Contrib. Astron. Obs. Skalnaté Pleso **53/4**, 49 – 61, (2023)
https://doi.org/10.31577/caosp.2023.53.4.49

D50: Autonomous robotic telescope in Ondřejov

J. Štrobl[1], M. Jelínek[1], C. Polášek[1] and R. Hudec[1,2]

[1] *Astronomical Institute of the Czech Academy of Sciences, Ondřejov, Czech Republic*

[2] *Czech Technical University in Prague, Prague, Czech Republic*

Received: August 21, 2023; Accepted: November 2, 2023

Abstract. The D50 is an autonomous robotic telescope, located at the Ondřejov observatory in the Czech Republic. Completed in 2007, the telescope's primary purpose was and is to respond to gamma-ray burst detections. After several years of use, some parts of the telescope have been redesigned to be more reliable and better suited to its primary purpose. In addition, the telescope serves as a testbed for development and student projects, so it is continuously being improved in hardware and software. We present the current status and parameters of the telescope as well as the level of data processing automation we have achieved.

Key words: gamma rays: bursts – instrumentation: miscellaneous – telescopes

1. Introduction

The D50 telescope is located at the Ondřejov observatory in the Czech Republic, at coordinates 49.909376N 14.781358E, at an altitude of 527 m above sea level.

In 1996 we started to develop and use a new small robotic telescope BART (Štrobl et al., 2019), primarily for the observation of optical counterparts of gamma-ray bursts (GRBs). Due to the relatively low accuracy of the localization of GRBs, the telescope was equipped with a wide-field camera, and the automatic control software allowed for a prompt response to the detection transmitted by the GCN network (Barthelmy, 2008).

Long before the discovery of the first optical detection of GRBs (GRB 970228, van Paradijs et al. 1997), many scientists expected for various reasons GRBs to be accompanied by low-energy emissions, including optical light. The scientists at the High Energy Astrophysics Group of Astronomical Institute CAS in Ondřejov were involved in various projects searching for these optical emissions, both using historical records as well as follow-up coverage by photographic telescopes without obvious success (Hudec, 1995; Greiner et al., 1995), probably due to both the low accuracy of old GRB localizations and to improper expectations about GRB recurrences.

The BART telescope was one of the first robotic instruments devoted to automatic alert observations of GRBs. Its early stages were related to the work of

Martin Jelínek and Petr Kubánek (Jelínek, 2002; Kubánek, 2003). The BART concept and idea were later adopted in an international collaboration with the Spanish team of the BOOTES project (Jelínek et al., 2016; Castro-Tirado, 2011) that began with RT installations in Spain and later extended worldwide (Castro-Tirado et al., 1999). The development and operation of the BART RT represented one of the key projects of the HEA group in Ondřejov, in addition to investigations of galactic and extragalactic high-energy sources and participation in various space projects.

A few years later, thanks to the new generation of GRB-detecting satellites (INTEGRAL, Swift) that could localize bursts much more precisely, ground-based follow up no longer needed the wide field-of-view that favoured smaller instruments. At the same time, there turned out to be very few bright GRBs, so something much bigger was obviously needed.

We used a funding opportunity for revitalizing the older, unused observatory equipment to build a new instrument. The older components (dome and mount) were refurbished and robotized. The body of the main telescope was built new (on order by an external supplier), and the primary mirror was made at the observatory by Cyril Polášek.

As a result, we got a new, suitable telescope for a very reasonable price. The first light of the D50 telescope was achieved in 2007, and regular observing followed (Nekola et al., 2010).

Operating experience soon showed reliability problems and inadequate performance (including the movement speed of the mount, but other parameters also). Most of these problems were eliminated during an additional reconstruction in 2012. Even since then, however, the configuration has never remained stable for long - the telescope has been gradually changed and improved, as it functions as a test facility for both hardware and software development, often carried out by students.

The telescope is cost-effective, yet progressive and inventive. Although it is based on old components and related technologies, it uses unconventional solutions and approaches.

2. Physical specifications

2.1. Optics and CCD

The optical design of the telescope is a Newtonian reflector with a field corrector. The primary mirror has a diameter of D = 500 mm and a focal length of f = 1975 mm. The flat secondary mirror has a diameter (i.e. the minor axis the ellipse) of 100 mm. The optical system further comprises a field corrector Tele Vue Paracorr PSB-1100, which extends the focal length of the whole system to $f_{eff} = 2277$ mm.

As a camera we use Andor iXon Ultra 888, model DU-888U3-CS0-BVF. It has a back-illuminated EMCCD chip with 1024×1024 pixels, and a pixel size

Figure 1. Photos showing the initial (left) and current (right) state of the D50 telescope.

of $13 \times 13\,\mu$m. This setup provides a field of view of 20' × 20' and a resolution of 1.18 arcsec per pixel. The chip has a visual-light optimized coating and also uses "Fringe Suppression" technology to reduce fringing. In addition to excellent parameters (cooling 95 °C below ambient, low readout noise, high quantum efficiency $QE_{MAX} \approx 95\,\%$), the camera can also use unique readout modes enabled by electron-multiplying (EM) technology. For normal observations we usually use the non-EM amplifier with 1 MHz readout rate, 16-bit, which gives gain of $0.81\,e^-$ per A/D count and single pixel noise of $4.63\,e^-$.

2.2. Focuser and filter wheel

We use a modified digital filter wheel from Moravian Instruments, containing SDSS g′, r′, i′, z′ filters. One position is left empty for unfiltered observations.

For focusing the telescope, we use a custom-made digital focuser, to bear the camera's considerable weight. The assembly also includes an additional dew-protection cover for the camera.

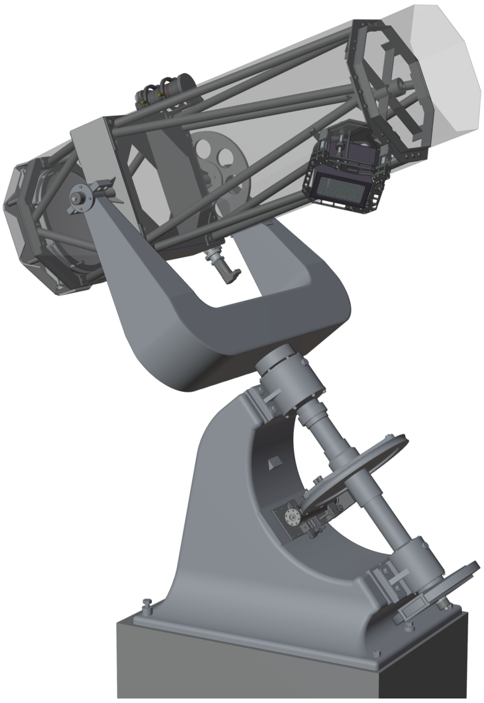

Figure 2. The internal arrangements of the D50 telescope, with the duralumin covers shown translucent. The covers of the worm drives of both axes are omitted.

2.3. OTA and mount

The telescope tube is a steel truss structure composed of tubes and profiles. It is relatively heavy but rigid, its shape is optimized to minimize flexure. The design and initial construction was carried out by AstroLab, a small consortium of specialists. Optical shielding is provided by covers made of duralumin sheets.

The mount is the telescope's oldest component, made in the 50's to carry the large wide-field Richter-Slevogt camera similar to one still in use at the Crimean Observatory (Terebizh, 2011). This camera was later damaged and replaced by another instrument for solar observations, then around 2000 the mount became available and was used (on the same site) for the construction of the D50 telescope.

The mount is a massive wide fork mount, made of steel. Each axis is driven by a servo motor through a worm drive and gearbox. The servos have an internal resolver, which is used for feedback positioning. Specifically, we use TGT2-0060-30-24/T1KX-2M 24 V AC synchronous motors, driven by TGA-24-9/20-04 servo

Table 1. Mechanical and performance parameters of both axes.

axis	gear ratio	v_{max}	acceleration	deceleration
RA	1:2304	$10.0\,^\circ s^{-1}$	$0.8\,^\circ s^{-2}$	$0.8\,^\circ s^{-2}$
Dec	1:4000	$5.5\,^\circ s^{-1}$	$1.8\,^\circ s^{-2}$	$0.9\,^\circ s^{-2}$

controllers (both produced by TG Drives).

The goal was to achieve the highest possible speeds of movement, and the selection of motor and gear ratio was adapted to this. In order to reduce gear wear at higher speeds in the RA axis, we use electromagnetically driven pressure control of the worm.

As a result, we achieve a movement speed of up to $10\,^\circ s^{-1}$ in the RA axis ($5.5\,^\circ s^{-1}$ in the Dec axis respectively, more detailed values are given in Tab. 1), which can be considered satisfactory for this mechanical setup and such a massive construction. These speeds are used only for GRBs observations, when slewing time must be reduced as much as possible. For normal operations we use a less demanding max. speed of $5.0\,^\circ s^{-1}$.

This wide range of required speeds led to insufficiently subtle control at slow speeds (e.g. during sidereal tracking). We solved the problem by switching the servo controller to its "stepper motor" mode, driven by pulses provided externally. In addition to this mode change, we also dynamically change the controller's PID feedback parameters as needed - looser when moving fast, tighter when tracking.

During the reconstruction in 2012 we paid great attention to reducing the periodic error in the RA axis. Despite a considerable improvement thanks to the new brushed worm, it still remains significant: a peak to peak amplitude of $\approx$7 arcsec, over a period of 3 minutes.

To ensure reliability, both axes are equipped with independent, on-axis optical position encoders, specifically ARC 425 13PA (produced by LARM), which are 13 bit resolution devices, providing 2.6 arcmin accuracy. These provide independent confirmation of the actual mount position, used by high level software checking.

The assembly further uses REMOTES drive units (Jakubec et al., 2012). This is a unique, sophisticated and tailor-made solution for controlling the entire observatory with a complex system of fail-safe mechanisms. Currently only the low-level functions of the system are deployed, to control the worm pressure, to generate the pulses for the RA servo in its stepper motor mode, and to read the position encoders. All its parameters can be changed dynamically, which is mainly used for changes in tracking speed when autoguiding is in progress.

2.4. Auxiliary devices

To enable long exposures, an autoguider was necessary, and for this we mounted a separate external instrument, based around an MC Rubinar 500 mm f/ 5.6 photographic mirror lens, D $\approx$ 10 cm, $f = 500$ mm, an MI (Moravian Instruments) C1-5000 camera and a FLI digital focuser. Since the camera lacks a shutter, we provide a custom-built external shutter, whose electronics also provide information about temperature and humidity inside and outside of the main telescope.

2.5. Dome

The dome is another old and refurbished component, wooden with a steel sliding roof. The roof mechanism is now motorized, controlled from the driving PC. This configuration is very cramped when closed - the telescope must be parked before the roof can close - and unfortunately the open roof also partially restricts the movement of the telescope in the northern parts of the sky. This is why we are considering replacing the dome with a new, less restrictive solution in the future.

2.6. Enviromental sensors

We use set of meteorological sensors, shared by both the D50 and BART telescopes: an anemometer, a thermometer-and-hygrometer, rain sensors and cloud detectors. The anemometer and the rain sensors are professional products (made by Meteoservis and MIRES CONTROL), while the remaining sensors, especially two different versions of the cloud detectors are the result of an experimental open-hardware project MLAB (Horkel et al., 2003). In addition to these shared sensors, the D50 has local sensors measuring temperature and humidity in the dome and also inside the telescope.

Usage of the sensor values is simple - there are distinct threshold values for good and bad weather, and a delay interval for the transition from bad to good weather to prevent oscillation. The telescope will only observe if all sensors show fair weather.

3. Software equipment

3.1. Observatory control system

The entire autonomous observatory is driven by the RTS2 (Kubánek, 2010) robotic observatory control system, running on an ordinary PC. Originally written for the BART telescope, it is now used by various telescopes around the world, but the Ondřejov telescopes still serve as its primary development environment.

The RTS2 system is designed in a very general way to allow modifications according to the requirements of a specific telescope. For the D50 telescope we use a number of locally specific features. The mount driver is particularly advanced - for example, before any movement, we search for a safe path between the current and new position, so as not to enter the forbidden zones defined by the proximity of the dome and its roof (taking into account its state, so the telescope can be safely manipulated even when the dome is closed). The movement is planned and implemented with respect to the properties of the RTS2 system - using a sequence of successively changed target positions for individual servos so that the duration of the movement is as short as possible and yet everything is safe, i.e. no collision occurs even in case of any postponement in the sequence. We call this the "Successive Safe Points" method.

The mount-driver uses the TPoint system (Wallace, 1994) to improve pointing accuracy. And we use the standard Debian Linux distribution as an operating system.

3.2. Automated data processing

Images are automatically matched to the catalogue immediately, as part of RTS2's acquisition process, so that the detected position can be used as feedback for the mount position. This step is carried out using a script to control the Astrometry.net (Barron et al., 2008) software package. As a result, we can normally assume all our images have correctly filled WCS data in their FITS headers.

The next stage of automatic processing follows within minutes: after the application of the basic calibrations (master versions of dark frame and flatfield), all stars are found and photometrically measured in each image. The photometric calibration is then performed by fitting according to the catalogue and all photometric measurements (of all stars in the image) are then stored in the database. The automated image-processing pipeline is written in Python and uses the IRAF (Tody, 1993) and SExtractor (Bertin & Arnouts, 1996) software packages.

4. Observational plan

4.1. General considerations and strategies

As mentioned before, the primary mission of the telescope is to promptly react to GRB detections and to try to observe their optical counterparts in both their early and later phases. However, as GRBs are not very frequent, most of the observational time is spent observing other targets, typically cataclysmic variable stars (CVs), blazars/AGNs and others. The telescope also functions as a ground segment for INTEGRAL and Gaia space missions, which implies occasional simultaneous/campaign observation, as well as subsequent observation and long-term monitoring of objects of interest.

4.2. Per-night target selections and scheduling

The RTS2 system currently allows two internally defined approaches - either automatically select a target from the database according to the simple internal priority system (based on interval since last observation, zenith distance, etc.) and bonus ratings, along with per-target boundary conditions for observation. Or alternatively, to use a system of priority queues, where after the highest queue has been emptied of observable targets, the next queue is approached for observation, and so on.

At the D50 telescope, we use the latter approach - the system of queues, which are automatically filled by a daily script launched by the Unix system cron service. We use this to maintain a group of objects to be observed once per night (and removed from the queue after observation), and a group that is renewed once every 10 days. In addition, there are bottom queues, containing targets for repeated observations, where targets are not removed after observation, and so get observed repeatedly until some object from a higher queue becomes available. At the top of the queue hierarchy there are the queues for recent GRBs and for manual or campaign observations. This approach provides natural control matching what we want to do, and ensures the telescope is always doing something useful.

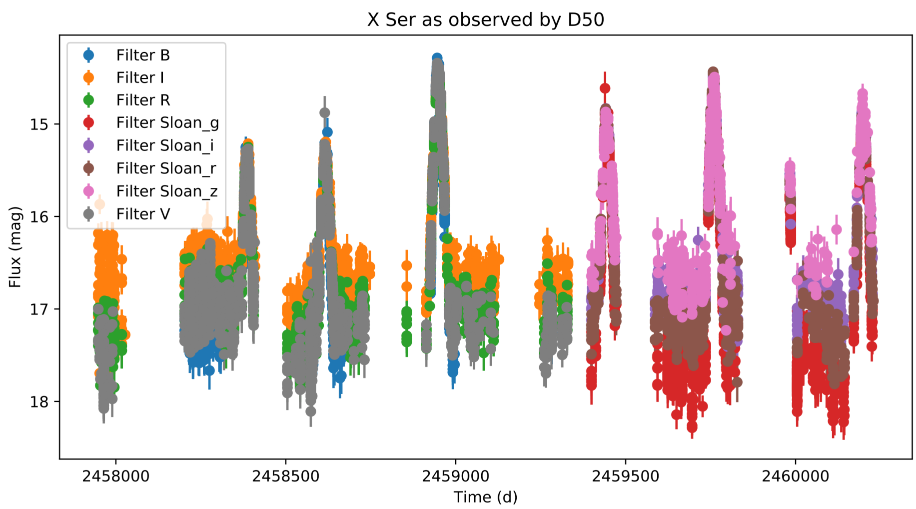

Figure 3. The light curve of the variable star X Ser, observed with the D50 telescope, generated via a web interface from a database of automatically processed data.

5. Results

5.1. Direct results

So far, we have been lucky to observe multiple GRBs, including several really interesting ones. For example, the very bright GRB 210619B with prominent reverse-shock (Oganesyan et al., 2023) or GRB 190919B with an unusual light curve, which we suspect is the result of a combination of two peaks (Jelínek et al., 2022).

We have also observed several very interesting secondary targets. For example, the blazar OJ 287, a supermassive black hole (SBH) binary, where brightenings are caused by the interference of the secondary SBH with the accretion disc around the primary SBH (Valtonen et al., 2023). Another example is the gravitational microlensing event Gaia16aye, discovered by the Gaia space mission, where the the complicated light curve variations with five brightening events was explained as a gravitational lensing of a bright single star, lensed by much closer and fainter, randomly passing binary star system (Wyrzykowski et al., 2020). Often, the value of this kind of studies arises from long-term monitoring, one of the main strengths of robotic observatories.

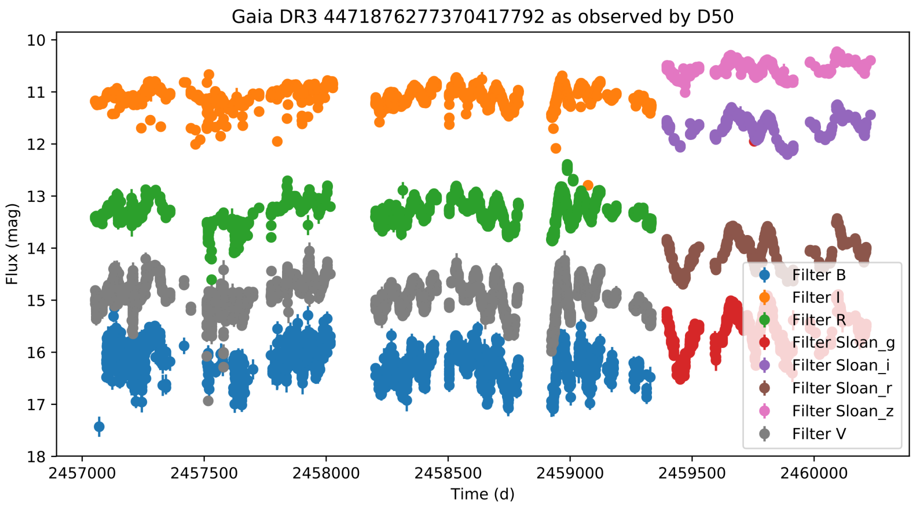

Figure 4. Light curve of the variable star CzeV1266, discovered in the D50 telescope data. The object was in the field of another object observed. The graph was generated via a web interface to a database of automatically processed data.

5.2. Archive

Every object, in every image that the D50 has ever taken since first light, was measured, photometrically calibrated and stored in the database. Thanks to this, we now have (as of 24/11/2022) a total of 845 859 396 photometric measurements in the database - all automatically generated.

Any target can be examined using our web interface (currently not publicly available), providing quick access to measured data. For example, Fig. 3 shows a light-curve of X Ser (which is one of our observational long-term targets) and Fig. 4 which shows CzeV1266 (Gaia DR3 4471876277370417792), a newly discovered variable star that happened to lie in the field of view of a different object we regularly observe. CzeV1266 was one of the variable objects discovered in the initial period of our photometric database, as a result of a search for new variables in our data, an assignment for one of our high school student internships.

6. Recent status and future plans

The telescope has been observing every clear night since its opening, with the exception of a few technological breaks required for rebuilding, configuration adjustments and solving technical problems. Observation statistics can be seen in the graph of the number of images in a given month (Fig. 5).

In the future, in addition to the aforementioned reconstruction of the dome, we are considering adding the possibility of capturing low-dispersion spectra with the help of a rotating secondary mirror and an independent telescope exit, equipped with the new low-dispersion spectrograph. A student internship is currently underway to verify the basic considerations and create an initial trial version of the spectrograph.

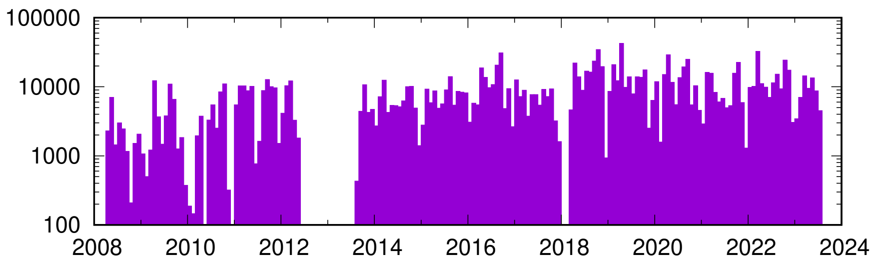

Figure 5. The number of images the D50 has taken in a given month. Includes only high quality images of the sky that have passed the automated data processing.

7. Conclusion

The aim of this paper was to give a report on the actual state and properties of the autonomous robotic telescope D50. The telescope is rather small, however the autonomous robotic mode that it operates in gives it valuable abilities and also makes it very cost-effective.

The importance of observing GRBs is obvious, but even secondary science leads to meaningful results. Thanks to automatic processing, it is possible to obtain reasonable and photometrically calibrated data easily and quickly after it's acquisition.

The telescope is being continuously improved, largely with the help of students, and is thus also valuable for educational purposes. One of the philosophies of the telescope is to make meaningful use of old things for modern science, thus reducing costs while being environmentally friendly.

Acknowledgements. Support by the project RVO:67985815 is acknowledged. This research made use of data provided by Astrometry.net. We sincerely thank a number of students and other people, especially Michal Jakubec, who contributed greatly to the design and implementation of the telescope modifications. We thank also to Ronan Cunniffe for several improvements to the telescope and for proofreading this paper.

References

Barron, J. T., Stumm, C., Hogg, D. W., Lang, D., & Roweis, S., Cleaning the Usno-B Catalog Through Automatic Detection of Optical Artifacts. 2008, *Astronomical Journal*, **135**, 414, DOI: 10.1088/0004-6256/135/1/414

Barthelmy, S., GCN and VOEvent: A status report. 2008, *Astronomische Nachrichten*, **329**, 340, DOI: 10.1002/asna.200710954

Bertin, E. & Arnouts, S., SExtractor: Software for source extraction. 1996, *Astronomy and Astrophysics, Supplement*, **117**, 393, DOI: 10.1051/aas:1996164

Castro-Tirado, A. J., Robotic Astronomy and the BOOTES Network of Robotic Telescopes. 2011, *Acta Polytechnica*, **51**, 16

Castro-Tirado, A. J., Soldán, J., Bernas, M., et al., The Burst Observer and Optical Transient Exploring System (BOOTES). 1999, *Astronomy and Astrophysics, Supplement*, **138**, 583, DOI: 10.1051/aas:1999362

Greiner, J., Wenzel, W., Hudec, R., et al., Simultaneous Optical/Gamma-ray Observations of GRBs. in , *IAU Colloq. 151: Flares and Flashes*, ed. J. Greiner, H. W. Duerbeck, & R. E. Gershberg, Vol. **454**, 381

Horkel, M., Kákona, J., Kákona, M., et al. 2003, MLAB: Open-Hardware Modular Laboratory, https://www.mlab.cz/

Hudec, R., Search for GRB Counterparts in the Optical. 1995, *Astrophysics and Space Science*, **231**, 239, DOI: 10.1007/BF00658624

Jakubec, M., Skala, P., Sedlacek, M., et al., REMOTES: reliable and modular telescope solution for seamless operation and monitoring of various observation facilities. 2012, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. **8451**, *Software and Cyberinfrastructure for Astronomy II*, ed. N. M. Radziwill & G. Chiozzi, 84511I

Jelínek, M. 2002, Detection of bursting sources of gamma-ray radiations using instruments with CCD detection., Master's thesis, Charles University, Prague, Praha, CZ

Jelínek, M., Castro-Tirado, A. J., Cunniffe, R., et al., A Decade of GRB Follow-Up by BOOTES in Spain (2003-2013). 2016, *Advances in Astronomy*, **2016**, 192846, DOI: 10.1155/2016/1928465

Jelínek, M., Topinka, M., Karpov, S., et al., GRB 190919B: Rapid optical rise explained as a flaring activity. 2022, *Astronomy and Astrophysics*, **662**, A126, DOI: 10.1051/0004-6361/202143010

Kubánek, P. 2003, Improvement of the observation software for telescope BART, Master's thesis, Charles University, Prague, Praha, CZ

Kubánek, P., RTS2—The Remote Telescope System. 2010, *Advances in Astronomy*, **2010**, 902484, DOI: 10.1155/2010/902484

Nekola, M., Hudec, R., Jelínek, M., et al., Robotic telescopes for high energy astrophysics in Ondřejov. 2010, *Experimental Astronomy*, **28**, 79, DOI: 10.1007/s10686-010-9190-5

Oganesyan, G., Karpov, S., Salafia, O. S., et al., Exceptionally bright optical emission from a rare and distant gamma-ray burst. 2023, *Nature Astronomy*, DOI: 10.1038/s41550-023-01972-4

Terebizh, V. Y., New designs of survey telescopes. 2011, *Astronomische Nachrichten*, **332**, 714, DOI: 10.1002/asna.201111576

Tody, D., IRAF in the Nineties. 1993, in Astronomical Society of the Pacific Conference Series, Vol. **52**, *Astronomical Data Analysis Software and Systems II*, ed. R. J. Hanisch, R. J. V. Brissenden, & J. Barnes, 173

Valtonen, M. J., Zola, S., Gopakumar, A., et al., Refining the OJ 287 2022 impact flare arrival epoch. 2023, *Monthly Notices of the RAS*, **521**, 6143, DOI: 10.1093/mnras/stad922

van Paradijs, J., Groot, P. J., Galama, T., et al., Transient optical emission from the error box of the γ-ray burst of 28 February 1997. 1997, *Nature*, **386**, 686, DOI: 10.1038/386686a0

Štrobl, J., Jelínek, M., & Hudec, R., Small Binocular Telescope: The new epoch of Burst Alert Robotic Telescope. 2019, *Astronomische Nachrichten*, **340**, 633, DOI: 10.1002/asna.201913668

Wallace, P. T., TPOINT – Telescope Pointing Analysis System. 1994, *Starlink User Note*, **100**

Wyrzykowski, Ł., Mróz, P., Rybicki, K. A., et al., Full orbital solution for the binary system in the northern Galactic disc microlensing event Gaia16aye. 2020, *Astronomy and Astrophysics*, **633**, A98, DOI: 10.1051/0004-6361/201935097