f/1.44 TEC300VT-7DEG 0.5 m, f/6.8 Corrected Dall-Kirkham	10micron GM4000 KAF-16803 4k x 4k, 9 um KAF-16803 4k x 4k, 9 um	5° x 5°, 7°, 4.4"/pixel 37' x 37', 52', 0.54"/pixel	100% 2900 hours
9	**Panoptes-2** Location tbd 2018/2019 290 clear nights (La Palma, Canary Islands)	0.7-1.0 m	tbd	tbd	100% 2900 hours
10	**Panoptes-BG 1,2,3** La Silla (Chile) 2018/2019 290 clear nights	0.6-m, f/5.5 Corrected Dall-Kirkham	Fornax 200 STA1600 10k x 10k, 9 um	1.65° x 1.65°, 2.33° 0.56"/pixel	30% 2610 hours
				Total clear hours per year	15 940 hours

Tab. 1 The Solaris-Panoptes network of robotic telescopes. For Panoptes 1 and 2 La Palma (Canary Islands) was assumed as the final destination for the purpose of available observing time calculations. A flat number of 10 hours per night throughout the year was assumed in the calculations. Maximum estimated percentage of time available for SST is shown.

The Panoptes 1AB and 2 initiative of Baltic Institute of Technology, Sybilla Technologies and Cillium Engineering aims to deploy a series of sensors fully devoted to SST. Panoptes-1AB will be a double system composed of a 0.3-m f/1.44 TEC300VT-7DEG astrograph and a 0.5-m telescope (Fig. 5). Panoptes-1AB will be initially installed in Poland in mid 2017 and later relocated to a site with better observing conditions. Panoptes-2 will be a 0.7-1.0-m class telescope to be installed at a yet not determined global location in 2018/2019.
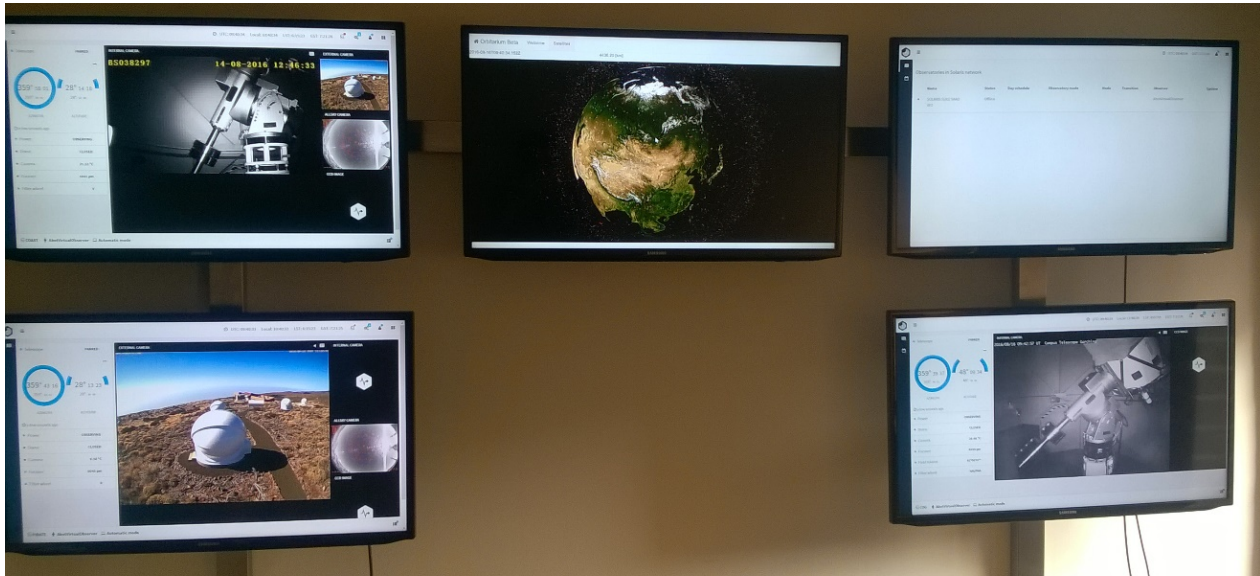
Fig. 4 Current state of "Abot: Network Management Centre" for the Solaris-Panoptes network at the Nicolaus Copernicus Astronomical Center (Torun, Poland) where an operator can easily monitor status of the whole network, add new schedules and/or monitor their execution. Position of objects in an orbit is computed in real time and displayed in the central top monitor. With TLE catalogue updated from www.space-track.org each object within the sensors' range can be selected in a web based UI and tracked by the network. The remaining monitors display current information on the network of telescopes in the form of interactive screens. User interface is intuitive and the presentation of the parameters of the individual components, such as e.g. the dome, telescope, scientific camera and weather parameters are in the form of graphs which allow an operator to quickly assess the status of individual observatories, as well as the network as a whole.
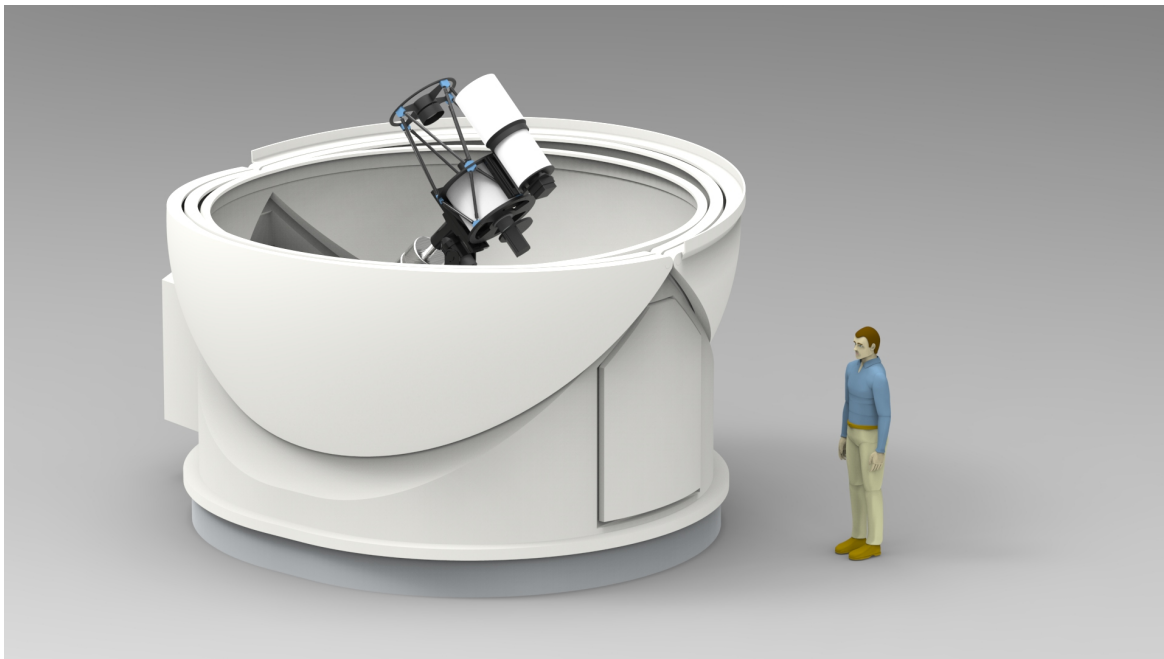

Fig. 5 Panoptes-1AB double system (Baltic Institute of Technology) composed of 0.3-m f/1.44 TEC300VT-7DEG astrograph and a 0.5-m f/6.8 telescope. It will be initially installed in Poland in mid 2017 and later relocated to a site with better observing conditions.

Last but not least, the project of M. Konacki to deploy a robotic 1.5-m telescope fully devoted to SST was earlier this year approved by the Polish Ministry of Economic Development with the Nicolaus Copernicus Astronomical Center (Toruń branch, Fig. 6) as the lead institution. The project will now enter a detailed feasibility study. Assuming that the study is approved by the authorities of the Kuyavian-Pomeranian voivodeship, it will be funded from the European structural funds available to this region. The project can then start in mid 2017 and the first light should be expected in mid 2020. For legal aspects related to the source of funding, the telescope will be placed in the European Union territory.
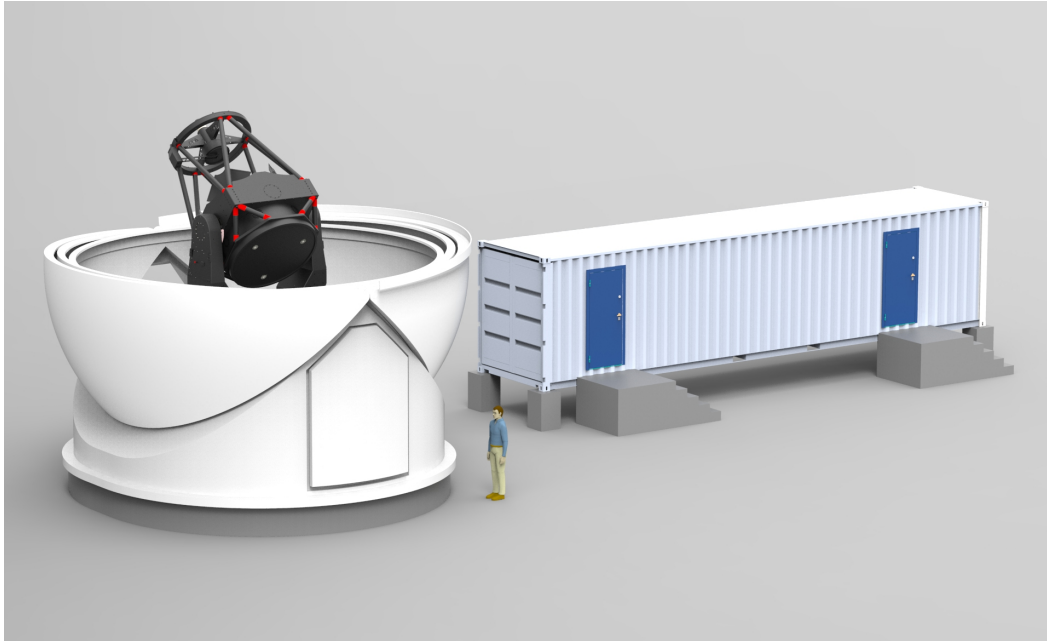

Fig. 6 A very preliminary concept of a robotic 1.5-m f/4 telescope for SST employing a clamshell dome and a ruggedized container with a server/control room. 3D model of an alt-az telescope courtesy ASA Astrosysteme GmbH.

Installation of new sensors is part of a larger plan of our collaboration to have a full presence in the SST field in the optical and laser domains. Under the lead of ST, we are working to create the full package of optimized SST solutions, ranging from equipment, control interfaces through hardware abstraction layer interfaces and command and control software to advanced algorithms for data reduction, analysis, orbit propagation, collision detection, deorbit predictions and potential fragmentation analysis. The cooperation takes place both in research and development, as well as commercial products introduction. Roadmap for the collaboration is presented in Fig. 7.

2. THE "SOLARIS" PROJECT

The "Solaris" project is carried out at the Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences. The project and the network was named after "Solaris" a novel by a Polish writer Stanislaw Lem (1921-2006). The novel is about a circumbinary planet covered with a supposedly conscious ocean. Project's primary goals in the time frame 2010-2016 are the search for circumbinary planets via eclipse timing of eclipsing binary stars and precise stellar astronomy. To this end precise multicolor photometry of targets of interest is obtained with the network.

Project is based one the global network of four robotic telescopes placed at three locations: the South African Astronomical Observatory (SAAO, South Africa, Fig. 8), the Siding Spring Observatory (SSO, Australia) and the Complejo Astronómico El Leoncito (CASLEO, Argentina). Its separation in longitude allows for a 24-hour night time sky coverage in favorable weather conditions. Each of the telescopes has a 0.5-m primary mirror and similar equipment. This includes a set of filters U, B, V, R, I and u', g', y', z' and a high-end camera (see Table 1). One of the telescopes at SAAO is also equipped with a compact, high throughput echelle spectrograph BACHES (resolution ~20 000 [4,5]). The spectrograph is currently used to carry out a survey of spectroscopic and eclipsing binaries.

The installation of the network stared in April 2011 and ended in December 2013. It took over 1100 person-days on

site to carry out the installation of the telescopes and over 1200 person-days including the installation of the spectrograph in the Spring of 2014. One of the team members spent over 500 days at the three locations. The network has begun its operation in the Spring of 2014. In its current shape, in terms of the scientific goals, the project will be carried out until the end of November 2016. The project was financed from several sources. These include the European Research Council (ERC), the National Science Center, the Ministry of Science and Higher Education. The total budget of the project in the time frame 2010-2016 is about 2.5 million Euro. However, the beginnings of the project date back to December 2008 and the instrumentation FOCUS grant of 110 thousand Euro from the Foundation for Polish Science that allowed to buy the first telescope and camera.
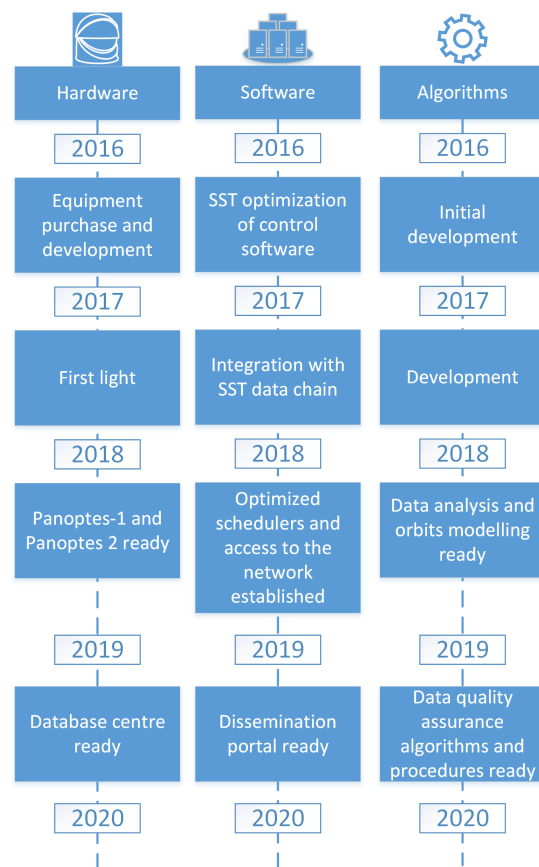
Hardware	Software	Algorithms
2016	2016	2016
Equipment purchase and development	SST optimization of control software	Initial development
2017	2017	2017
First light	Integration with SST data chain	Development
2018	2018	2018
Panoptes-1 and Panoptes 2 ready	Optimized schedulers and access to the network established	Data analysis and orbits modelling ready
2019	2019	2019
Database centre ready	Dissemination portal ready	Data quality assurance algorithms and procedures ready
2020	2020	2020

Fig. 7. In the timeframe 2016-2020 our work is organized through three paths of development based on the leading areas: *hardware, software and algorithms*. Full functionality of the ecosystem of monitoring and tracking of space objects will be reached in 2020.

Fig. 8 Solaris-1 and Solaris-2 at the South African Astronomical Observatory (Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences).

3. CILLIUM ENGINEERING

Cilium Engineering is a spin-out company that has its roots in Project Solaris [1,2] and has been founded by members of the Project's team. The company specializes in providing tailored systems engineering solutions for autonomous astronomical observatories. The range of services offered by Cilium includes observatory design, installation and commissioning, counseling, custom optomechatronics design and manufacturing, embedded systems design and software solutions. Cilium also offers a range of hardware products designed for autonomous astronomical observatories. 2πSky is a computer vision-based cloud detection embedded system that utilizes all-sky images to determine the cloud coverage and atmosphere transparency during the night (Fig. 9). The system is standalone with its own web server and database and can be accessed by human or machine and is powered by a custom photometric and astrometric engine (Fig. 10). Optionally, the system can integrate weather station data and make them available using a modern high-level interface.

2πSky's capabilities to connect new environmental sensors and apply sophisticated algorithms play an important role in autonomous observatories design. A lot of effort has been put to create robust computer vision system for whole sky cloudiness analysis that is able not only to provide zero one nature information but primarily detect cloud distribution on the sky and measure its transparency. The main idea behind the algorithm is all-sky real-time photometry, which is compared with cataloged measurements of brightest of stellar objects. As presented on the schematic (Fig. 11) this goal is achieved by transforming sky coordinates to image coordinates based on camera projection parameters, time and location input of processed image. At the very basis of this real time acquisition and computation works well tested hardware and software compound that is designed to work as distributed network of same devices serving different environmental information like temperature, humidity or irradiance from multiple dedicated sensors as well as third-party weather stations. In such grid 2π-based devices made of ARM single board computers and dedicated peripherals are connected to the observatory network wired or wirelessly and feeding on sensors or cameras data through industrial communication buses.

The project's extensibility covers not only a number and verity of sensing devices but also the way the gathered data is processed online, logged to local databases, uploaded to remote servers, shared with the observatory's main computer, combined with observing data or presented on a simple observatory dashboard. Further consideration about 2πSky's future leads us to projects like large area networks for meteor detection or mobile vision system powered by solar used for measuring possible remote observing site parameters like number of clear nights throughout a year. In our opinion taking care of every detail of environmental data processing and embedding it into robust and easy to use design plays an important role in not only robotic observatory operation or manual observations but also can speed up observation data reduction pipelines.

Another example of bringing industry standards to robotic observatories is ObservatoryWatch – a PLC-based building management system dedicated for astronomical domes. It integrates weather data, interprets them and provides low-level dome security using OPC-UA communication standard and a web interface.
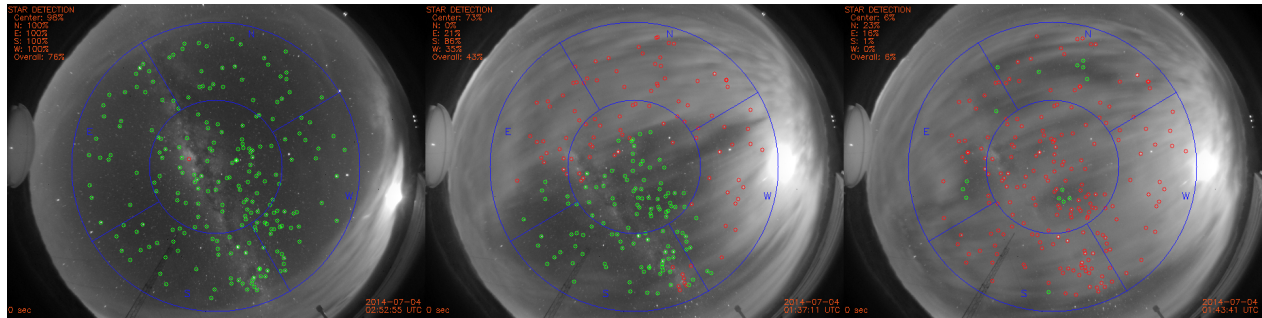

Fig. 9 Examples of cloud detection results obtained with 2PiSky installed at the Solaris-3 site, CASLEO, Argentina. Thanks to a sophisticated algorithm the rising Moon does not interfere with the results.

Cilium's design philosophy focuses on providing high quality industrial standard-based products and services in the astronomical observatory area. Cilium's solutions have been chosen by Project Solaris (four observatories, South Africa, Australia and Argentina [1,2]), Campus Observatory Garching, two Open University observatories at El Teide, Tenerife and the MeerLICHT and BlackGEM projects [3]. In the near future Cilium will be strongly involved in the design, installation and commissioning phases of several optical observatories devoted to the Polish and European SST activities, and assuming acceptance of the feasibility study – an installation and commissioning of a 1.5-m telescope.
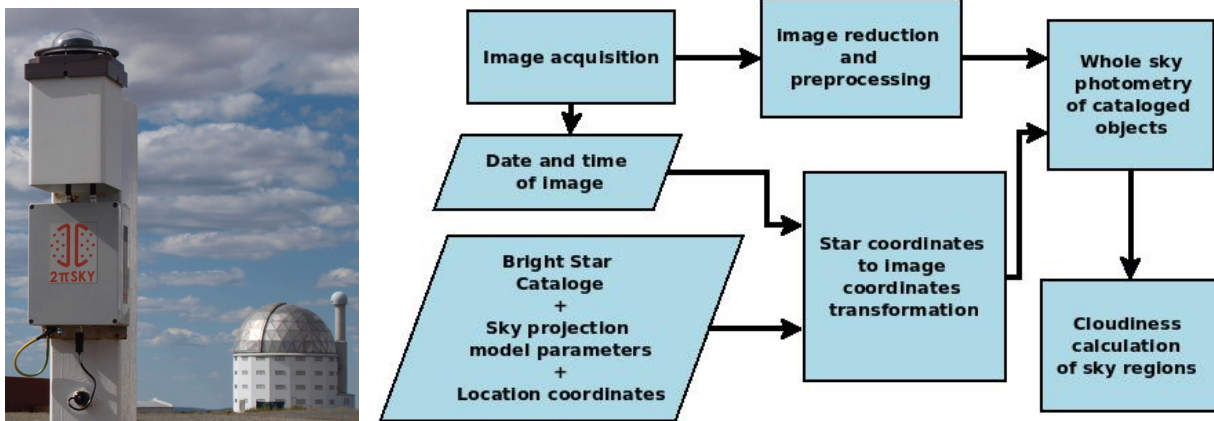

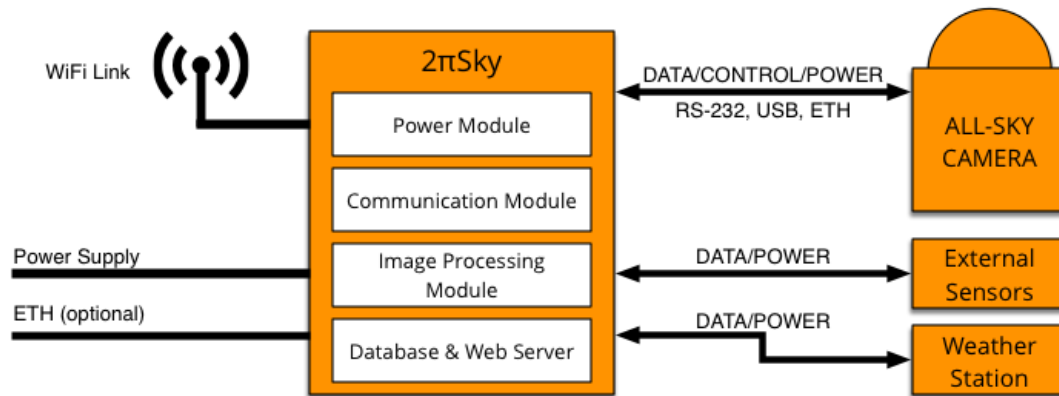Fig. 10 2πSky installed in SAAO, South Africa (left). 2πSky functional diagram (right).

Fig. 11 2πSky hardware/software architecture diagram.

4. SYBILLA TECHNOLOGIES

Sybilla Technologies (ST) is a spin-out company from Project Solaris. It provides the industry standards' based IT solutions for robotic observatories. The company focuses on the fields of observational astronomy, astrodynamics and SST. It utilizes a contemporary approach and modern software architecture, and techniques to address the needs of the owners and operators of robotic observatories.

ST seeks to create and promote reliable, user friendly software and hardware for robotic observatories. The company's goal is to introduce fully autonomous observatories to the market within the next five years and then pursue the goal of adaptive observatories, with special focus on the SST domain, where highly responsive and autonomous sensors are key to efficient monitoring of the space and quickly changing conditions. In this context, we propose the following level of robotic observatories autonomy:

1) **Direct operation** - direct human operation or remote operation is having someone behind a computer control all the observatory's operations from the control room which is a few meters or a thousands of kilometers away.
2) **Assisted operation** - human-assisted is when the observer is responsible for the start and end procedures (calibration, cooling instruments, opening the dome and so on), but can let the equipment observe itself while during the night in normal conditions
3) **Human delegation** - in human delegation, the observer just has to instruct the observatory to start and finish observations and give it observing plan to execute.
4) **Human-supervised** - in human-supervised, the operator is no longer really an observer, but just monitors what information observatory sends back. Mitigation of minor errors requires human assistance. Major problems require expertise and qualified personnel.
5) **Mixed-initiative** - in mixed-initiative, the human might give a robotic observatory an observing plan to complete or even loosely instruct to be „independent" in choosing targets from predefined list and only report back when it finishes. System can mitigate minor failures on itself and major failures by notifying the operator about the problem and potential options that can be executed to recover.
6) **Autonomous** - in fully autonomous mode, the system decides on its own what to observe and how to do it. It also mitigates more serious faults like hard drive failure or inconsistent sensor data.
7) **Adaptive** - finally, an observatory is adaptive when it can learn. It can update or change what it should search out, even evolving to gather information in new ways. It can reconfigure its observing configuration and schemas to optimize the data quality and rate.

Abot (Astronomical Robot) is company's key product dedicated to professional and semi-professional observations currently with 5th level of autonomy. It can be utilized in single observatory or in a network of observatories with special set of services and user interfaces (Fig. 12 and 13). Typical observing station uses numerous computers, monitors and keyboards to make things running. Multiple windows are open and general clutter of various standard and application is quite common. With each piece of hardware and software requiring sophisticated knowledge for maintenance and even simple operation. We decided to introduce special hardware abstraction layer and unification of interfaces to present clear and easy to maintain image of the observatory.

Abot is an end-to-end solution that has a layered (vertical) and modular (horizontal) structure. This allows for a highly adaptive composition in terms of equipment and services. Moreover, layered structure is divided into two access domains: local (from Hardware to Web Service) and public (from Web Service to Cloud Service).

Local access domain is mandatory for a single sensor to work. It comprises reliable, asynchronous drivers to the equipment which then are utilised by Robotic Service layer. This layer includes the logic for operating the equipment through the drivers, but also consists of software-only services that perform auxiliary actions in the system (e.g. preprocess the images, prepare the metadata, etc.) as well as administer the overall process of operation (e.g. performing observations, flat fielding, focusing, weather monitoring, etc.). Web Service layer is a gateway to the local access domain. The connection is established as a secure and resilient full-duplex web socket connection. It is important to note that this is the observatory that registers and opens the connection for communication with the upper public access domain. This allows for a natural growth of networks of telescopes without any re-setting of the public access domain and its services.

Public access domain allows for utilization of a global scheduler, connecting sensors into networks, transferring data and a secure access through a user interface. UI also provides a near real-time a/v transmission if the sensor is equipped with a capable camera. This gives a quick-examination possibility for all the end-users with appropriate access level.
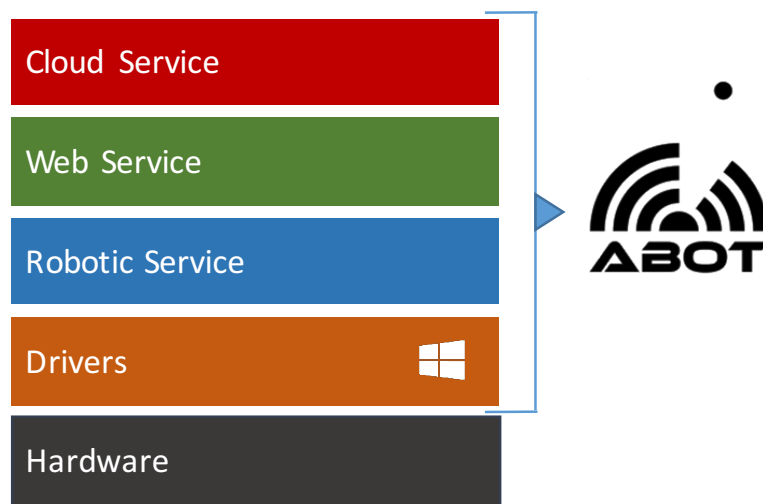

Fig.12 The layered architecture in Abot. Abot encompasses layers from Drivers to Cloud Service. Drivers are a software representation of the hardware. They are consumed by a robotic service, that is an asynchronous service allowing for fault-tolerance. These can be accessed with a secure websocket-based connection through the WebService. Layers from Drivers up to Web Service are deployed on a local sensor workstation and provide for a secure, reliable administration and coordination of single sensor activities. Cloud Service is a family of services that allow for combining sensors into networks, provide a global scheduler, assist in data transfer, system and data presentation through a web UI and are the gateway for extended, dedicated services.
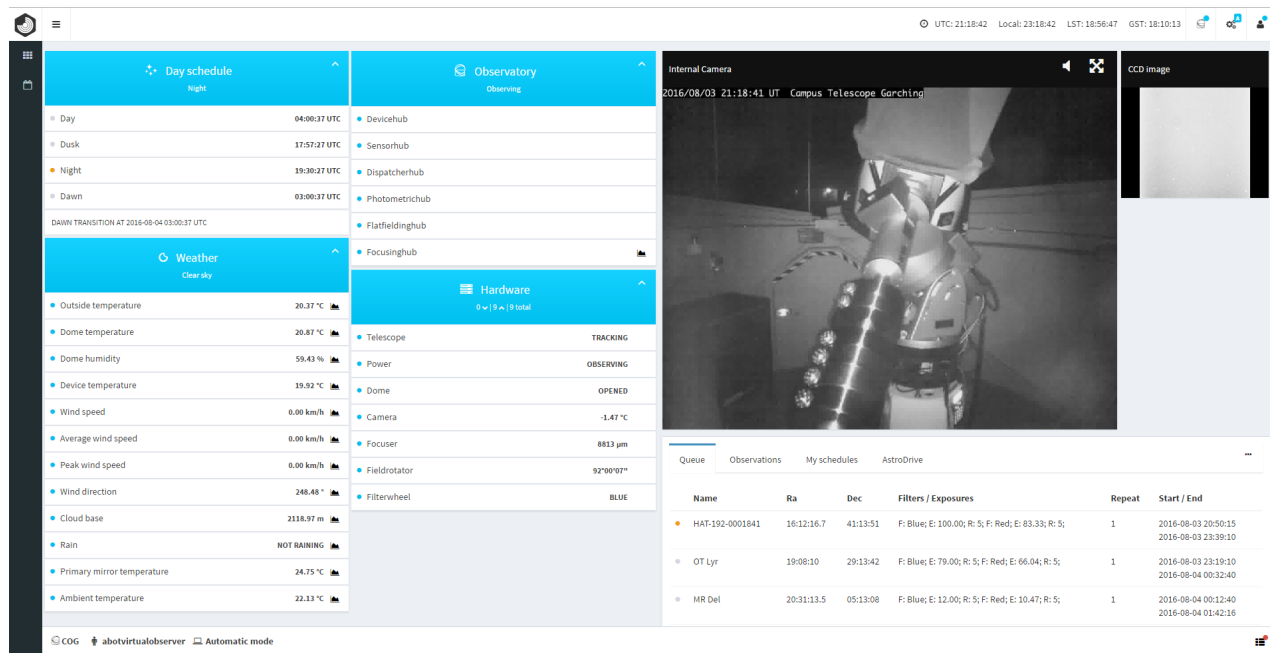
Fig. 13 Example of Abot user interface for a single observatory. All important for observatory operation data is presented in a single dashboard. The dashboard can be customized per observatory and typical usage scenarios. In this design no important message will be missed and is always placed in the same position. The operator of the observatory can easily take an informed decision on the necessary action based on a quick dashboard overview. The figure presents current observing plan in the bottom right, CCTV and CCD images in top right corner, sensors, operational and hardware data on the left. Multiple additional icons are available through the screen to give a quick access to the most important options.

5. BOROWIEC LASER RANGING STATION

In the long observational history, since 1976 to present, Borowiec Satellite Laser Ranging Station (BSLRS) belonging to the Space Research Center of the Polish Academy of Sciences (SRC PAS) has tracked 71 different satellites (52 LEO and 19 MEO), providing more than 8 million good shots (single measurements) for more than 12 400 passes of satellites over the Borowiec station. In August, 2016 BSLRS hast started to track first typical rocket bodies from LEO region (Arianne40RB, Cosmos2251, SL8RB, SL14RB and SL16RB) by means of Continuum laser module. Fig. 14 presents a general view of BSLRS with its main elements.
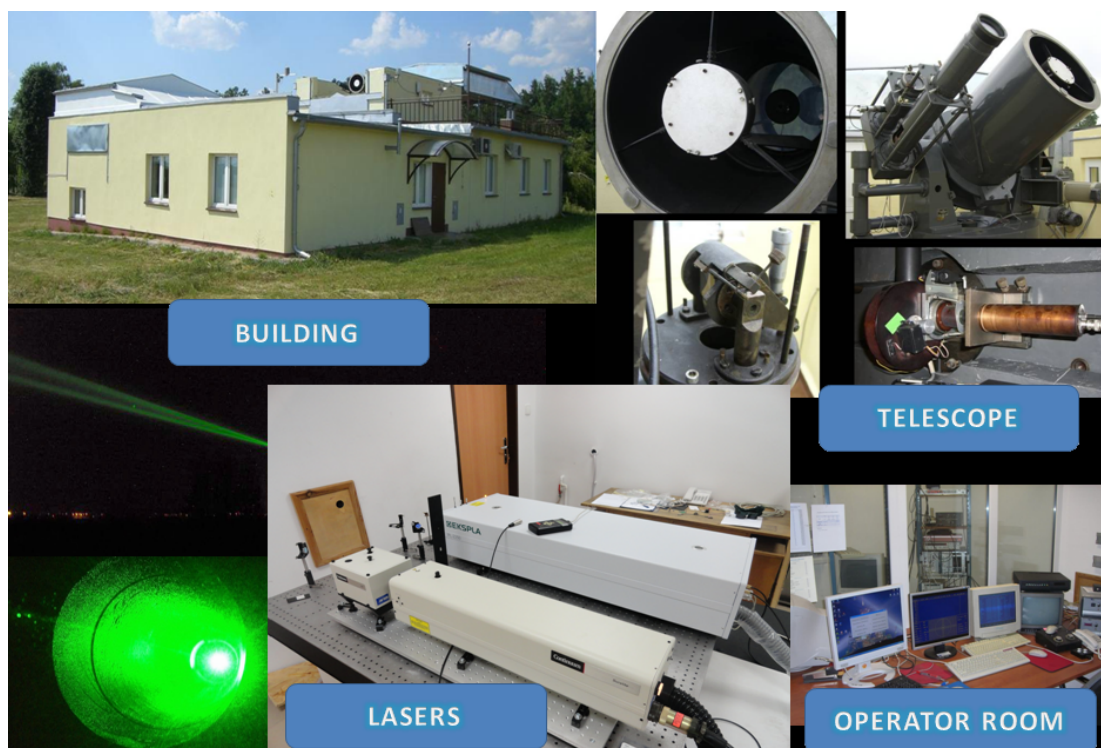
Fig. 14 Borowiec SLR station.

In the year 2014 the Borowiec SLR system was modernized. In the first step two laser modules were installed, the standard unit used for laser observations of all satellites equipped with retroreflectors (EKSPLA PL-2250) and high-energy module (Continuum Surelite III) dedicated to laser observations of space debris (Fig. 15). Additionally, a new optic was replaced in the transmitting-receiving telescope including primary and secondary mirrors of the telescope and special dielectric mirrors transferring laser pulse from laser unit to telescope.

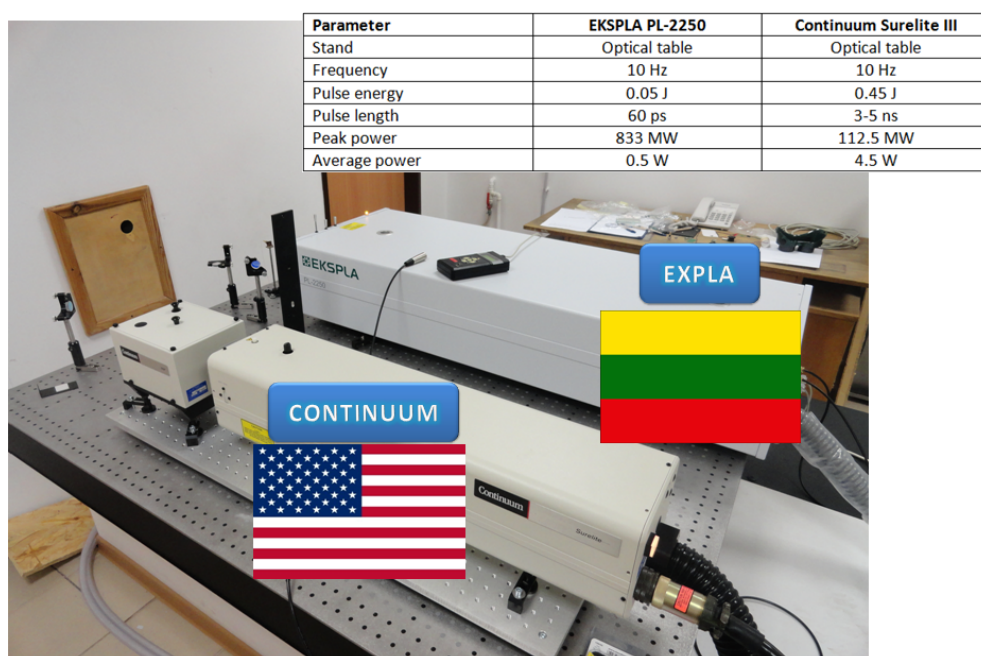| Parameter	EKSPLA PL-2250	Continuum Surelite III
Stand	Optical table	Optical table
Frequency	10 Hz	10 Hz
Pulse energy	0.05 J	0.45 J
Pulse length	60 ps	3-5 ns
Peak power	833 MW	112.5 MW
Average power	0.5 W	4.5 W

Fig. 15 Nd:YAG laser modules installed in Borowiec.

The station is working with two high-energy Nd:YAG pulse laser modules (50 and 450 mJ pulse energy for 532 nm), transmitting-receiving Cassegrain telescope with aperture of 0.65 m (the effective area diameter is 60 cm). The FOV of the main optical system is 5 arcmin. The mount is also equipped with 20 cm guiding Maksutov telescope that enables visual control. Its diameter is 20 cm and FOV of 1 deg.

All observations gathered by BSLRS are sent to three data banks, Crustal Dynamics Data Information System (CDDIS), EUROLAS Data Center (EDC) and Space Debris Data Information System (SDDIS). Since two years the all results obtained by BSLRS are published in real-time on the Borowiec website (http://www.cbk.poznan.pl/stacja_laserowa/lista_obserwacji.php) in the format given in Fig. 16.
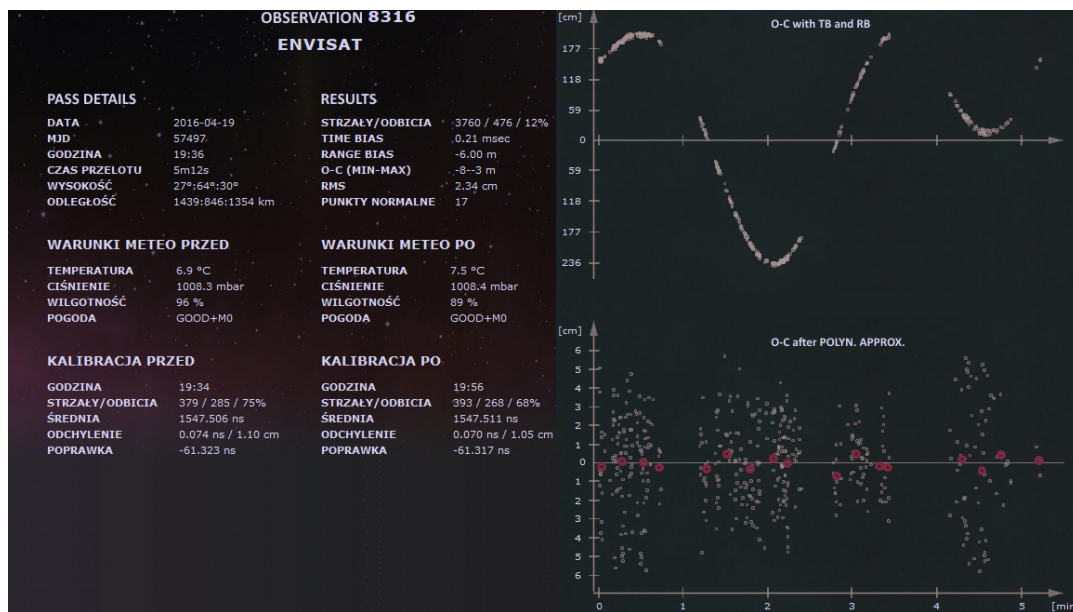

Fig. 16 Sample results of ENVISAT (pass no. 8316) available on BSLRS website.

In 2014 the BSLRS has joined the Space Debris Study Group (SDSG) ILRS and actively participates in development of the Polish SST program. In the last few months, station has participated in several campaigns of space debris objects like ENVISAT, TOPEX/Poseidon, JASON-1. In Fig. 17 the sample results for TOPEX are shown. These results were obtained with EKSPLA laser module.

The altimeter mission of TOPEX/Poseidon (altitude of 1340 km) has ended in January 2006. The satellite is equipped with a retroreflector array ring of 1.5 m diameter which assures high accurate measurements. As a big space junk: the TOPEX platform size is: 5.5 m in length, 6.6 m in height, and 2.8 m in width, span length of 11.5 m; the solar array size is 8.9 m x 3.3 m, the dry mass of the spacecraft is about 2100 kg), TOPEX constitutes a serious threat for active satellites and requires regular observations. During the mission, TOPEX has been nadir stabilized, but after January 2006 the satellite lost the stabilization and started to rotate. The analysis of the data collected during observational campaign points that TOPEX spins with a period of about 11 seconds and its spin period decreases over time. The spin axis of the spacecraft is not stable in space and precesses with a period of about 108 days. In order to obtain as much information as possible about TOPEX spin dynamics a full pass length is needed.
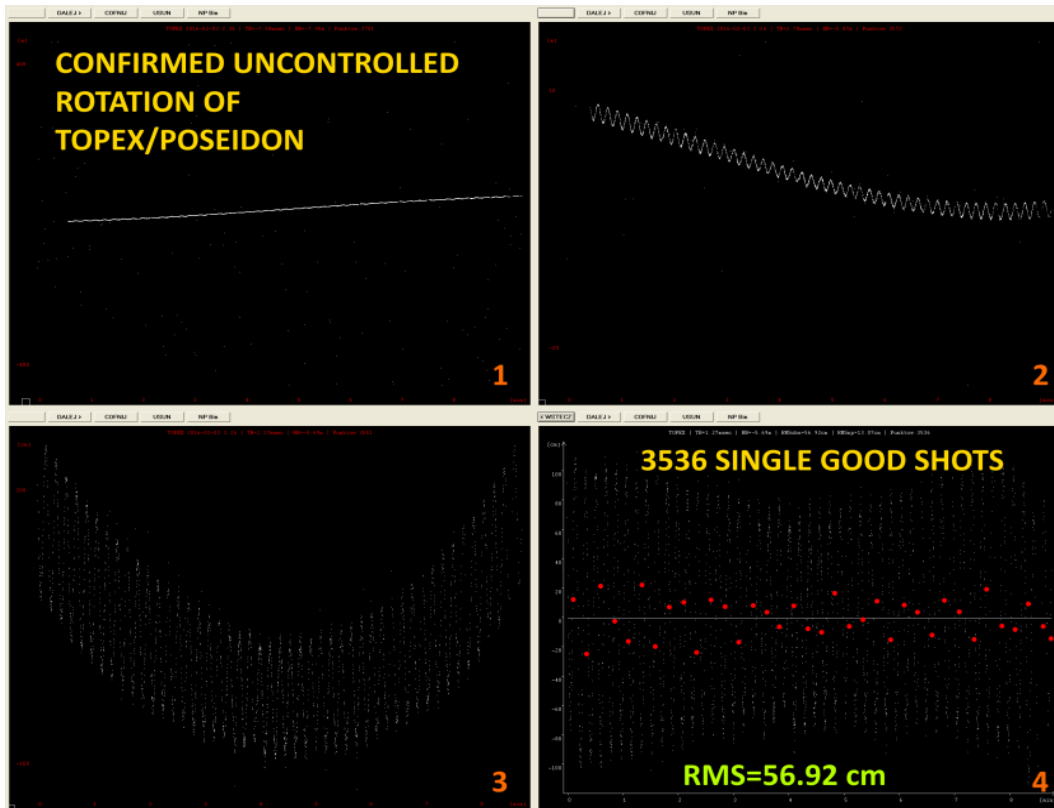
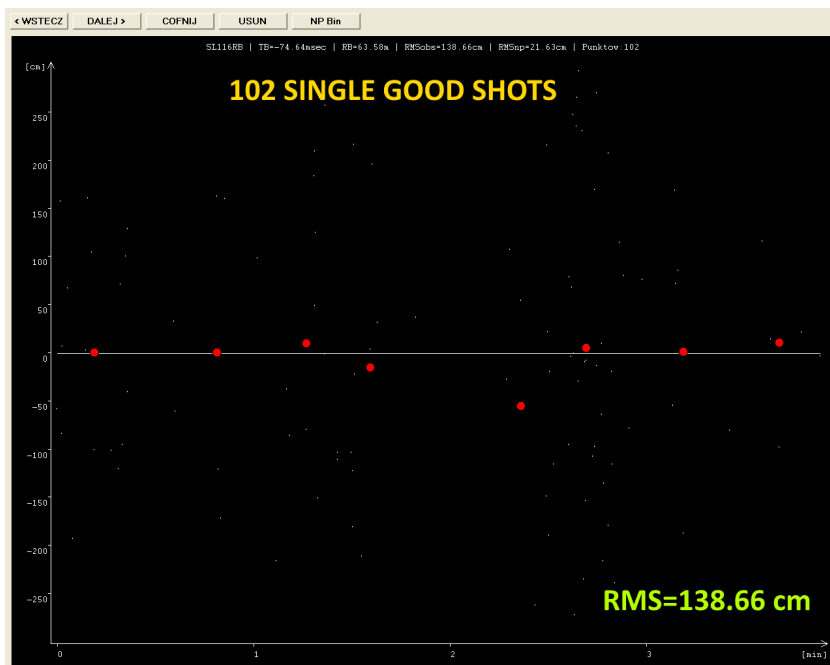Fig. 17 Uncontrolled rotation observed by BSLRS on February 3, 2016.

Fig. 18 Results for SL16RB observed by BSLRS on August 10, 2016.

Fig. 18 shows sample results for SL-16 R/B junk orbiting at an altitude of approximately 850 km. All results obtained by BSLRS confirm that the station is prepared for SST program, the only such group in Poland.

6. REFERENCES

[1] Kozlowski, S. K., Sybilski, P., Konacki, M., Pawłaszek, R. K., Ratajczak, M., Helminiak, K. G. (2014): Solaris: a global network of autonomous observatories in the southern hemisphere. In: Proceedings of the SPIE, Volume 9145, id. 914504 16 pp.

[2] Sybilski, P. W., Pawłaszek, R., Kozlowski, S. K., Konacki, M., Ratajczak, M., Helminiak, K. G. (2014): Software for autonomous astronomical observatories: challenges and opportunities in the age of big data. In: Proceedings of the SPIE, Volume 9152, id. 91521C 14 pp.

[3] Steven Bloemen, Paul Groot, Patrick Woudt, Marc Klein Wolt, Vanessa McBride, et al. (2016): MeerLICHT and BlackGEM: custom-built telescopes to detect faint optical transients, Proc. SPIE 9906, Ground-based and Airborne Telescopes VI, id. 990664

[4] Kozłowski, S. K.; Konacki, M.; Sybilski, P.; Ratajczak, M.; Pawłaszek, R. K.; Hełminiak, K. G. (2016): Spectroscopic Survey of Eclipsing Binaries with a Low-cost Echelle Spectrograph: Scientific Commissioning, Publications of the Astronomical Society of Pacific, Volume 128, Issue 965, pp. 074201

[5] Kozłowski, S. K.; Konacki, M.; Ratajczak, M.; Sybilski, P.; Pawłaszek, R. K.; Hełminiak, K. G. (2014): BACHES - a compact échelle spectrograph for radial-velocity surveys with small telescopes, Monthly Notices of the Royal Astronomical Society, Volume 443, Issue 1, p.158-167