Revista Mexicana de Astronomía y Astrofísica Serie de Conferencias (RMxAC), **59**, 167–172 (2025)

https://doi.org/10.22201/ia.14052059p.2025.59.26

VII Workshop on Robotic Autonomous Observatories (October 16-20, 2023)
Editors: Maria Gritsevich, Alberto J. Castro-Tirado, Petr Kubánek, Shashi B. Pandey, and David Hiriart - DOI: https://doi.org/10.22201/ia.14052059p.2025.59.26

BLACK HOLE TOM – AN AUTOMATIC TOOL FOR PHOTOMETRIC TIME-DOMAIN DATA

P. J. Mikołajczyk[1,2], P. Zieliński[3], Ł. Wyrzykowski[1], A. Krawczyk[4], and K. Kotysz[1,2]

RESUMEN

Presentamos una nueva herramienta automática para la astronomía del dominio temporal, llamada Black Hole Target and Observation Manager (BHTOM), desarrollada en el marco del programa OPTICON RadioNet Pilot. BHTOM es una herramienta de coordinación para una red global de telescopios capaces de procesar datos fotométricos automatizados para objetos transitorios y en el referido dominio temporal. La herramienta se ha utilizado para procesar alrededor de 150.000 observaciones de varios cientos de objetos transitorios, principalmente reportados por la misión espacial *Gaia*. Demostramos las principales características y ejemplos de uso de BHTOM y presentamos las mejoras que se realizarán en un futuro próximo. Los ejemplos de imágenes y curvas de luz presentados aquí confirman la capacidad de procesar datos de imágenes CCD/CMOS de múltiples telescopios y una gran variedad de instrumentos de manera automatizada.

ABSTRACT

We present a new automatic tool for time-domain astronomy dubbed Black Hole Target and Observation Manager (BHTOM), developed under the OPTICON RadioNet Pilot programme. BHTOM is a coordination tool for a global network of telescopes capable of automated photometric data processing for time-domain and transient targets. The tool has been used to process around 150,000 observations of several hundreds of transients, primarily reported by the *Gaia* space mission. We demonstrate the main features and use cases of BHTOM and present improvements to be made in the near future. The examples of images and light curves presented here confirm the ability to process CCD/CMOS imaging data from multiple telescopes and a whole variety of instruments in an automatic manner.

Key Words: data processing — time-domain astronomy — transients

1. INTRODUCTION

In the era of massive sky surveys, like *Gaia*[5], PTF[6], ASAS-SN[7], OGLE[8], ZTF[9] and forthcoming LSST[10], there are thousands of transient phenomena reported every year. The *Gaia* mission alone published almost 25,000 alerts up to now[11]. The average number of alerts per night that would be observed during a 10-year-long survey by Vera Rubin Observatory/LSST is estimated at 10 million objects. Understanding the nature of as many transients as possible is crucial in modern time-domain astronomy (TDA). It enables, for instance, the selection of the most interesting and promising ones for further follow-up observations (both photometric and spectroscopic). Therefore, first of all, the detailed ground-based monitoring of the transients is fundamental to obtain good coverage of their light curves. Secondly, multi-wavelength photometry informs how an event develops in brightness and colour, allowing for early characterisation and discovery of new types of objects.

To conduct such time-, resource- and manpower-consuming observing programs, one needs to have a global telescope network and dedicated central coordinated system that allows for requesting, managing and processing of the observational data. Transient events, e.g., supernovae, flaring young stellar objects (YSOs), gravitational wave optical counterparts, and microlensing or tidal disruption events, often require immediate follow-up observations, very soon after their discovery. It, in turn, implies the need for automatic reduction processes of the large amount of

[1]Astronomical Observatory, University of Warsaw, Al. Ujazdowskie 4, 00-478 Warszawa, Poland (bhtom@astrouw.edu.pl).

[2]Astronomical Institute, University of Wrocław, Kopernika 11, 51-622 Wrocław, Poland.

[3]Institute of Astronomy, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University in Toruń, Grudzikadzka 5, 87-100 Toruń, Poland.

[4]AkondLab, Wałbrzyska 6-8, 52-314 Wrocław, Poland.

[5]http://sci.esa.int/gaia

[6]https://www.ptf.caltech.edu/iptf

[7]https://www.astronomy.ohio-state.edu/asassn/index.shtml

[8]http://ogle.astrouw.edu.pl

[9]https://www.ztf.caltech.edu

[10]https://www.lsst.org/

[11]http://gsaweb.ast.cam.ac.uk/alerts/home

VII Workshop on Robotic Autonomous Observatories (October 16-20, 2023)
Editors: Maria Gritsevich, Alberto J. Castro-Tirado, Petr Kubánek, Shashi B. Pandey, and David Hiriart - DOI: https://doi.org/10.22201/ia.14052059p.2025.59.26

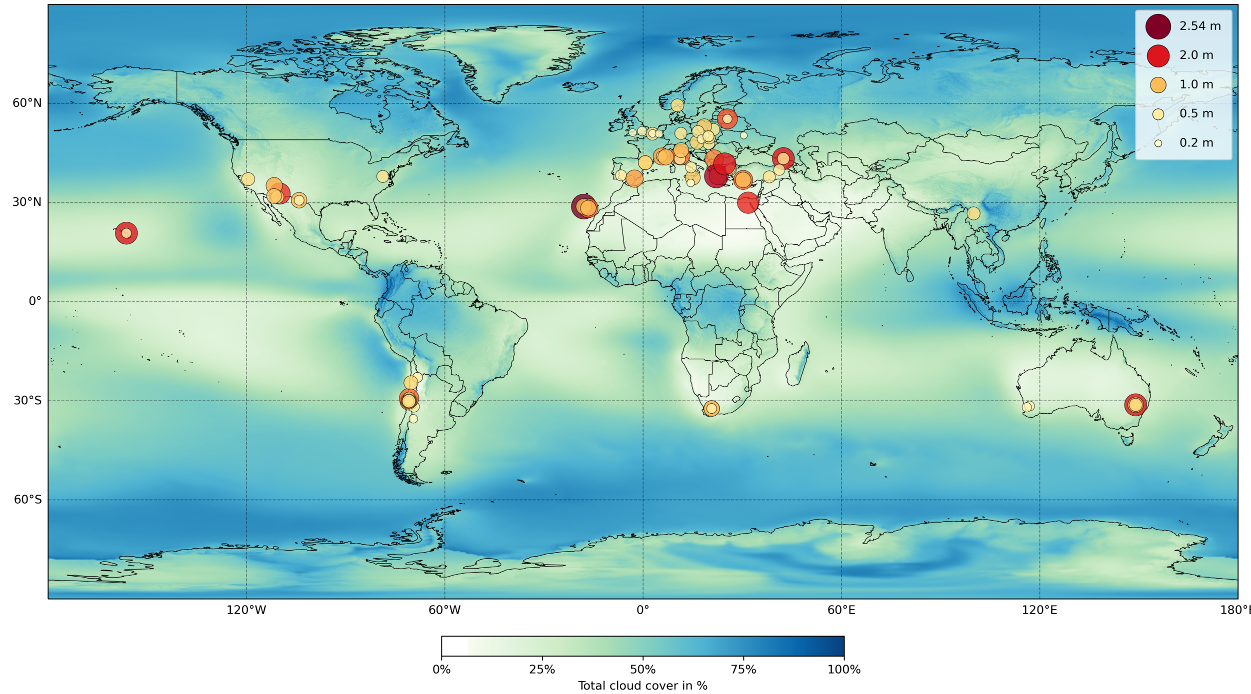

Fig. 1. The global distribution of telescopes involved in the BHTOM follow-up network overplotted on the total average cloud cover (Brun 2022).

photometric data gathered by various telescopes and instruments.

2. TDA FOLLOW-UP NETWORK

The process of preparation, submission and allocation of observing time is inefficient in the context of monitoring thousands of transient events. Observational data must therefore be provided by the active participation of many observers spread around the world. Since 2013, thanks to the EU FP7 and Horizon2020 funds, we have been developing a TDA telescope network for follow-up monitoring of interesting transients, mainly microlensing events alerted by *Gaia*. Within the OPTICON RadioNet Pilot (ORP) programme, we coordinate the operation of about 100 small- and medium-sized telescopes scattered globally. Our activity includes technical support, training, help with the observations, data processing and organizing the annual workshops. However, our main product is the automatic tool, dedicated to TDA, which is described in Sec. 3.

The members of the ORP TDA follow-up network are volunteers (both professional astronomers and amateurs). Some, contributed thousands of observations, while others contributed only a few data points. Figure 1 presents the geographical distribution of our partners. Many of these telescopes are located in Europe (Fig. 2) with poor weather conditions, compared to the best-observing sites like Chile, the Canary Islands, Hawaii, South Africa or Australia. But working in a network, they can still provide extremely useful scientific data and serve as perfect training facilities for young generations of astronomers.

The TDA follow-up network consists of about 20 robotic telescopes, while the rest is operated manually. The main mirror sizes of the telescopes in the network are within the range from 0.2 up to 2.5 m. Certainly, we also use world-class telescopes with apertures $8 - 10$ m for the (spectroscopic) follow-up based on the observing proposals and awarded time. However, the ORP TDA network of telescopes is the core of the available observational infrastructure coordinated by us.

3. BLACK HOLE TOM

The main product of the ORP TDA network is the Black Hole TOM (BHTOM)[12] which allows fast and automatic reduction and calibration of photometric data delivered by various network instruments. Recently, we have been releasing the new version of this software BHTOM 2.0 which improves the old version in several issues.

[12] `bhtom.space`

VII Workshop on Robotic Autonomous Observatories (October 16-20, 2023)
Editors: Maria Gritsevich, Alberto J. Castro-Tirado, Petr Kubánek, Shashi B. Pandey, and David Hiriart - DOI: https://doi.org/10.22201/ia.14052059p.2025.59.26

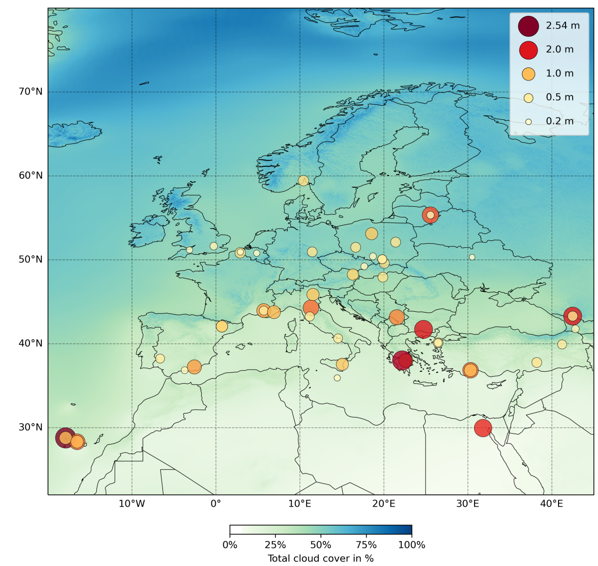

Fig. 2. The distribution of BHTOM telescopes in Europe and beyond overplotted on the total average cloud cover (Brun 2022).

BHTOM is based on the Target and Observation Manager (TOM) – open-source tool developed by Las Cumbres Observatory[13] (Street et al. 2018). It also uses our other, previously developed tools – CCDPhot and CPCS – that are built in the current version (Zieliński et al. 2019, 2020). In general, BHTOM performs the measurements of the target's brightness (photometry) and position (astrometry). It accepts both ASCII or CSV files with photometric measurements provided in a specific format, or FITS[14] files from CCD/CMOS cameras that have to be initially calibrated in the meaning of bias- and dark-subtraction and flat-field correction. This allows less experienced observers, including amateurs and school pupils, to collect scientifically important observations and deliver them to BHTOM directly.

3.1. *Main features*

The main features and workflow of BHTOM processing are as follows:

- automatic photometric and astrometric reduction of CCD/CMOS images by using CCDPhot based on BASH shell and Python scripts, IRAF/PyRAF[15], SExtractor (Bertin & Arnouts 1996), SCAMP (Bertin 2006), DAOPHOT (Stetson 1987) and WCSTools[16];
- direct uploading of photometric data as ASCII, CSV files or images as FITS files, also spectroscopic data possible to upload as simple ASCII or CSV file;
- astrometric solution obtained based on several reference astrometric catalogues: URAT-1 (Zacharias et al. 2015), UCAC-4 (Zacharias et al. 2013), USNOB1 (Monet et al. 2003) and Gaia-DR3 (Gaia Collaboration et al. 2023a) for final astrometric solution;
- photometry calibrated to standard magnitudes based on *Gaia* Synthetic Photometry (GaiaSP, Gaia Collaboration et al. 2023b) and 2MASS (Skrutskie et al. 2006) reference catalogues: transformation of instrumental magnitudes to the standard ones is done by zero-point calibration and colour term application;
- standardization of CCD/CMOS file headers originated from different observatories according to FITS standard[17];
- the Point Spread Function (PSF) model of the whole image constructed in automatic procedure;
- aperture and PSF photometry for all stars detected in the field-of-view based on DAOPHOT calculation procedure obtained with precision $\sim$0.01 mag (and better);
- final astrometric solution for all stars detected in the image based on Gaia-DR3 coordinates and proper motions obtained with precision $\sim$0.01 arcsec (and better);
- archival data from optical (*Gaia*, Gaia Collaboration et al. 2023a; ZTF, Masci et al. 2019; CRTS, Drake et al. 2009; LINEAR, Stokes et al. 2002; SDSS, Almeida et al. 2023; Pan-STARRS-DR1, Flewelling et al. 2020; DECAPS, Saydjari et al. 2023; ATLAS, Tonry et al. 2018), infrared (2MASS, Skrutskie et al. 2006; WISE, Wright et al. 2010; NEOWISE, Mainzer et al. 2011) and radio-databases (LOFAR, Shimwell et al. 2022; FIRST, Becker et al.

[13] `https://lco.global/tomtoolkit/`

[14] Flexible Image Transport System, `https://fits.gsfc.nasa.gov`

[15] IRAF is written and supported by the National Optical Astronomy Observatories (NOAO) in Tucson, Arizona. NOAO is operated by the Association of Universities for Research in Astronomy (AURA), Inc. under a cooperative agreement with the National Science Foundation. PyRAF is a product of the Space Telescope Science Institute, which AURA operates for NASA.

[16] `http://tdc-www.harvard.edu/wcstools`

[17] `https://fits.gsfc.nasa.gov/fits_dictionary.html`

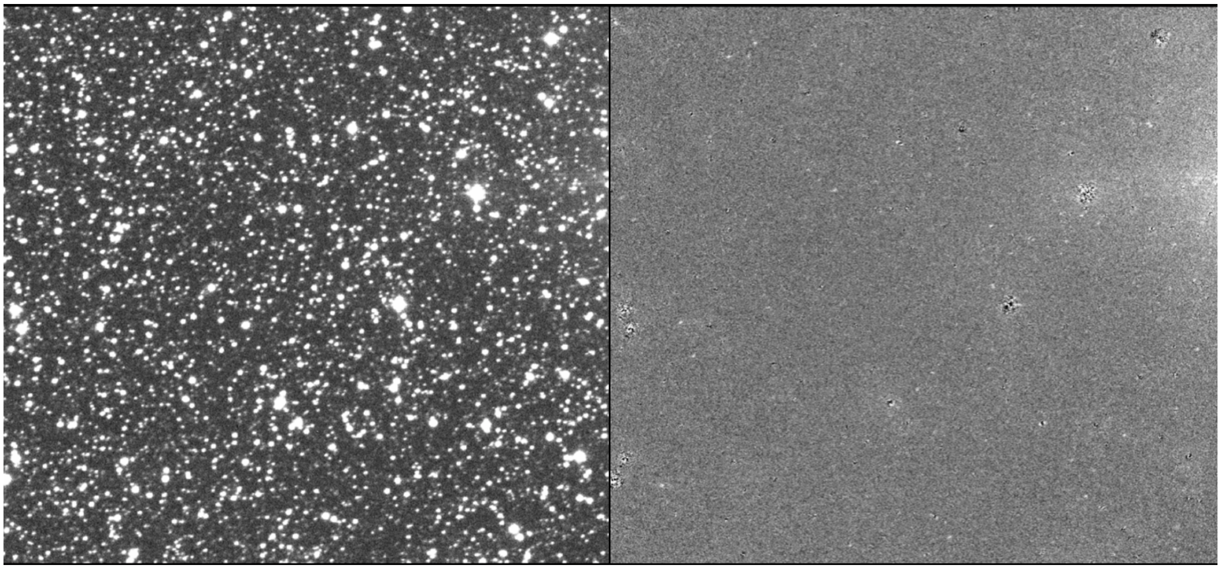

Fig. 3. The example images demonstrating the BHTOM processing result. Left: image of the Gaia16aye stellar field obtained in Bialkow Observatory before uploading to BHTOM; Right – the same image after processing by BHTOM. The result of the subtraction of 14,133 objects identified in the image is visible. The FoV is 13x12 arcmin in both cases.

VII Workshop on Robotic Autonomous Observatories (October 16-20, 2023)
Editors: Maria Gritsevich, Alberto J. Castro-Tirado, Petr Kubánek, Shashi B. Pandey, and David Hiriart - DOI: https://doi.org/10.22201/ia.14052059p.2025.59.26

1994) collected via dedicated brokers for every newly created target in automatic way;

- interactive targets map and easy-to-use target list that can be sorted and filtered by coordinates, magnitudes, priority, number of observations, class of object, etc.; target grouping is also possible;
- interactive light curves for every target (displayed per filter or facility);
- modelling procedure of light curves for microlensing events (at the moment) with and without parallax effect;
- publication feature that uses ChatGPT3.5 from OpenAI[18] to improve the title of the paper, abstract, and portions of the introduction as well as generate the description of the photometric data collected for the target;
- all functionalities of BHTOM are available via Application Programming Interface (API), i.e. data upload, download, target list filtering, standardization results, etc.[19]

3.2. *Future improvements*

The work on the new features and improvements of BHTOM is ongoing. Thanks to the feedback obtained from the users of BHTOM, this tool is getting more and more user-friendly and valuable. The cooperation between observers, astronomers and software engineers leads to continuous improvements, debugging and error detection in the system. In the future we are going to implement the following features, among others:

- live feedback provided for users reducing their FITS files with our dedicated CCDPhot pipeline;
- automatic triggering of robotic observations (already underway for the REM telescope) along with subsequent data reduction;
- introducing other photometric reduction procedures, i.e. SExtractor profile photometry;
- displaying many photometry products (aperture, profile, Kron-like and others);
- database containing light curves for all objects observed in the TOIs field-of-views.

3.3. *Examples*

The examples of processed images (before and after uploading to BHTOM) is presented in Fig. 3. Moreover, the light curves for example targets observed within the TDA follow-up network are shown in Fig. 4

[18] https://chat.openai.com/auth/login

[19] https://github.com/BHTOM-Team/bhtom2/blob/bhtom2-dev/Documentation/Documentation.md

VII Workshop on Robotic Autonomous Observatories (October 16-20, 2023)
Editors: Maria Gritsevich, Alberto J. Castro-Tirado, Petr Kubánek, Shashi B. Pandey, and David Hiriart - DOI: https://doi.org/10.22201/ia.14052059p.2025.59.26

Fig. 4. The example light curves of transients as presented in BHTOM. From top to bottom: Gaia21fkl microlensing event, 8C0716+714 highly variable quasar, SN2023ixf a supernova in M101. Colour-coded are the photometric follow-up observations in various filters calibrated to GaiaSP bands or from various sky surveys.

4. SUMMARY

Black Hole TOM is the automatic tool for processing photometric follow-up data from various telescopes and instruments. The photometric data from about 100 instruments were already tested successfully and stored in the cloud. In total, we have processed $\sim 150,000$ FITS images since the project's inception. At the moment, there are 257 users registered in BHTOM and the data can be uploaded for more than 2500 targets created.

The tool was already used in several scientific studies of microlensing events (e.g., Kruszyńska et al. 2022, Rybicki et al. 2022), young stellar objects (e.g., Nagy et al. 2022, 2023) or symbiotic stars (e.g., Merc et al. 2020). The papers on many other *Gaia* alerts are in the preparation phase as well. It confirms that the new version of our tool ensures fast and automatic processing of TDA data from various instruments. Nevertheless, the work on developments of other improvements of BHTOM is still in progress.

If you are interested in using Black Hole TOM for your research please visit the BHTOM webpage that can be found under the link `bhtom.space` and join the dedicated Slack channel `slack.bhtom.space` to stay updated.

Acknowledgements: The BHTOM project has received funding from the EU's Horizon 2020 research and innovation programme under grant agreement No. 101004719 (OPTICON RadioNet Pilot, ORP). BHTOM acknowledges the following people who helped with its development: M. Jabłońska, P. Sivak, K. Raciborski, P. Trzcionkowski and AKOND Lab company. This paper made use of the Whole Sky Database (wsdb) created by S. Koposov and maintained at the Institute of Astronomy, Cambridge, by S. Koposov, V. Belokurov and W. Evans with financial support from the Science & Technology Facilities Council (STFC) and the European Research Council (ERC), with the use of the Q3C software (`http://adsabs.harvard.edu/abs/2006ASPC..351..735K`). This work has made use of data from the European Space Agency (ESA) mission *Gaia* (`https://www.cosmos.esa.int/gaia`), processed by the Gaia Data Processing and Analysis Consortium (DPAC, `https://www.cosmos.esa.int/web/gaia/dpac/`). Funding for the DPAC has been provided by national institutions, in particular, the institutions participating in the Gaia Multilateral Agreement.

REFERENCES

Almeida, A., Anderson, S. F., Argudo-Fernández, M., et al. 2023, ApJS, 267, 44
Becker, R. H., White, R. L., & Helfand, D. J. 1994, ASPC, 61, 165
Bertin, E. & Arnouts, S. 1996, A&AS, 117, 393
Bertin, E. 2006, ASPC, 351, 112
Brun, P., Zimmermann, N. E., Hari, C., Pellissier, L., & Nikolaus Karger, D. 2022, ESSD, 14, 5573
Drake, A. J., Djorgovski, S. G., Mahabal, A., et al. 2009, ApJ, 696, 870
Flewelling, H. A., Magnier, E. A., Chambers, K. C., et al. 2020, ApJS, 251, 7
Gaia Collaboration, Vallenari, A., Brown, A. G. A., et al. 2023a, A&A, 674, A1
Gaia Collaboration, Montegriffo, P., Bellazzini, M., et al. 2023b, A&A, 674, A33
Kruszyńska, K., Wyrzykowski, Ł., Rybicki, K. A., et al. 2022, A&A, 662, A59
Mainzer, A., Bauer, J., Grav, T., et al. 2011, ApJ, 731, 53
Masci, F. J., Laher, R. R., Rusholme, B., et al. 2019, PASP, 131, 018003
Merc, J., Mikołajewska, J., Gromadzki, M., et al. 2020, A&A, 644, A49
Monet, D. G., Levine, S. E., Canzian, B., et al. 2003, AJ, 125, 984
Nagy, Z., Ábrahám, P., Kóspál, Á., et al. 2022, MNRAS, 515, 1774
Nagy, Z., Park, S., Ábrahám, P., et al. 2023, MNRAS, 524, 3344
Rybicki, K. A., Wyrzykowski, Ł., Bachelet, E., et al. 2022, A&A, 657, A18
Saydjari, A. K., Schlafly, E. F., Lang, D., et al. 2023, ApJS, 264, 28
Shimwell, T. W., Hardcastle, M. J., Tasse, C., et al. 2022, A&A, 659, A1
Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, AJ, 131, 1163
Stetson, P. B. 1987, PASP, 99, 191
Stokes, G. H., Evans, J. B., & Shelly, F. C. 2002, AAS, 34, 1315
Street, R. A., Bowman, M., Saunders, E. S., & Boroson, T. 2018, SPIE, 10707, 11
Tonry, J. L., Denneau, L., Heinze, A. N., et al. 2018, PASP, 130, 064505
Wright, E. L., Eisenhardt, P. R. M., Mainzer, A. K., et al. 2010, AJ, 140, 1868
Zacharias, N., Finch, C. T., Girard, T. M., et al. 2013, AJ, 145, 44
Zacharias, N., Finch, C., Subasavage, J., et al. 2015, AJ, 150, 101
Zieliński, P., Wyrzykowski, Ł., Rybicki, K., et al. 2019, CoSka, 49, 125
Zieliński, P., Wyrzykowski, Ł., Mikołajczyk, P., et al. 2020, XXXIX PAS Meeting, 10, 190