A green observatory in the Chilean Atacama desert

Michael Ramolla[a], Christian Westhues[a], Moritz Hackstein[a], Martin Haas[a], Klaus Hodapp[b], Roland Lemke[c], Angie Barr Domínguez[d], Rolf Chini[a,d], and Miguel Murphy[d]

[a]Astronomisches Institut, Ruhr–Universität Bochum, Universitätsstraße 150, 44801 Bochum, Germany
[b]Institute for Astronomy, 640 North A'ohōkū Place, Hilo, HI 96720-2700, USA
[c]Luftfahrt-Bundesamt, Hermann-Blenk-Straße 26, 38108 Braunschweig, Germany
[d]Instituto de Astronomía, Universidad Católica del Norte, Avenida Angamos 0610, Casilla 1280 Antofagasta, Chile

ABSTRACT

Since 2007, the Ruhr-Universität Bochum (RUB) in Germany and Universidad Católica del Norte (UCN) in Chile jointly operate the Universitätssternwarte der Ruhr-Universität Bochum (USB), which is located in direct neighborhood of the future E-ELT of ESO. It is the only observatory powered exclusively by solar panels and wind turbines. Excess power is stored in batteries that allow uninterrupted operation even in windless nights.

The scientific equipment consists of three robotic optical telescopes with apertures ranging from 15 cm (RoBoTT) over 25 cm (BEST II) to 40 cm (BMT) and one 80 cm (IRIS) infra-red telescope. The optical telescopes are equipped with Johnson and Sloan broad band filters together with a large number of narrow and intermediate bands. In the infrared, J, H and K filters are available, accompanied by several narrow bands near the K band wavelength. The second Nasmyth focus in the 80 cm telescope feeds a high resolution echelle spectrograph similar to the FEROS instrument of ESO. This variety of instruments has evolved from different collaborations, i.e. with the University of Hawaii (IfA) in the USA, which provided the near-infrared-camera of the IRIS telescope, or with the Deutsches Zentrum für Luft- und Raumfahrt (DLR) in Germany, which provided the BEST II telescope. The highly automatized processes on all telescopes enable a single person to run the whole facility, providing the high cost efficiency required for an university observatory.

The excellent site conditions allow projects that require daily observations of astronomical objects over epochs of several months or years. Here we report on such studies of young stellar objects from the Bochum Galactic Disk Survey, the multiplicity of stars, quasar variability or the hunt for exo-planets.

Keywords: Green energy, robotics, observatories, instruments

1. INTRODUCTION

The motivation for an observatory was driven by three issues: i) The Astronomical Institute of the Ruhr-Universität Bochum (AIRUB) became owner of the famous Hexapod-Telescope (HPT) which is a 1.5 m innovative-design instrument built by Vertex Antennentechnik, Germany. Obviously, Bochum is not the ideal site for an observatory which brought up the need for a decent site. ii) Today's observing techniques (e.g. service mode, satellites) as well as the heavy demand for telescope time (factors of five in telescope overbooking are quite common) make it very difficult to train young students at real telescopes and instruments. iii) Eventually, when the project was started twenty years ago, studies of the time domain were rather rare in astronomy, providing a niche for long-term projects.

Bochum has a long history with operating a telescope in Chile. Obviously the 60 cm Bochum telescope at La Silla was the driver to inquire whether this location might be also a potential site for the HPT. However, ESO's offer to host the HPT at La Silla came with an infrastructural fee that was way out of the financial possibilities of the AIRUB. The next mountain under consideration was Cerro Tololo where American colleagues were extremely

Further author information: E-mail: ramolla@astro.rub.de, Telephone: +49 (0) 234 32 23463

obliging in hosting the HPT. This cooperation failed due to a minor juristic detail on the German side. Eventually, the coincidence of a meeting with a former Chilean PhD student, who was meanwhile astronomer at Universidad Católica del Norte (UCN) in Antofagasta, brought Cerro Armazones into focus.

The area around this mountain was lent UCN by the Chilean government as a terrain for scientific investigations. At the geographical location $24°35'53"S, 70°11'47"W$ Cerro Armazones has a smaller side hill of 2817 m which was chosen as the site for our future observatory. In a collaboration with UCN and with the financial support of the Akademie der Wissenschaften und der Künste it was possible to start the construction of the Universitätssternwarte Bochum (USB) in 2005. As soon as the HPT was successfully observing at this excellent site further complementary telescopes were installed to cover a broader range of scientific applications.

Meanwhile the Chilean government has given the Cerro Armazones area to ESO to facilitate the construction of the European Extremely Large Telescope. As a consequence the telescopes of USB have become national telescopes of ESO.

2. OBSERVATORY INFRASTRUCTURE

2.1 Green energy

The exterior structure of the observatory is shown in Figure 1. Clearly visible in the center of the image is the white pyramidal dome of the HPT (Sect. 2.2.5) that opens sideways along a rail structure. Left behind this dome is the main building complex, covered with two fields of photo-voltaic (PV) panels and two roll-off roofs for the BMT (Sect. 2.2.4) and IRIS (Sect. 2.2.3) telescopes. On the right hand side one can see two smaller buildings with roll-off roofs for the BEST II and RoBoTT telescopes. Behind them is the battery house with the third PV field and three wind turbines arranged around it. Below the HPT dome are the habitable containers of the two security guards provided by UCN.

Operation of our equipment during night consumes on average between 2.5 and 4.5 kW, depending on instrument setup and environmental conditions. Mostly, this energy is consumed by the computers and temperature regulation systems of the CCDs and the echelle spectrograph's optical assembly. The ample solar energy available during the day is used for the liquid nitrogen production plant of the IRIS telescope, requiring an average of 6 kW.

The structure of the electric grid is shown in Fig. 2. The three phase AC grid is formed and governed by two independent groups (clusters), each consisting of three inverters*. Two of the inverters serve one phase of the grid. The inverters use a communication interface in order to harmonically regulate the grid parameters, such as frequency, phase and load distribution to the individual clusters. Each inverter is able to supply a permanent load of 3.3 kW and supply a peak load of 7 kW for a short duration of 5 seconds.

Main source of energy at the observatory is solar power. Three PV fields provide a peak electric output of 12.7 kW total. The panels are oriented at an angle of 45° above the horizon northwards. This optimization for winter homogenizes the yield of the solar panels throughout the year, as can be seen in Fig. 3. Three *Sunny Boy* inverters transform the generated power of each PV field to a different phase of our grid. In June the solar electric yield is 65 kWh during a typical day with clear sky. In order to store this energy, we installed 56 valve regulated lead-acid gel (VRLA) batteries†, each providing 3200 Ah at 2 V. The VRLA cells have been chosen because of their excellent durability (design life of 18 years per cell) and because they are maintenance free. The batteries are divided into two equally sized clusters which are connected to the three *Sunny Island* inverters respectively. The inverters regulate frequency, phase and load of the three phase power grid.

Based on a full charge and constant total consumer load of 4 kW, the batteries would theoretically supply the observatory for a total of 90 hours, if no energy were produced. However, if the battery charge falls below 40% an automatic start of an emergency diesel generator will be triggered in order to prevent deep discharge of the batteries. The generator has an electric output of 30 kW. After a warm-up of about 30 seconds, the grid forming inverters adapt frequency and phase of the grid to the generator, so that it can be smoothly connected.

* *SMA Sunny Island 4500*
† *Sonnenschein A600*

Figure 1. The USB as seen from Cerro Armazones.

Further electricity is provided by three vertical rotor wind turbines[‡], having a peak combined power output of 18 kW. The vertical rotor concept was chosen because it has lower maintenance requirements when compared to horizontally rotating wind turbines and they are independent of the wind direction. Figure 4 shows the cumulative time that a specific windspeed was measured during the year 2008. The data was recorded at a height of 3 m over ground. Overplotted in red is the combined power (by design) of all three wind turbines. The turbines are installed on a tower at a height of 10 m over ground. Below 3 m/s windspeed, no energy is produced and above 14.5 m/s, the energy output should remain constant at 18 kW. The figure shows that over half of the time of the year, the output of the turbines should be above 2 kW. During 30% of the time, output should be above 6 kW and for about 10% of the time, the output should be 18 kW.

Since commissioning in 2007, we have produced 234 000 kWh of renewable electric energy, which averages out to 73 kWh per day. Most of the electricity is generated during daytime and stored in our battery clusters. Since conversion efficiency of the inverters is max. 90% and coulombic of the batteries efficiency is around 95%, our liquid nitrogen production plant (6 kW) is ideally used during daytime, avoiding conversion losses.

A solar thermal heating system provides the observatory with warm water. Warm air of our main server room is transported to the living area of the observer by a heat exchange air circulation system. Therefore, no air conditioning system is necessary to cool the computers, while the observer has also less need to heat the rest of the building.

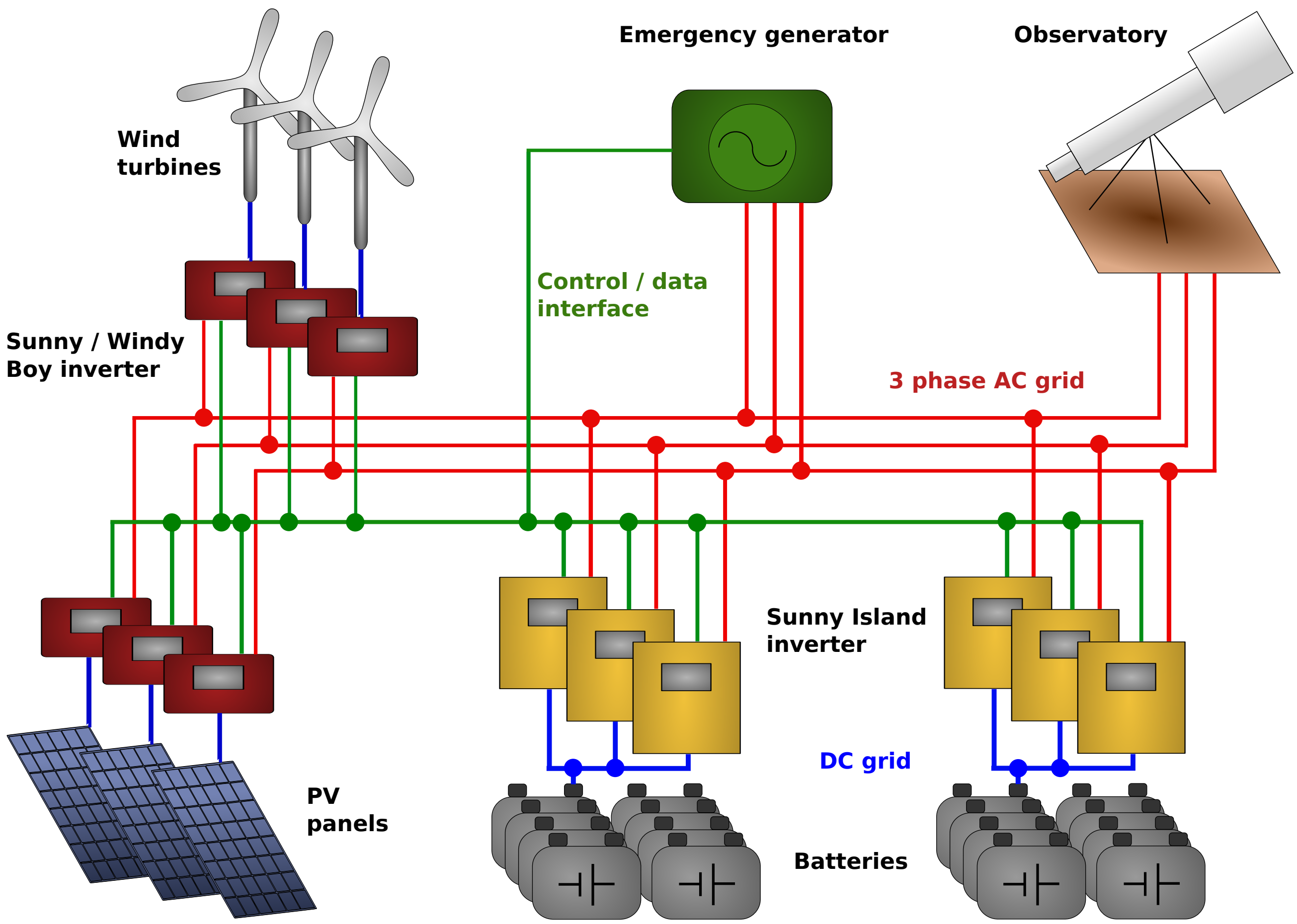

Figure 2. Electric grid infrastructure. Black labels describe device groups. These devices are interconnected by different line types. For clarity, the blue DC grid is represented by a single line and the three AC phases are represented by red lines. Green lines are generalizing all communication paths. Dots mark interconnections of grid lines.

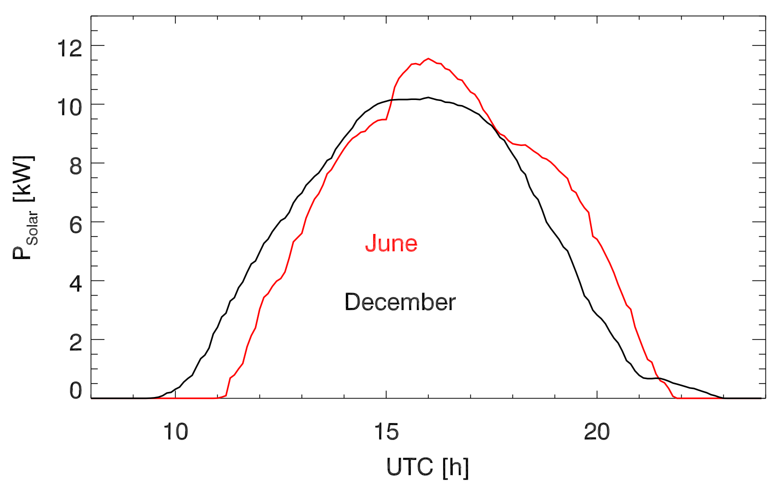

Figure 3. Combined solar power generated by all fields. Data was measured in the year 2011.

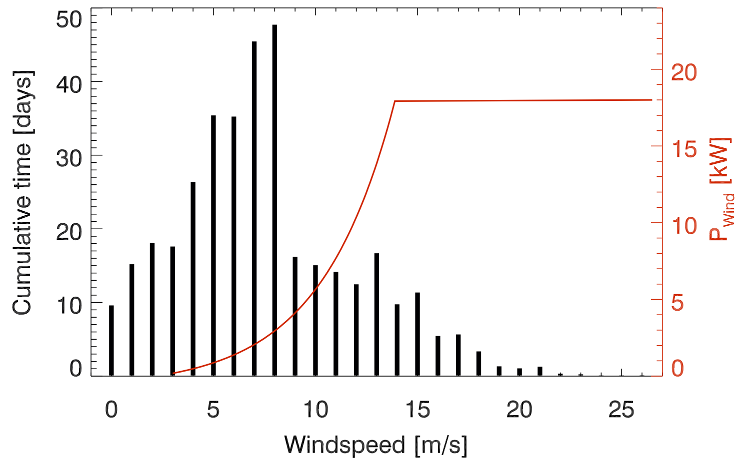

Figure 4. Cumulative windspeed measured over the year 2008. The red overplotted line show the expected total energy production by our three wind turbines.

2.2 Telescopes and instruments

2.2.1 RoBoTT

Formerly known as the VYSOS 6 telescope,[1] the Robotic Bochum Twin Telescope (RoBoTT, Fig. 5, top left) consists of two refractor telescopes (Takahashi TOA 150) attached to the same German equatorial mount. Both refractors are equipped with KAF16801 CCDs. The field of view is $2.7° \times 2.7°$. Both refractors (denoted A/B) have independent filter wheels as shown in Tables 1 and 2. It may be controlled remotely, but is generally used in robotic mode. The telescope is controlled by a custom made Visual Basic script.

2.2.2 BEST II

The Berlin Exoplanet Search Telescope (BEST II, Fig. 5, top right) is a 25 cm aperture Baker-Ritchey-Chrétien system on a German equatorial mount. It was set up by the DLR as ground support telescope for the Corot mission.[2] A KAF16801 4096×4096 pixel CCD is used with $9\,\mu$m pixel size. The field of view is $1.7° \times 1.7°$. Recently the original filter wheel with Johnson B, V, R and I filters was replaced by a new 10 slot filter wheel filled with Sloan and narrow band filters as described in Table 3. It is also remotely accessible and usually run in robotic mode. Telescope control is realized using the *ACP* observatory control software.

2.2.3 IRIS

The Infrared Imaging System[3] (IRIS, Fig. 5, middle left) telescope is mounted on one of the two Nasmyth foci of our 80 cm telescope. The field of view is $12.5' \times 12.5'$ with a pixel size of 0.74" × 0.74". It has a 1024×1024 pixel QIRC[4] near-infrared detector provided by the IfA. The telescope can be operated remotely and is usually controlled by autonomous software. The filter wheel configuration is shown in Table 4. The telescope control software is realized[5] using the component container model of the Alma Common Software[6] (ACS).

2.2.4 BMT

The Bochum Monitoring Telescope[7] (BMT, Fig. 5, middle right) features a 40 cm diameter primary mirror with a SBIG STL-6303 CCD with 3072×2048 $9\,\mu$m pixels in Coudé focus. The resulting field of view is $41.2' \times 27.5'$. The filter wheel is configured with Johnson B and V filters combined with three narrow band filters, as shown in Table 5. It may be operated remotely and is normally used in robotic mode. The control software is also integrated into the ACS[6] framework.

‡ *Ropatec Maxi Vertical*

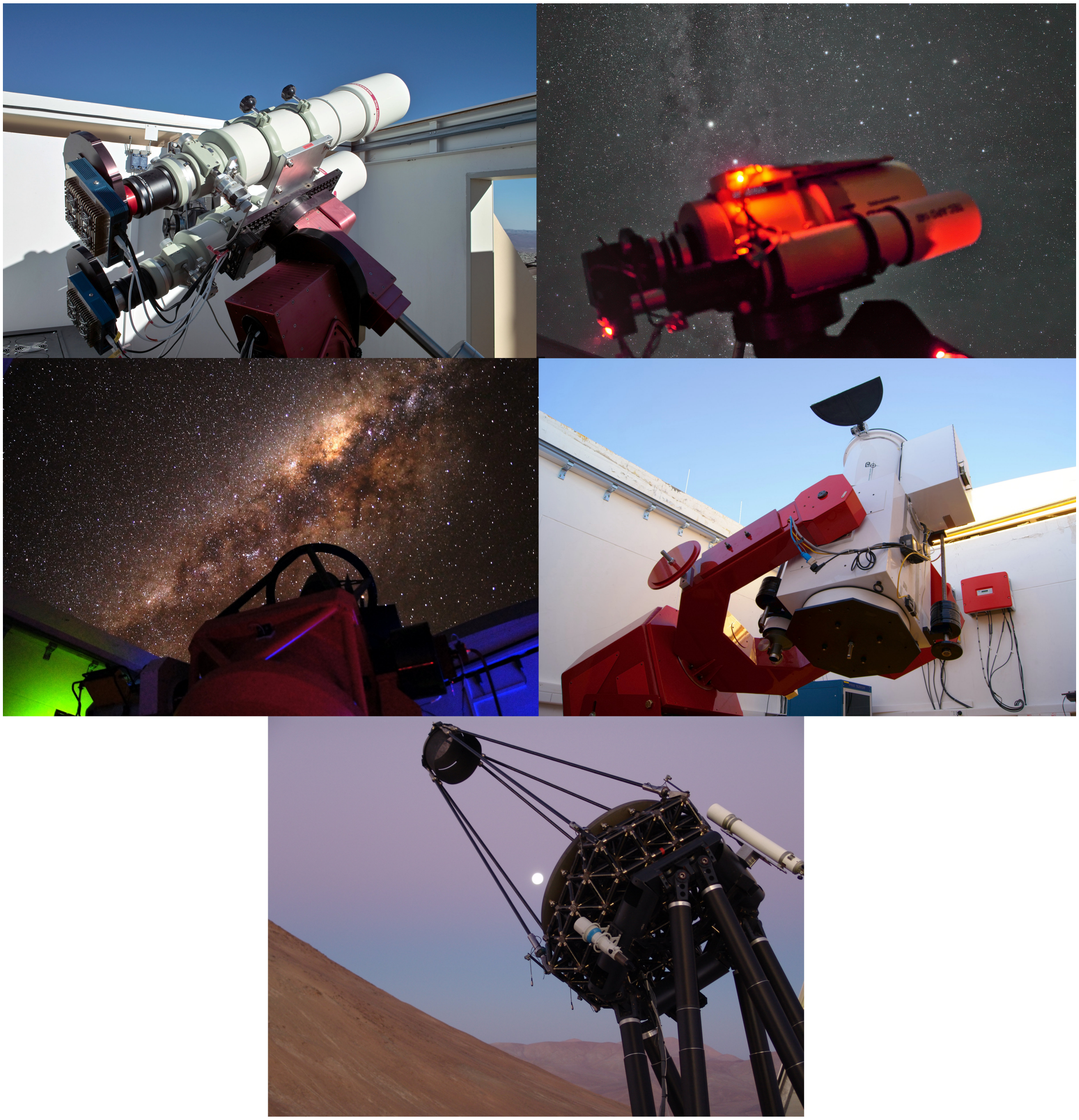

Figure 5. Telescopes at USB. Top left RoBoTT; top right BEST II; middle left IRIS; middle right BMT; bottom HPT.

Table 1. Center wavelength and bandwidth of the filters installed in the RoBoTT telescope A.

Filter	Center wavelength [nm]	FWHM [nm]
U	365	52
V	550	82
R_C	641	158
g'	483	99
i'	767	154
Hα	656.3	6.0
S II	672.1	6.0

Table 2. Center wavelength and bandwidth of the filters installed in the RoBoTT telescope B.

Filter	Center wavelength [nm]	FWHM [nm]
B	445	101
I_C	798	154
u	355	60
r'	626	138
z'	910	137
O III	500.7	6.0
NB	645.0	6.0

2.2.5 Hexapod Telescope

The Hexapod Telescope[8] (HPT, Fig. 5, bottom) features an actively supported 1.5 m primary mirror. It was developed by Vertex Antennentechnik GmbH as a prototype of a large telescope mounted on a hexapod mount. Until 2010 it was used in combination with the BESO spectrograph. Because its operation is not robotic and not feasible by remote access, a second staff observer would be required at the observatory. To reduce maintenance cost, it has been taken out of service. A large part of the control software is integrated into the ACS[6] framework.

Table 3. Center wavelength and bandwidth of the filters installed in the BEST II telescope.

Filter	Center wavelength [nm]	FWHM [nm]
g'	483	99
r'	626	138
i'	767	154
z'	910	137
ASAHI YBPA550	550	10
ASAHI YBPA630	630	12
ASAHI YBPA650	650	12
ASAHI YBPA740	740	12
ASAHI YBPA850	850	12
ASAHI YBPA880	880	12

Table 4. Center wavelength and bandwidth of the filters installed in the IRIS telescope.

Filter	Center wavelength [nm]	FWHM [nm]
J	1235	162
H	1662	251
K	2159	262
Brγ	2167	24
H2 S(1)	2137	20
He I	2180	22
K-cont	2270	53
CO	2300	35

Table 5. Center wavelength and bandwidth of the filters installed in the BMT telescope.

Filter	Center wavelength [nm]	FWHM [nm]
B	436	89
V	545	84
ASAHI YBPA670	670	12
ASAHI YBPA680	680	12
ASAHI YBPA690	690	12

2.2.6 BESO

Mounted to the second Nasmyth focus is the optical fiber entrance to the Bochum Echelle Spectroscopic Observer (BESO) instrument. The telescope can switch between IR imaging and optical spectroscopy within seconds by flipping the M3 mirror. BESO is a clone of the FEROS spectrograph[9] by ESO with a resolution of $\lambda/\Delta\lambda = 48\,000$, covering 370 nm to 860 nm. The optical fiber transports light from source and sky to the spectrograph that is located in a separate air-conditioned room. A robotic calibration unit is currently being commissioned. The telescope uses an automatic guiding system to optimize positioning of the fiber on a star in the focal plane.

3. OPERATION

3.1 Observations

The long-term monitoring campaigns require a continuous operation throughout the whole year. To achieve this goal on low costs the telescope controls are completely automatized. This enables a single observer at site to run the whole observatory. Optimal duty cycles and highest scientific relevance of observations during the night for all telescopes are achieved through pre-defined plans. Staff astronomers at RUB will communicate required observation objectives among our group and external collaborators. Then our staff uses a suite of our astronomical scheduling software to optimally distribute observing loads among the telescopes. Figure 6 shows the average collected science exposure times per month for all our instruments. The values are influenced by length of night, weather conditions and overheads of the equipment.

Throughout the whole year, staff astronomers are stationed at the observatory, changing in a monthly rhythm. Due to the high automatization level this duty can be carried out by students who can be trained in one week. The observer is accommodated directly at the observatory. For this purpose, the main control building includes two dormitories (each with bathroom), a kitchen, a control room and a living room. The major duty of the observer is monitoring of instrument- and environment parameters in order to intervene in case of malfunctions or emerging dangers. Furthermore, he or she may help commission further instrumentation. To support the observer, a weather station and an all-sky fish-eye camera are installed at the observatory. The telescope control

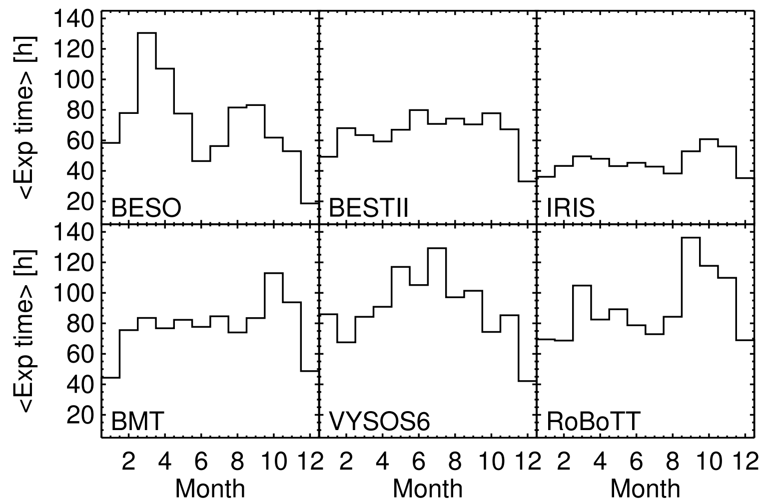

Figure 6. Cumulative exposure time per month. Averaged over all months when the instrument was respectively active. VYSOS 6 was the name of RoBoTT before it became a twin telescope.

software does automatic checks of these sensor parameters as well. For instance, if the wind velocity surpasses a given threshold for the telescope, it will stop observations and move into parking position, without waiting for a reaction of the observer. Whenever economically feasible, spare parts are stored directly at the observatory in order to minimize disturbances in our observing schedules if equipment is damaged.

To guarantee the security of the observer, the UCN stations two guards directly at the observatory, making weekly shifts. They protect the observatory equipment during day, but also take care of the observer should medical emergencies occur.

In principle, the observatory can be run without anyone at site which has already been done in the past due to staff shortage. This is however not desired, because staff at site can respond quickly to upcoming problems in order to ensure the uninterrupted operation of all telescopes. By this strategy all telescope are operating during the whole year from dusk till dawn with little outage due to bad weather or malfunctions since 2010 until now.

3.2 Data management

The robotic observations with the four telescopes produce a daily stock of scientific and calibration images in fits-format which need to be evaluated. The daily production can pile up to tens of GB of raw data which are transferred through the optical gigabit fiber (EVALSO[10]) to the astronomical institute in Bochum. The synchronization already starts during observations, so image quality can be judged within the night. The raw data is archived on distributed servers in a scalable Andrew-File-System (AFS). Also a lossless compressed backup of each raw frame is stored using the fits compression tool *fpack*.[11] From 2008 until now ~ 60 TB of raw data were obtained.

Usually dithered observations are carried out for all telescopes in photometric mode. For the optical telescopes a pipeline reduction was developed within the framework of the Interactive Data Language (IDL). Standard bias-, dark- and flatfield corrections are followed by source extraction, astrometry and resampling, applying tools from *AstrOmatic*[§], such as *SExtractor,*[12] *SCAMP*[13] and *SWarp*[14]. For the infrared observations with IRIS, a special treatment of the images is necessary due to the shutter-less camera and the special conditions at infrared wavelength. In cooperation with IfA, observational sequences and a reduction pipeline were developed in IRAF[¶], IDL, *Python* and using the *AstrOmatic* tools.

The corrected single frames with astrometric solution are stored and co-added (average and min/max rejection) to achieve combined images of photometric quality without biases of cosmic rays or bad pixels on the CCDs.

[§] http://www.astromatic.net/

[¶] Image Reduction and Analysis Facility

An absolute calibration is provided for the optical filters by comparison to standard stars[15] and for the infrared-filters by comparison with the 2MASS catalogue. Airmass dependent extinction, based on the atmospheric profile of Cerro Paranal[16] is taken into account. Intermediate bandpass and narrow-band filters are interpolated by a blackbody-fit to suitable standard stars. The 2d-spectroscopic data, science and calibration frames, from the Echelle-spectrograph BESO are also transferred to Bochum university. A reduction[17] to 1d-spectra and relative flux calibration are achieved within a pipe-lined process written in MIDAS.[18]

4. SCIENTIFIC OBJECTIVES

4.1 Galactic Disk Survey

The Bochum Galactic Disk Survey (GDS) is an on-going long-term project dedicated to recording the light curves of the intermediately bright stellar population ($7\,\text{mag} < r', i' < 18\text{mag}$) across the Galactic plane, and identifying variable sources among these stars. It covers an area of 1323 square degrees between RA 6h42' and RA 19h00', the current coverage is shown in 7. The survey is executed by RoBoTT, recording data with two cameras and filters simultaneously every night. Each camera has a field-of-view of $2°42'$x$2°42'$, hence the GDS coverage is split into 268 observation fields accordingly. Observations are executed robotically at USB and the data is then transferred to and processed at AIRUB by the GDS Analysis and Photometry Pipeline (GDS-APP). Since its beginning in 2010 the GDS has recorded over 400 000 exposures in six filters (U, B, V, r', i', and z') for $\sim 1.6 \times 10^7$ stars. The night-by-night light curve observations are executed simultaneously in the filters i' and r' with 10 s exposure time. The other four filter are only observed sporadically to get a rough SED estimate for each source with an exposure time of 30 s. A more detailed description[1,19] is also available.
From all observed stars $\sim$ 57 000 could be identified as previously unknown variable sources. These sources cover all different types of variable stars, e.g., eclipsing binaries, pulsating stars, novae, or young stellar objects like TTauri stars. The data has already contributed to the research on high-mass binaries and stellar multiplicity,[20,21] as well as star formation. FU-Orionis star V960 Mon has been recorded by the GDS prior to and after its 3 mag outburst,[22] indicating the formation of a young binary star.

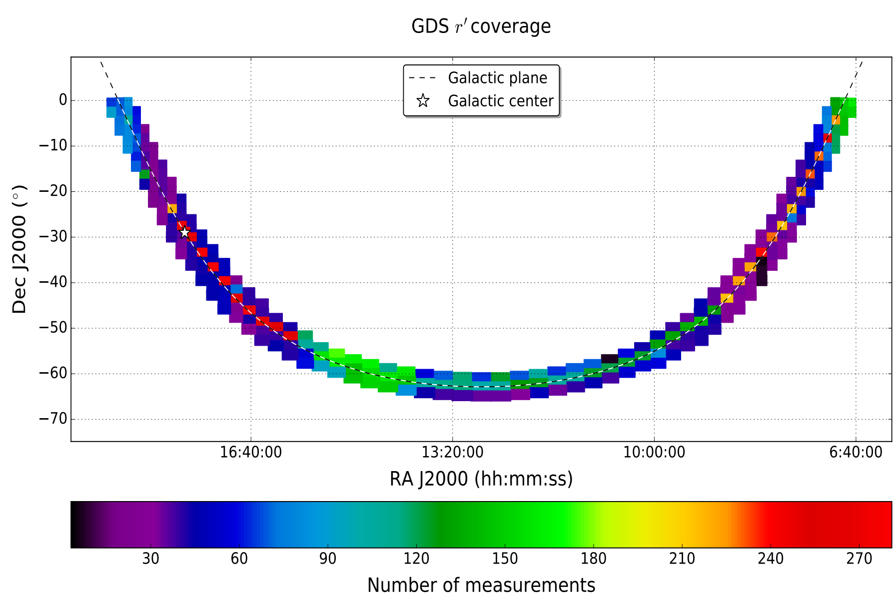

Figure 7. Current r' filter coverage of the GDS. The GDS fields are color-coded according to the number of observation nights for each field.

4.2 Active Galactic Nuclei (Quasars)

The project aims to establish a reliable method for measuring distances to active galactic nuclei (AGN), leading to supernova-independent tests for cosmological models. Active galactic nuclei (AGN) are among the most luminous phenomena in the universe. Many show a variability in brightness driven by the stochastic accretion of matter onto the central black hole. The central region cannot be resolved by current instrumentation, but can be studied by means of the reverberation mapping technique.[23]

Thermal radiation, set free by the hot accretion disk (AD), is reprocessed by gas and dust regions. These regions have characteristic signatures, e.g. broad emission lines of Hydrogen, the so-called broad line region (BLR). The distance of these regions from the nucleus can be inferred from the light travel time that passes until a reprocessed response signal is seen in the emission line. An example of a lightcurve of such a region is found in Fig. 8 (left), where the 680 nm narrow band catches the delayed response of the continuum variation seen in the other bands. The shape of such a response allows us also to determine geometric parameters of the involved regions. Combining this information with the 5100 Å luminosity of the AD, a radius luminosity relationship[24,25] has been found to be $R_{\mathrm{BLR}} \propto L^{\alpha}$ with $\alpha \approx 0.5$.

Such observations were traditionally carried out by spectroscopic instruments on large telescopes. The USB was the first observatory to successfully demonstrate that these observations can instead be carried out photometrically with small telescopes when using suitable broad and narrow band filters. The dense sampling and stable photometric calibration in our data enables us to reduce the scatter in the $R_{\mathrm{BLR}} \propto L^{\alpha}$ relationship, as shown by our results in Fig. 8 (right). Thus, L can be predicted from a measurement of R_{BLR}. If this relationship can be firmly established, also at higher redshifts, it may be used to measure cosmological distances.

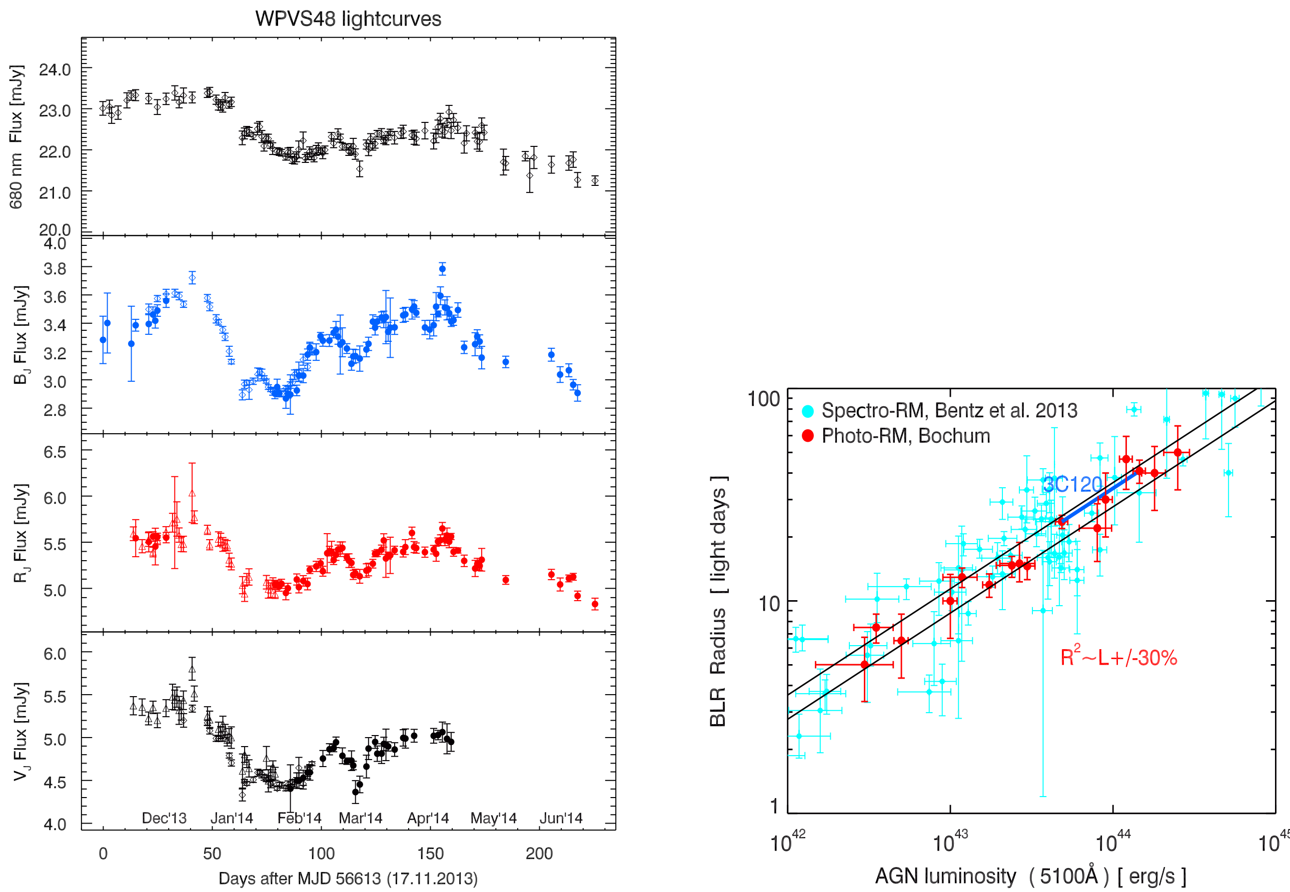

Figure 8. Left: Example data of our AGN lightcurves of WPVS 48 in three optical bands and the 680 nm narrow band filter. Triangles are taken by the RoBoTT, diamonds by the BMT and circles by BEST II. Right: $R_{BLR} \propto L^{\alpha}$ relationship of our photometric reverberation mapping campaign (red points), together with the expected slope $\alpha = 0.5$ and 30% scatter. The light blue data points mark the collection of all previous spectroscopic rev. mapping data.[25] Our 3C120 measurements shift exactly along the slope by a factor 3 between low and high brightness state, as marked in dark blue.

4.3 Multiplicity of Stars

Another ongoing key investigation at the USB is the question of stellar multiplicity as a function of stellar mass. For this purpose a number of spectroscopic and photometric projects have been started some of which will be briefly described in the following:

- O stars – A complete magnitude-limited sample of 249 southern O stars has been monitored with BESO with the aim to detect spectroscopic binaries and to provide an unbiased view about the fraction of multiple high-mass stars. For 137 stars with $V \leq 8\,\mathrm{mag}$ the average binary fraction is 79% (61% SB2, 18% SB1), increasing to even 89% for stars brighter than $V = 6\,\mathrm{mag}$.
- B stars – From 2008 to 2014 580 B stars were observed with BESO; a total of 4019 high-resolution spectra could be secured. The multiplicity rate decreases from 44% (B0 - B2) to 18% (B9 - A4). The sample also contains 75 Be stars of which 65% showed variability within the observing period of six years. More than 20% of the Be stars showed at least one normal B star phase during this time, while other well known Be stars did not show emission lines at all. This leads to the assumption that many B stars pass through a Be phase at least once during their lifetime.
- F stars in the solar neighborhood – Another spectroscopic multiplicity study deals with solar-type stars within 25 pc. This ongoing study revealed a solid increase of the fraction of binary and higher level systems among a subset of 150 F-type stars as a function of the primary mass. There is even the prospect that on account of many companion candidates the single-star fraction may already converge to zero at the transition to the A-type stars.

4.4 Targets of opportunity

Although our observing schedule is never empty, we are open for suggestions for targets of opportunity. In the past, there were a number of requests from the international community for all sorts of observations – optical/infrared photometry or spectroscopy. The various requests comprised FUors, SNs, GRBs, X-ray variables, flare stars and transit events. Of particular interest was the fact that we could flexibly schedule our observations in parallel to any other ground-based and/or satellite observations for dedicated objects or events.

5. EXPENSES

Considering a diesel price of €1 per liter (excluding transportation cost to the observatory) and an average fuel consumption of 6 l per hour by our emergency generator, the total cost of operation for the electric grid of the observatory would have been about €52 000 annually. This does not include the required maintenance of the generator after 50 hours of operation. Based on an initial cost of €250 000 for our renewable energy system, the use of clean energy has already paid off in an economic sense as well.

Most of the currently running costs are spent on staff being stationed at the observatory. Yearly, about €20 000 are spent on flight tickets and transfer of astronomers coming from Bochum. The UCN pays the salaries (€55 000 total) of the two guards stationed at the observatory. Further cost (maintenance, vehicles, water supply) amounts to about €10 000 per year.

6. IMPROVEMENTS

Though the observatory achieved more than its initial goals, there are some aspects of the project that could be optimized, based on the experiences that we made. One of them is the energy powerhouse. Initially, the observatory was planned around the HPT telescope and its requirements in power. The required consumption would be around 3 kW average during night and about 2 kW during daytime. With the factory capacity of the batteries, the depth of discharge would be less than 20% during windless nights, thus guaranteeing maximum lifetime of the VRLA batteries of 18 years. During the first months after commissioning in 2007, the battery capacity dropped dramatically to about 60% of the initial capacity. There were no confirmed malfunctions of the SMA inverters charging and discharging them, so this issue may be related to the climatic conditions at the observatory. Since this time, the capacity has remained stable, despite the fact that the reduced capacity forces us to use deeper discharge cycles (up to 60% discharge) of the batteries in order to run the observatory with clean energy alone. Momentarily, the capacity is about 1660 Ah at 2 V. Shortly after commissioning, other projects from collaborations were integrated into the observatory. This led to a total of four robotic telescopes that are nowadays used instead of the HPT, having different power requirements as well. Using the air conditioning of the spectrograph, the average consumption during night is about 4 kW on average, while during daytime, the production plant of liquid nitrogen uses on average 6 kW with peak power consumption being over 10 kW during startup. Bad weather conditions force us then to use the emergency diesel generator to avoid deep discharges of the batteries and continue observations. We saved about 1.2 kW of constant load by replacing old computer hardware with newer systems that often require only a fraction of energy for the same computing power of machines from a decade ago. Another advantage is that these new computers dissipate much less heat and can be accommodated in fan-less housings, which minimizes dust ingress.

Output of the solar panels is not optimal since the construction company did not align the buildings perfectly to the North–South axis. They are rotated 18 ° to the east instead. This causes the asymmetry of the electric power profile seen in Figure 3.

Wind conditions at our site have been theoretically useful for the chosen design of wind turbines (see Fig. 4). Integrating the recorded wind conditions of 2008 with the expected output power of the turbines, the revenue under ideal conditions would be 36 000 kWh total. The three wind turbines have been installed in accordance with the manufacturer requirements in tower height, distance between the towers, orientation towards average wind directions and local topology at our observatory. However, the total generated energy is much lower than expected. The effective usable windspeed of the turbines is usually only 8 – 12 m/s. Due to the design with three vertically rotating wings, a periodic force is exerted periodically on the tower. If the frequency of this stress is close to the resonance frequency of the tower and its shaking motion reaches a given threshold, an accelerometer on top of the tower triggers an emergency stop of the turbine, blocking a restart for several minutes. The design of the turbine should avoid these situations, but they occur often and prohibit operation at windspeeds > 12 m/s, where energy output would be much better.

The heat exchange air circulation system of the observatory was not working as efficiently as desired. Because of the dry air at our site, (annual average is 20%) heat transport away from the main server to the living rooms was inefficient, so cooler air from the outside must be used for cooling purposes during the warmest days of summer, this will also draw dust into the heat exchanger, requiring frequent exchange of air filters. An air-conditioning system with air moisturizing would probably be more suitable, but also energy intensive. The dust entry to control computers at the telescopes was minimized by utilization of server rack enclosures with air filters.

To reduce cost, the telescope roofs are designed as single roll-off roofs, allowing observations 30 ° above horizon. They can only be opened/closed if the telescope is in parking position. This introduces two disadvantages. First, it must always be made sure that the telescopes are correctly parked. For the BEST II telescope, there is only 2 cm play between roof and telescope. In case of a failure of the power grid, uninterrupted power supplies (UPS) will support the telescopes for a few minutes. Before closing the roof, parking must be initiated and verified before these UPS batteries are exhausted. This poses a risk for remote observations, where one must make sure that measures are taken promptly. Secondly, opening a large roof surface makes the equipment prone to vibrations and increased dust entry during breezy nights. Consequently, strong winds above 15 m/s force us to stop observations. Furthermore, sharp edges of the walls of the building will trigger turbulent motions of air, which is usually lower for a spherical dome with a small window.

7. SUMMARY

The Observatory Cerro Armazones has evolved significantly since start of operations in 2007. Today it is the home of four robotic telescopes, being almost permanently in operation. Using the ideal observing conditions in the Chilean Atacama desert, this allows research in time domain astronomy; doing long-term monitoring of astronomical objects with daily sampling.

Until now, the facility stands alone as the only clean energy observatory in the world. Yet we demonstrate that operations are not only possible with minimum maintenance effort, but also with economic efficiency.

There remain challenges and optimization potential, as the observatory has been growing and due to our limited resources. For the future we aim to improve energy efficiency and expand instruments and infrastructure accordingly. Since observing time is shared between all collaborators, a more flexible central scheduling database with web access would be desirable, distributing the observing requests optimally between instruments. This could be linked to our pipeline data products in the archive.

Many of the scientific projects we presented before are still ongoing and accompanied by new upcoming research. However, continuation of operations in the future requires additional funding, perhaps from new partners in our collaboration.

ACKNOWLEDGMENTS

This project was supported by the Nordrhein–Westfälische Akademie der Wissenschaften und der Künste in the framework of the academy program by the Federal Republic of Germany and the state Nordrhein-Westfalen. We are grateful to Bo Reipurth, IfA Hawaii, for his technical support. This work is supported by the DFG Program (HA 3555/12-1). The observations on Cerro Armazones benefited from the care of the guardians Hector Labra, Gerardo Pino, Roberto Munoz, and Francisco Arraya.

REFERENCES

[1] Haas, M., Hackstein, M., Ramolla, M., Drass, H., Watermann, R., Lemke, R., and Chini, R., "The Bochum survey of the southern Galactic disk: I. Survey design and first results on 50 square degrees monitored in 2011," *Astronomische Nachrichten* **333**, 706 (Oct. 2012).

[2] Kabath, P., Erikson, A., Rauer, H., Pasternacki, T., Csizmadia, S., Chini, R., Lemke, R., Murphy, M., Fruth, T., Titz, R., and Eigmüller, P., "Periodic variable stars in CoRoT field LRa02 observed with BEST II," *A&A* **506**, 569–587 (Oct. 2009).

[3] Hodapp, K. W., Chini, R., Reipurth, B., Murphy, M., Lemke, R., Watermann, R., Jacobson, S., Bischoff, K., Chonis, T., Dement, D., Terrien, R., Bott, K., and Provence, S., "Commissioning of the infrared imaging survey (IRIS) system," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **7735**, 1 (July 2010).

[4] Hodapp, K.-W., Hora, J. L., Hall, D. N. B., Cowie, L. L., Metzger, M., Irwin, E., Vural, K., Kozlowski, L. J., Cabelli, S. A., Chen, C. Y., Cooper, D. E., Bostrup, G. L., Bailey, R. B., and Kleinhans, W. E., "The HAWAII Infrared Detector Arrays: testing and astronomical characterization of prototype and science-grade devices," *New A* **1**, 177–196 (Oct. 1996).

[5] Westhues, C., Ramolla, M., Lemke, R., Haas, M., Drass, H., and Chini, R., "ACS (Alma Common Software) operating a set of robotic telescopes," in [*Software and Cyberinfrastructure for Astronomy III*], *Proc. SPIE* **9152**, 915210 (July 2014).

[6] Chiozzi, G., Jeram, B., Sommer, H., Caproni, A., Plesko, M., Sekoranja, M., Zagar, K., Fugate, D. W., Di Marcantonio, P., and Cirami, R., "The ALMA common software: a developer-friendly CORBA-based framework," in [*Advanced Software, Control, and Communication Systems for Astronomy*], Lewis, H. and Raffi, G., eds., *Proc. SPIE* **5496**, 205–218 (Sept. 2004).

[7] Ramolla, M., Drass, H., Lemke, R., Westhues, C., Pozo Nuñez, F., Barr Dominguez, A., Haas, M., Chini, R., and Murphy, M., "The 40 cm Monitoring Telescope of the Universitätssternwarte Bochum," *Astronomische Nachrichten* **334**, 1115 (Dec. 2013).

[8] Chini, R., "The Hexapod Telescope – A Never-ending Story," in [*Reviews in Modern Astronomy*], Schielicke, R. E., ed., *Reviews in Modern Astronomy* **13**, 257–268 (2000).

[9] Kaufer, A., Stahl, O., Tubbesing, S., Nørregaard, P., Avila, G., Francois, P., Pasquini, L., and Pizzella, A., "Commissioning FEROS, the new high-resolution spectrograph at La-Silla.," *The Messenger* **95**, 8–12 (Mar. 1999).

[10] Lemke, R., Comeron, F., Chini, R., Filippi, G., Emerson, J., Kuijken, K., Dobrzycka, D., Wright, A., Zampieri, S., and Liello, F., "EVALSO, a high-bandwidth communication infrastructure to efficiently connect the ESO Paranal and the Cerro Armazones Observatories to Europe: demonstration activities and start of operations," in [*Software and Cyberinfrastructure for Astronomy II*], *Proc. SPIE* **8451**, 84511G (Sept. 2012).

[11] Pence, W. D., Seaman, R., and White, R. L., "Lossless Astronomical Image Compression and the Effects of Noise," *PASP* **121**, 414–427 (Apr. 2009).

[12] Bertin, E. and Arnouts, S., "SExtractor: Software for source extraction.," *A&AS* **117**, 393–404 (June 1996).

[13] Bertin, E., "Automatic Astrometric and Photometric Calibration with SCAMP," in [*Astronomical Data Analysis Software and Systems XV*], Gabriel, C., Arviset, C., Ponz, D., and Enrique, S., eds., *Astronomical Society of the Pacific Conference Series* **351**, 112 (July 2006).

[14] Bertin, E., Mellier, Y., Radovich, M., Missonnier, G., Didelon, P., and Morin, B., "The TERAPIX Pipeline," in [*Astronomical Data Analysis Software and Systems XI*], Bohlender, D. A., Durand, D., and Handley, T. H., eds., *Astronomical Society of the Pacific Conference Series* **281**, 228 (2002).

[15] Landolt, A. U., "UBVRI photometric standard stars in the magnitude range 11.5-16.0 around the celestial equator," *AJ* **104**, 340–371 (July 1992).

[16] Patat, F., Moehler, S., O'Brien, K., Pompei, E., Bensby, T., Carraro, G., de Ugarte Postigo, A., Fox, A., Gavignaud, I., James, G., Korhonen, H., Ledoux, C., Randall, S., Sana, H., Smoker, J., Stefl, S., and Szeifert, T., "Optical atmospheric extinction over Cerro Paranal," *A&A* **527**, A91 (Mar. 2011).

[17] Fuhrmann, K., Chini, R., Hoffmeister, V. H., Lemke, R., Murphy, M., Seifert, W., and Stahl, O., "BESO échelle spectroscopy of solar-type stars at Cerro Armazones," *MNRAS* **411**, 2311–2318 (Mar. 2011).

[18] Banse, K., Crane, P., Grosbol, P., Middleburg, F., Ounnas, C., Ponz, D., and Waldthausen, H., "MIDAS - ESO's new image processing system," *The Messenger* **31**, 26–28 (Mar. 1983).

[19] Hackstein, M., Fein, C., Haas, M., Ramolla, M., Pozo Nuñez, F., Barr Domínguez, A., Kaderhandt, L., Thomsch, K., Niedworok, N., Westhues, C., and Chini, R., "The Bochum Survey of the Southern Galactic Disk: II. Follow-up measurements and multi-filter photometry for 1323 square degrees monitored in 2010 - 2015," *Astronomische Nachrichten* **336**, 590–603 (Aug. 2015).

[20] Kaderhandt, L., Barr Domínguez, A., Chini, R., Hackstein, M., Haas, M., Pozo Nuñez, F., and Murphy, M., "Variable stars in the Bochum Galactic Disk Survey," *Astronomische Nachrichten* **336**, 677 (Sept. 2015).

[21] Barr Domínguez, A., Chini, R., Pozo Nuñez, F., Haas, M., Hackstein, M., Drass, H., Lemke, R., and Murphy, M., "Eclipsing high-mass binaries. I. Light curves and system parameters for CPD - 51° 8946, PISMIS 24-1, and HD 319702," *A&A* **557**, A13 (Sept. 2013).

[22] Hackstein, M., Haas, M., Kóspál, Á., Hambsch, F.-J., Chini, R., Ábrahám, P., Moór, A., Pozo Nuñez, F., Ramolla, M., Westhues, C., Kaderhandt, L., Fein, C., Barr Domínguez, A., and Hodapp, K.-W., "Light curves of the latest FUor: Indication of a close binary," *A&A* **582**, L12 (Oct. 2015).

[23] Peterson, B. M. and Horne, K., "Echo mapping of active galactic nuclei," *Astronomische Nachrichten* **325**, 248–251 (Mar. 2004).

[24] Kaspi, S., Smith, P. S., Netzer, H., Maoz, D., Jannuzi, B. T., and Giveon, U., "Reverberation Measurements for 17 Quasars and the Size-Mass-Luminosity Relations in Active Galactic Nuclei," *ApJ* **533**, 631–649 (Apr. 2000).

[25] Bentz, M. C., Peterson, B. M., Netzer, H., Pogge, R. W., and Vestergaard, M., "The Radius-Luminosity Relationship for Active Galactic Nuclei: The Effect of Host-Galaxy Starlight on Luminosity Measurements. II. The Full Sample of Reverberation-Mapped AGNs," *ApJ* **697**, 160–181 (May 2009).