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Occultation portal: A web-based platform for data collection and analysis of stellar occultations

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ABSTRACT

Recording a stellar occultation is one powerful method that gives direct information about the physical properties of the occulting Solar system object. In order to obtain reliable and accurate results, simultaneous observations from different locations across-track of the projected path are of great importance. However, organizing all the observing stations, aggregating, and analysing the data is time-consuming and not that easy. We have developed a web portal named *Occultation Portal (OP)* to manage all those occultation observation campaigns from a central server. With this portal, the instrumental and observational information of all observers participating in a stellar occultation campaign and the concerned data are archived systematically in a standard format. The researchers can then visualize the archived data on an event basis. The investigators can also extract the light curve for each data set with the added reduction pipeline to the portal base. This paper describes in detail the portal structure and the developed features.

Key words: methods: data analysis – techniques: image processing – occultations – minor planets, asteroids: general – software: development.

1 INTRODUCTION

A stellar occultation is a celestial event that occurs when a Solar System object obscures a source from the perspective of an observer. Apart from the occultation event caused by the main body, secondary events may also be observed caused by rings, dust, or satellites in the vicinity of the main body (Sicardy et al. 2011; Ortiz et al. 2012; Braga-Ribas et al. 2014; Ortiz et al. 2017). Similarly, a gradual dis/re-appearance of the main body can be recorded revealing an atmosphere. The duration of these occultations varies according to the size, shape, and sky motion rate of the object. When these events are recorded simultaneously from more than two locations across the occultation path, a multichord stellar occultation, we are able to obtain detailed information about the foreground object (Braga-Ribas et al. 2013; Souami et al. 2020). The multichord stellar occultation

technique is, at present, the only method able to determine the size and shape of the small objects of the outer Solar system with sub-km accuracy, with an exception made for a visiting spacecraft. In addition to estimating the physical properties of the foreground object, the stellar angular diameter of the occulted star may also be calculated from the occultation event (Widemann et al. 2009), or an unresolved stellar companion may be discovered (Bérard et al. 2017).

Before the *HIPPARCOS* mission (ESA 1997), stellar occultation predictions and observations were highly challenging because of the significant uncertainties in the position of occulted stars (Dunham et al. 2002). Afterwards, precise occultation predictions increased significantly thanks to the highly accurate astrometric positions provided by *Gaia* DR1, DR2, and eDR3 catalogues (Gaia Collaboration et al. 2016, 2018, 2021).

Considering the more than 15 000 observations from 4400 events provided by 3300 individuals from all over the world over the last 40 yr (Herald et al. 2020), we are seeing an extraordinary increase of successful occultation observations that will stand for

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the next decades¹ (Braga-Ribas et al. 2019). Not only the *Gaia* stellar catalogue, but also the accurate positions of small Solar system objects within *Gaia* next releases will strikingly increase the number of precise predictions of occultations (Ferreira et al. 2022). Besides, the involvement of the Vera Rubin Observatory with the *LSST*² will also have a significant impact (Ivezić et al. 2019). As a result, a remarkable amount of data will be produced.

Another factor in increasing the number of precise and successful occultation events is the development of accurate numerical methods for their prediction, such as NIMA³ (Desmars et al. 2015) for orbit determinations of moving objects. In addition, more affordable observational equipment, increased camera sensitivity, developments in the internet infrastructure, and investments in cloud services (Paunov et al. 2019; Canals 2021) have had an increasing effect on the data size produced along with the broadband data transmission. As a result of all these developments, the contribution of amateur astronomers in the observation campaigns increased tremendously (Herald et al. 2020), and most of their occultation light curves, produced from events involving the Moon and asteroids, are archived in the Occultation light curves catalogue⁴ (Herald et al. 2016).

Building on these developments, research groups such as the ERC Lucky Star project⁵ in France, Spain and Brazil and RECON⁶ in the USA, have seen the number of successful occultations increase which has led them to groundbreaking discoveries such as those of the rings around the Centaur (10199) Chariklo (Braga-Ribas et al. 2014) and the dwarf-planet (136108) Haumea (Ortiz et al. 2017), as well as the invaluable support to space missions such as New Horizons as the 2017 occultation by the TNO (486 958) Arrokoth (Buie et al. 2020). In addition, the ACROSS project,⁷ in collaboration with amateur observers, recorded the potentially hazardous asteroid (99942) Apophis using the stellar occultation technique for the first time (Tanga et al. 2021). These teams are seeking support from several groups of observers such as the International Occultation Timing Association (IOTA),⁸ the IOTA-European Section (IOTA-ES)⁹ as well as other groups in Australia, New Zealand,¹⁰ Japan,¹¹ South and Central America,¹² North and South Africa, India and more.¹³ Once confirmed, the predictions and calls for observers are made public through the above-cited project's websites (such as the <https://lesia.obspm.fr/lucky-star/>) or using tools such as the *Occult*,¹⁴ *OccultWatcher* (OW)¹⁵ (Pavlov 2018a, b) and its online version, the *OccultWatcher Cloud* (OWC)¹⁶ feeds.

We can illustrate the importance of coordination and developments in technology through the stellar occultation campaign of the 2002 MS₄ object dated 2020 August 8,¹⁷ which involved 116 telescopes

across Europe, North Africa, and Western Asia, with the most extensive participation ever on an event by a TNO (Rommel et al. 2021). Each stellar occultation campaign nowadays requires extraordinary coordination with observers from all over the world. A systematic follow-up of such participation is essential to ensure the successful and efficient interpretation of the data and to ensure the best scientific outcome while also ensuring the participation of each observer is gratified.

Collecting observational data and details on the instrumental setup from each observer through e-mail causes time delays, useless redundancies, and data loss. Professional observatories generally produce data in FITS format, while most amateur observers prefer the video format. Generally, the researcher contacts all the campaign participants by e-mail and receives all observational information and data from the observers via various cloud services. Since the requested observation time-span can sometimes be relatively long (about an hour, or so), the data size produced by observers may exceed the quotas of free data sharing cloud services. Moreover, the researcher collecting the data might face the problem of archiving the data coming from tens or even hundreds of observers.

In order to solve all these problems and to guarantee the participants being in the scientific publications in a systematic, practical, and cost-effective way, it became crucial to develop a common online platform where the needed data is collected and analysed (producing light curves/ photometry). In the light of this, we developed a platform called Occultation Portal (OP)¹⁸ to manage ERC Lucky Star Project observation campaigns effectively and efficiently. This paper is organized as follows: In Section 2, we introduce the current architecture of the OP and our approaches to creating its components. In Section 3, the use of the OP in current campaigns is discussed with general statistics as well as the photometric reduction and analysis. Finally, we discuss the future improvements, plans, and challenges for the platform in Section 4.

2 THE ARCHITECTURE AND ALGORITHM

The Occultation Portal (OP) is a data archiving, analysis, and visualization portal created to systematically assist in conducting observational campaigns of the ERC Lucky Star Project as its primary goal. The entire web-based portal consists of *User service*, *Prediction service*, *Analysis and Reduction service*, *Data service*, *Notification service*, and *Backup service* as shown in Fig. 1. Through these services, and depending on the mode they are using, users can perform operations such as: adding predictions, instruments, and coordinates of observing stations; uploading data associated with any listed campaign; managing campaigns, requesting information about specific events; or the use of the portal. Finally, the users can use the incorporated tools for data analysis and visualization depending on their access levels via the web interface. To create all this infrastructure and superstructure, we preferred the Django framework¹⁹ as it enables the rapid development of the OP's back-end and front-end and works in perfect harmony with the Python programming language.

2.1 User service

In order to ensure the security of the system and the data uploaded on the OP, users are authorized to access the OP services in four

¹Database on Stellar Occultations by Small Outer Solar System Objects.

²Legacy Survey of Space and Time.

³Numerical Integration of the Motion of an Asteroid.

⁴<https://cdsarc.cds.unistra.fr/viz-bin/cat/B/occ>

⁵<https://lesia.obspm.fr/lucky-star/>

⁶<http://tmorecon.net/>

⁷<https://lagrange.oca.eu/fr/home-across>

⁸<https://occultations.org/>

⁹<https://www.iota-es.de/>

¹⁰The Trans Tasman Occultation Alliance

¹¹Japanese Occultation Information Network

¹²Liga Iberoamericana de Astronomía - LIADA

¹³euraster.net - Asteroidal Occultation Sites

¹⁴<http://www.lunar-occultations.com/iota/occult4.htm>

¹⁵<https://www.occultwatcher.net/>

¹⁶<https://cloud.occultwatcher.net/>

¹⁷<https://lesia.obspm.fr/lucky-star/occ.php?p=39076>

¹⁸<https://occultation.tug.tubitak.gov.tr/>

¹⁹<https://www.djangoproject.com/>

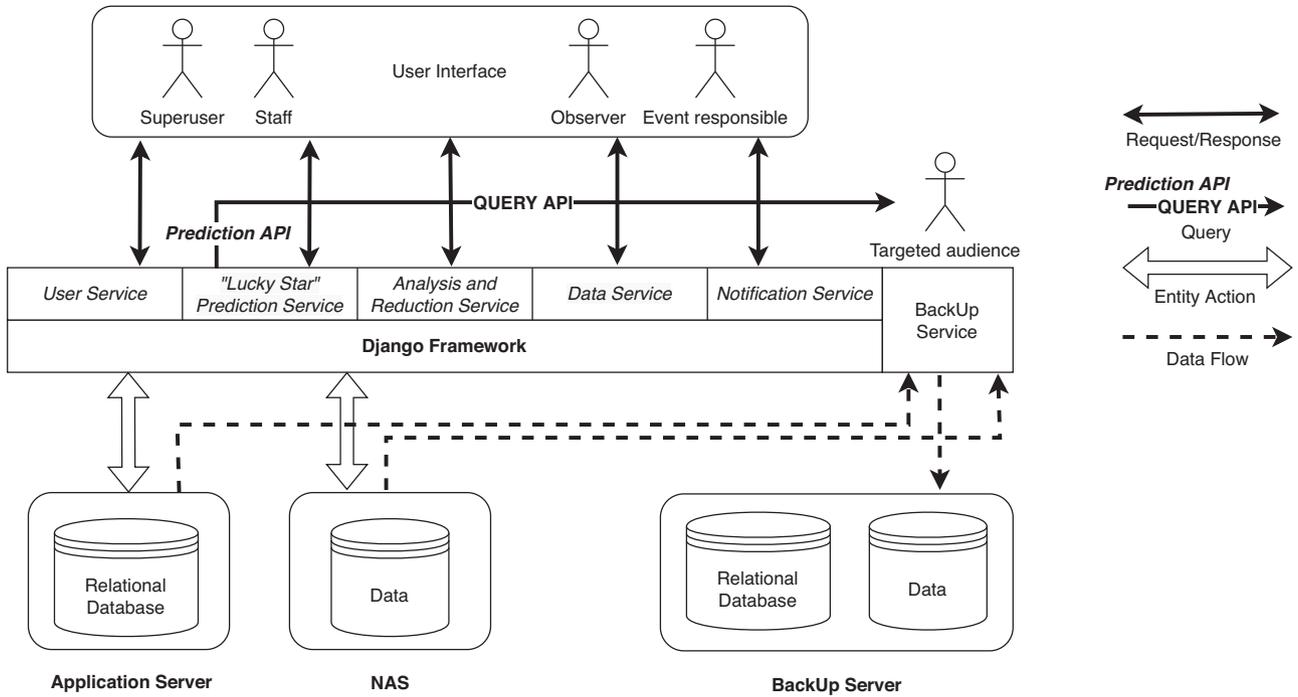


Figure 1. The Occultation Portal’s software architecture. Six different services are running and their relationship with the environment are represented. The two-way continuous arrows show the Request/Response relationship between the services and the users via the web interface. The one-way continuous arrow represents the query from the Prediction API (Application Programming Interface) service to Targeted audience with API key. The one-way dashed arrows indicate the data flow direction of the database and observational data run by the *BackUp Service*. The hollow two-way arrows represent the database and observation data *Entity Actions* coming through the framework.

different user levels: *superuser*, *staff*, *observer* (standard users) and *event responsible*. The first three levels were added with the help of the built-in Django authentication system, while the fourth level, which is more privileged than an *observer* user, was also added to allow the user to manage event-specific campaigns. Table 1 shows each user’s access levels and authorization groups on the OP.

Switching between user groups can only be made by superusers. Staff can also assign an event responsible for a specific prediction.

2.2 Lucky Star prediction service

The prediction sources that feed the Occultation Portal consist of TNOs, Centaurs, and asteroids (mostly Trojans, see Fig. 4) selected by the researchers generally from the Rio, Meudon, and Granada groups within the framework of the Lucky Star Project. Predictions are based on the studies of Assafin et al. (2010) for Pluto and its system, Assafin et al. (2012) for TNOs, and Camargo et al. (2014) for TNOs and Centaurs. The ephemerides of the selected objects are calculated using the NIMA software, as detailed in Desmars et al. (2015), and the ephemeris database is regularly updated. Observational data used in the ephemeris calculations are currently provided by the Minor Planet Center, and Lucky Star Project observations at ESO, Pic du Midi, Calar Alto, Sierra Nevada, and Observatório do Pico dos Dias. Additionally, astrometric data of the Dark Energy Survey (Banda-Huarca et al. 2019) are used. Ephemerides of the satellites of the TNOs are taken from the Genoid project (Vachier, Berthier & Marchis 2012). The astrometric positions and proper motions of the stars in the Gaia

catalogue releases are used in predictions (Gaia Collaboration et al. 2021).^{20,21}

The entire prediction Database of the Lucky Star Project is uploaded to the Occultation Portal. Each prediction in this Database carries an Occultation ID (*occ_id*). Suppose this ID is activated via the Prediction tab in OP by authorized users, then a campaign call is made for this prediction which makes it selectable by any users from the calendar. After this stage, for this announced prediction, the OP admins can appoint a user amongst registered users in the Portal as ‘event responsible’. The selected ‘event responsible person’ now accesses all information about this event and manages the data on the OP.

2.3 Lucky Star prediction API

Lucky Star Project presents its predictions through a website. Most professional and amateur observers can search for the prediction they are interested in here. However, this web interface is not practical for most programmers or researchers to quickly access more detailed information about the predictions. Since it is not as practical as Occultation Portal, Occult Watcher, OW Cloud, etc., an Application Programming Interface (API) service has been deployed using Django Ninja²² to facilitate access to predictions.²³ A user with an API key can scan the entire Lucky Star Prediction Database

²⁰Most recently Gaia eDR3

²¹<https://lesia.obspm.fr/lucky-star/predictions.php>

²²<https://django-ninja.rest-framework.com/>

²³<https://occultation.tug.tubitak.gov.tr/api/docs>

Table 1. Authorizations and access levels of users groups to the OP's services. The primary services available on the OP are listed as Feature. *Yes* indicates that a user group has access and management authority to the relevant service. *No* means the opposite. *Read-only* refers to a user group that can access a service in a read-only mode without administrative authority. Superuser(s) have administrative authority on all services. Staff users are mostly Lucky Star researchers with moderately limited controls designated by a Superuser. Observers are the OP's primary group and are only authorized to register an event to provide data and information. Event Responsible(s) are the researchers who can manage all processes of a peculiar event assigned by a Superuser or Staff.

Feature	Superuser	Staff	Observer	Event responsible
User service	Yes	No	No	No
Prediction services	Yes	Yes	Read-only	No
Analysis & Reduction service	Yes	Yes	No	Yes
Data service	Yes	Yes	No	Yes
Notification service	Yes	Yes	No	No
Backup service ^a	No	No	No	No

Note. ^(a) Service is controlled only by the server system admin.

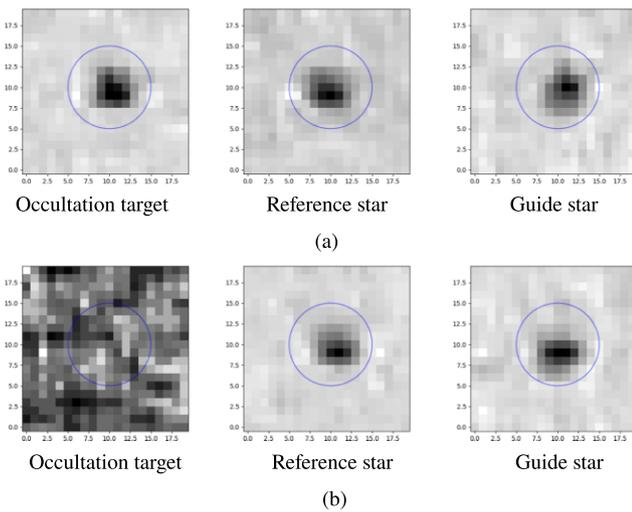


Figure 2. This figure shows the target, reference, and guide stars detected by the OP within 20 pixel of *ROIBOX* in each frame. In Fig. 2(a), the state of three stars is shown in a series of images where the occultation event does not happen. In Fig. 2(b), the state of three stars during the occultation moment is shown. As can be seen, the occultation target is not detected in Fig. 2(b) as the target star was occulted by the Solar system object, the former being too faint to be detected in the exposure.

through the Occultation Portal for desired location, specific date and brightness range, as seen in the code Listing 1.

Listing 1: Lucky Star Prediction API usage via curl.

```
curl -k -X GET 'https://occultation.tug.tubitak.gov.tr/api/predictions?start_date=2022-02-01&end_date=2022-02-15&mag_min=10&mag_max=18&object_name=Hektor&page=1' -H 'X-API-Key: SECRET_API_KEY'
```

Curl is preferred in the example, a terminal client used for data transfer. In the example, the Prediction API query of a user with an API KEY is sampled. Here, if desired, the start date of the prediction (*start_date*), the end date of the prediction (*end_date*), minimum magnitude value of the selected object (*mag_min*), the maximum magnitude value of the desired object (*mag_max*), Solar system object name (*object_name*), and requesting page number of result (*page*) arguments can be changed by the *targeted audience* as shown in Fig. 1.

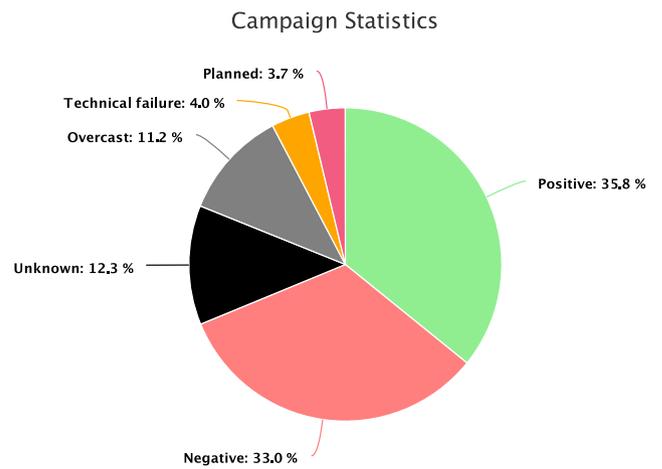


Figure 3. General statistics of campaigns run between 2020 August and 2022 May. In the chart, *Positive* means that at least one data set has disappearance of the target star because of occultation event while *Negative* means that none of the recorded data shows the disappearance of the star. *Planned* means an observer did not provide any information about the event despite it being planned to observe. *Technical failure* means that the observer experienced a technical issue at the moment of the occultation. *Overcast* means observation could not be conducted due to bad weather conditions. *Unknown* means there was no information, although data were provided.

2.4 Data service

The observational data is provided to the OP by observers who participated in the observational campaigns. In order to participate in a campaign, the user should register specifications of the telescope, camera, time recording system, filter, and location. The OP stores data systematically and delivers the data to the event responsible(s) and admins in a well-coordinated way using those registered information. Thus, authorized users may track and manage all this information in a table and also on OpenStreetMap.²⁴

It should be noted that one of the most critical information requested on the OP is the observers' accurate location, which is crucial for dependable analysis. To avoid any mistakes in location information, the OP has all IAU (The International Astronomical Union) registered observatories as selectable. Furthermore, the user

²⁴<https://www.openstreetmap.org>

may select a location easily with the help of the map assistant. Astropy (Astropy Collaboration et al. 2013, 2018) and geopy²⁵ are used together in the background of all these processes. After filling all the information in, the user is directed to the data upload section to upload the data in one of the available formats such as *fit(s),.zip,.rar,.gz,.7z,.avi,.adv,.aav,.ser*.

All the data uploaded on the OP is only available to researchers or groups approved by the Lucky Star Project members and collaborators on an event basis. As shown in Appendix A1, an observer can view other participants, excluding the uploaded data on the event attended, and only view and access their own data unless the observer has Data Service privileges given in Table 1. The authorized user who wants to access event-based data may request the event data anytime by pressing the *Request Event Data* button (see Appendix A2). OP queries all relevant data in the Database, creates a ZIP file, and sends an e-mail notification to the requesting user and system admin when the process is completed to ensure data privacy. The ZIP file contains all the event data, additional files (if provided), the ROI (Report Object Instance) file (if provided), and the auto-generated Asteroidal Occultation Report²⁶ by the OP. This file is served by *nginx*²⁷ on the server.

2.5 Data analysis and reduction service

All types of observational data uploaded to the Occultation Portal are stored systematically on the server in an event and user basis. In addition, each recording path is also kept in the Database for fast accessing purposes to data processing services. Only event responsible, staff, and superusers have the right to reduce and analyse each event-based observational data. User authorization alone is not enough to perform reduction and analysis on the OP. In line with the capabilities of the OP, the observational data to be uploaded must be in *fits* format. However, most of the observers prefer to upload their files as one single compressed file such as *zip,.rar,.gz,.7z* to make the upload faster. In this case, the authorized user must first decompress the archive. On the OP, there is a function called *extract_arch* that uses the *pyunpack*²⁸ package for this operation. Since the cameras used by amateur observers produce data in video formats, usually they upload files such as Audio Video Interleave (AVI), Astro Digital Video Data Format (ADV) (Pavlov et al. 2020), Astro Analogue Video (AAV) (Barry et al. 2015), SER.²⁹ In this case, a video-to-FITS format conversion is required to analyse video frames. Although such a conversion module has been developed, it has not yet been implemented to the OP as a service which is still in the testing phase. The developed module named *video2fits* can easily read each video frame and convert it to FITS format, has been developed taking advantage of *stacker.py* in *PyMovie* (Anderson 2019). Moreover, reading the timestamps from the video formats such as AVI, where the observational timestamp is inserted into the video stream directly, is recognized by *easyOCR*³⁰ module, not *PyMovie*'s OCR (Optical Character Recognition) module.

Once all the data is uploaded in FITS format or converted properly to FITS format, OP activates the *Analyze tab* for authorized users, and all data are available for examining via *JS9* tool (Mandel & Vikhlinin

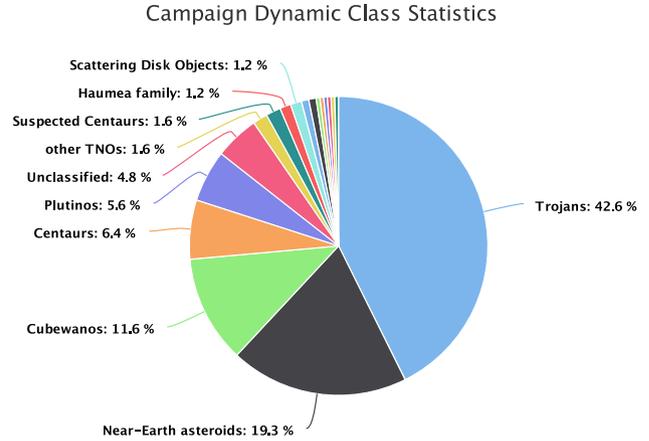


Figure 4. Statistics on the dynamical classes of the occulting objects that were announced predictions on OP between 2020 August and 2022 May. For the sake of clarity, the names of the dynamical classes that contribute less than 1 per cent are not shown in the chart.

2022). Before analysing, the user should first select a best-seeing reference image (Alard & Lupton 1998; Huckvale, Kerins & Sale 2014) amongst the listed frames and locate the target, comparison, and guide (tracking) stars on this reference image. However, it may be challenging to find the target star in a crowded area. In this case, the OP has a *Locate Occ. Star* button to make the astrometric calibration of the field via *astrometry.net*, which compares quadruple or quintuple geometric hash sets created from detected stars on the image with pre-indexed patterns (Lang et al. 2010). The OP uses the index files for those pre-indexed patterns generated by Kilic, Erece & Kaplan (2018) from *Gaia* DR1 catalogue, which is more than adequate to automatically find the target star on the reference image. Moreover, the OP will perform the pre-reduction process as long as the pre-reduction option is active from the web interface since images have *IMAGETYP* keywords in the FITS header as Bias, Dark, or Flat. Lastly, it is essential to determine the suitable measuring aperture parameters of the target, comparison, and guide stars for the best photometric results.

The images must also be well-aligned to match the target, comparison, and guide stars over entire image series for a successful photometry. On OP, there are different alignment methods in use. Images are aligned with *alipy*³¹ on the first attempt. If this process fails for any reason, the *Astroalign* package (Beroiz, Cabral & Sanchez 2020) is used. If the *Astroalign* package does not succeed, OP finally triggers another alignment method named *find_source_in_roi*. This method is based on finding the brightest star in the desired *ROI* (*Region of Interest Box*), which limits the area shifting over box size, indicating the maximum shifting limit over sub-frames. If all alignment attempts fail, the OP system has the ability to do photometry as long as a coordinate file containing three stars' physical coordinates in all images is given. As an example, *PyMovie*'s result file may be used to provide those coordinates. After identifying the sources on each frame, the OP proceeds to the photometry stage. Here, photometry is performed using IRAF's *phot* task (Tody 1986; Stetson 1987) via *myraflib* (Kilic et al. 2016). The user defines the photometric aperture and sky annulus, in the web interface, which are kept fixed throughout the process. Once the photometry process is completed, the photometric results can be displayed for the target (occulted

²⁵<https://github.com/geopy/geopy>

²⁶<https://www.occultations.org.nz/planet/AsteroidReportFormTextV2.txt>

²⁷<https://www.nginx.com/>

²⁸<https://github.com/ponty/pyunpack>

²⁹<https://free-astro.org/index.php/SER>

³⁰<https://github.com/JaiedAI/EasyOCR>

³¹<https://github.com/japs/alipy>

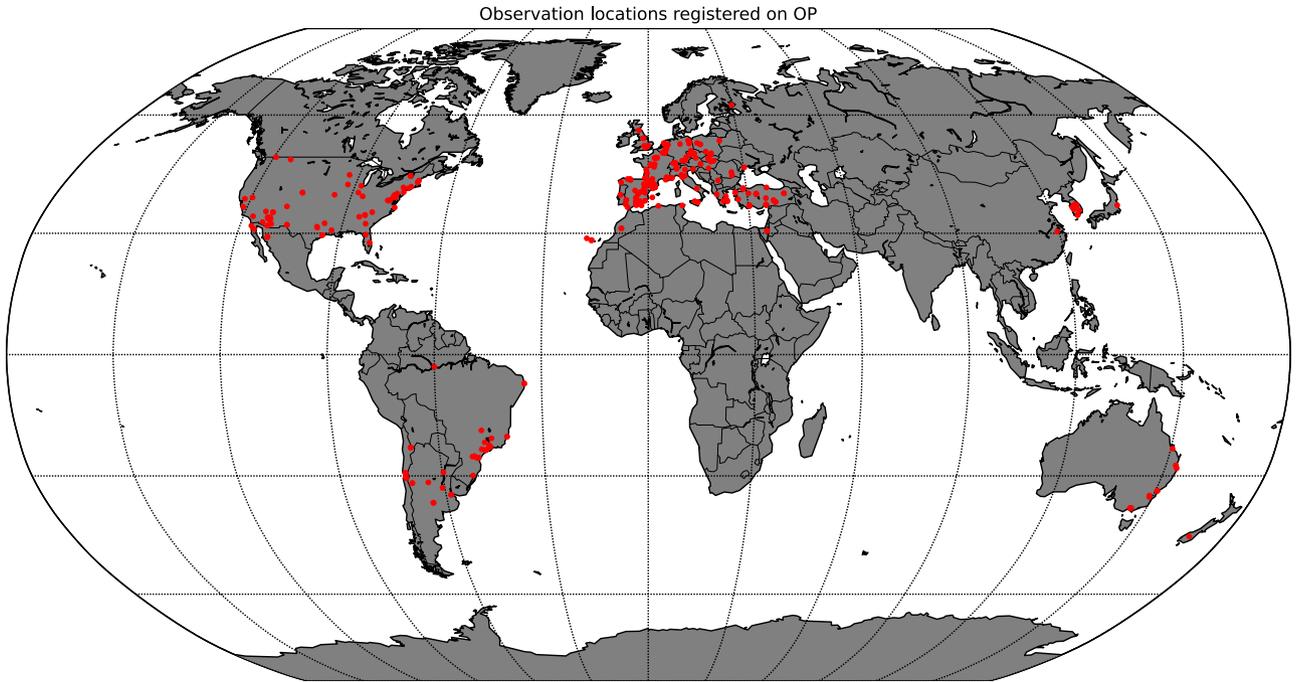


Figure 5. Occultation Portal: observers’ network. A total of 331 red dots indicate the observers’ locations registered on the OP. These could show either mobile stations or fixed telescopes. It is clearly seen that most of the locations are in Europe, while others are spread over North Africa, North America, South America, far East Asia, and some parts of Australia. As occultation events are announced in different parts of the world, we expect the number of registered observers to increase in the future and red dots to spread out.

star), reference, and guide stars as three light curves in the Results section, and the user is notified by the *Notification Service* via e-mail. These three light curves displayed using Highcharts³² are created with the help of the following equations.

Equation (1), where $F_{T(i)}$ denotes the normalized flux of the target star in each frame, $f_{T(i)}$ the instrumental flux of the target star measured from the i^{th} frame, and \bar{f}_T is the median flux of the target star calculated from all frames.

$$F_{T(i)} = \frac{f_{T(i)}}{\bar{f}_T}. \quad (1)$$

Equation (2), where $F_{R(i)}$ is the normalized flux of the reference star in each frame (i), $f_{R(i)}$ the instrumental flux of the reference star measured from the i^{th} frame, and \bar{f}_R denotes the median flux of the reference star calculated using all frames.

$$F_{R(i)} = \frac{f_{R(i)}}{\bar{f}_R}. \quad (2)$$

Equation (3), where $F_{N(i)}$ represents the ratio of $F_{T(i)}$ and $F_{R(i)}$ in each frame. This ratio mainly eliminates the variations on the target star due to atmospheric and instrumental effects, which cause a false variation in flux measurement. Nonetheless, as shown in Fig. 2, the OP allows users to visualize the *ROI BOX* where the photometry is applied to check whether it is an occultation event itself or not by clicking any point on the light-curve graph (see Appendix A3).

$$F_{N(i)} = \frac{F_{T(i)}}{F_{R(i)}}. \quad (3)$$

Finally, the user is now able to export the light curve (LC) in various formats, such as graphics or ASCII files. The ASCII LC

file is specially designed to be compatible with the SORA (Stellar Occultation Reduction and Analysis) software (Gomes-Júnior et al. 2022) to further exploit the data and characterize of the occulting object.

2.6 The Notification Service

The Notification Service informs the user and/or superuser(s) at the start or end of most running processes on the OP. All notifications, such as user management (registration, activation, account update, etc.), archive data requests, data analysis processes, announcements, user issue tracking, and server notifications are carried out by the Notification Service over the SMTP (Simple Mail Transfer Protocol) server via transactional e-mails.

2.7 Backup service

The database on the application server seen in Fig. 1 is backed up to the NAS (Network-attached storage) server with the *django-dbbbackup* tool.³³ After that, the data on the NAS is cloned to an asymmetric backup server daily with the *rsync* tool³⁴ incrementally.

3 RESULTS

The Occultation Portal (OP) has officially been in service since the 2002 MS₄ TNO occultation campaign event occurred in 2020 August 8, but as it was a test case, it was used by a restricted number of observers. As of 2022 May 23, 249 different occultation predictions provided by the Lucky Star Project and its collaborators have been

³²<https://www.highcharts.com/>

³³<https://github.com/jazzband/django-dbbbackup>

³⁴<https://rsync.samba.org/>

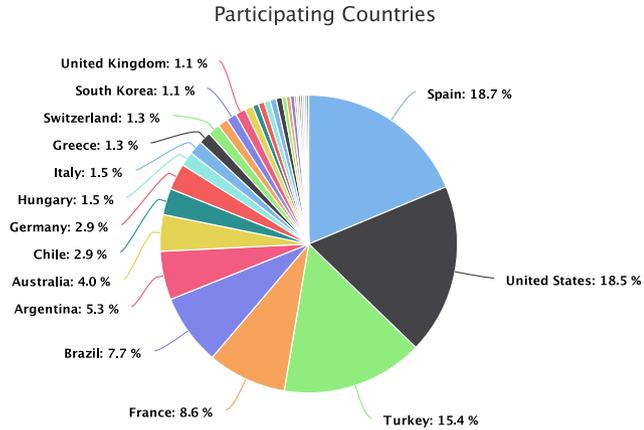


Figure 6. Occultation Portal participating countries so far between 2020 August and 2022 May. For the sake of clarity of the figure, the names of the countries contributing less than 1 per cent are not shown in the chart.

announced on OP as occultation campaign calls. For 115 out of those 249 campaigns, data is provided by at least one observer (chord). Due to various reasons, such as bad weather conditions, inaccurate predictions, observations from outside the occultation path, insufficient star brightness, etc., it is not expected to see the occultation event from all these data. 35.8 per cent of the events were reported as Positive, which means the disappearance of the target star can be seen because of the occultation event. All these statistics are shown in detail in Fig. 3, which can be accessed at any time via the OP.³⁵

Another important statistic that should be given is that of the dynamical classes of the objects that have been announced on the OP between 2020 August and 2022 May. It is clearly seen from Fig. 4 that the vast majority of the objects are beyond the main belt, which is mainly because the Lucky Star project focuses on primordial bodies. These objects are the unaltered remnants of the protoplanetary disc that existed in the early stages of our Solar System, they can thus supply us with critical information and invaluable constraints about the evolution of our Solar System (Lykawka & Mukai 2008; Morbidelli, Levison & Gomes 2008). In Fig. 4, NEAs are also seen at a proportion of ~ 20 per cent since the inclusion of occultation predictions of the ACROSS project,³⁶ whose primary goal is to improve the position accuracy of the NEAs in the Gaia frame.

The campaign conducted on OP with the highest participation of 56 chords was the occultation by TNO 2002 TC302 (84522) in 2021 November 11.³⁷ Together with this successfully conducted campaign, it can be expressed that OP has become an essential platform for occultation research. As of 2022 May 23, there are 301 registered users on the OP. The number of observation locations recorded by these users is 331. These locations are shown on the map in Fig. 5. Besides, the status of these observers based in their countries is given in Fig. 6, it should be noted that these graphs may change over time.

Another interesting result from the OP is the number of telescopes by aperture size used in the campaigns. Statistics of the number of telescopes by aperture size generated from the information provided by those 301 registered users are represented in Fig. 7. These statistics show us that, the biggest proportion (~ 28 per cent of the

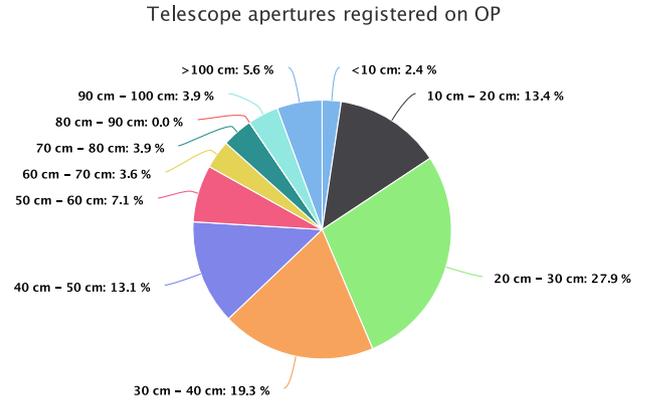


Figure 7. Telescope diameters registered on OP between 2020 August and 2022 May. In the chart, the most notable point is that most of the registered telescope diameter (> 75 per cent) are less than 50 cm in diameter. It means that stellar occultation observations can be considered independent of telescope diameter as long as the occulted star is bright enough.

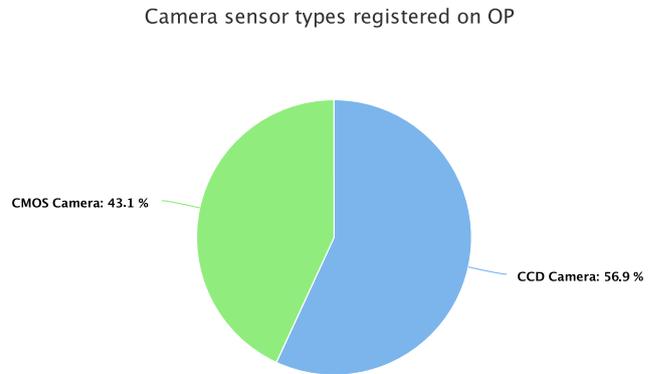


Figure 8. Camera types registered on OP between 2020 August and 2022 May. While CCD Camera refers to an astronomical detector with a CCD sensor produced mainly by Andor, FLI, Apogee, SBIG and, Watec, etc., CMOS Camera refers to a camera that uses a CMOS-based image sensor that most observers are using, such as QHY cameras, RunCam, ZWO ASI, etc.

registered telescopes) are small telescopes with diameters in the range of 20–30 cm. Furthermore, most of the registered telescope apertures are less than 50 cm (> 75 per cent). It can be clearly stated that as long as the occulted star is bright enough,³⁸ relatively small aperture telescopes are of paramount importance for stellar occultation observations. This is also an indication that the substantial number of participants taking part in the campaigns are amateur astronomers.

In Fig. 8, it is seen that 56.9 per cent of the cameras attached to the telescopes are CCD (Charge-coupled device) cameras, and ~ 20 per cent of them consist of only Watec video cameras, followed by CMOS (Complementary metal-oxide-semiconductor) cameras (43.1 per cent). It can be seen that the number of CCD and CMOS cameras are close to each other. This shows that not only CCD cameras but also CMOS cameras are now contributing on observational studies.

One of the most important services of the OP is *Data analysis and reduction service*, where photometric results are produced. To measure the reliability of the photometric results, *photutils* (Bradley

³⁵<https://occultation.tug.tubitak.gov.tr/statistics/>

³⁶<https://lagrange.oca.eu/fr/goals>

³⁷<https://lesia.obspm.fr/lucky-star/occ.php?p=75799>

³⁸<https://occultation.tug.tubitak.gov.tr/statistics/>

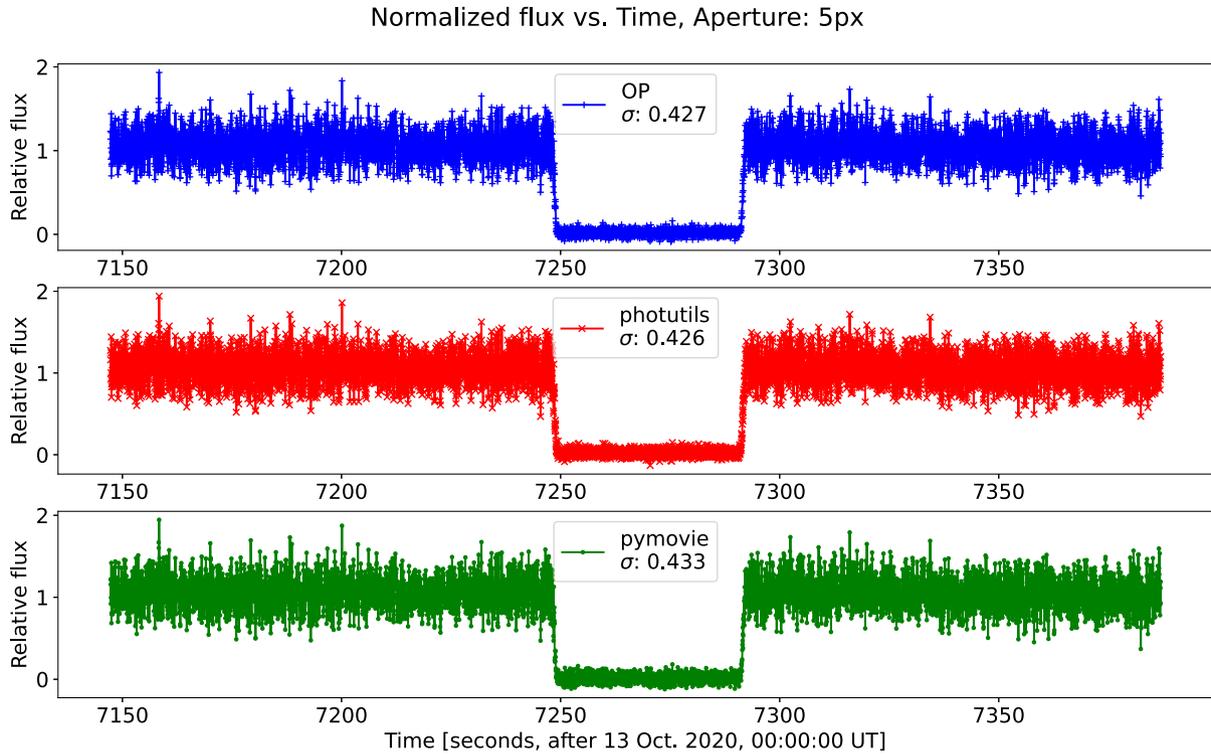


Figure 9. Data analysis and reduction service benchmarking. This graphic was created as a result of photometry of 7184 frames. It shows the light curves for a positive stellar occultation observation of a large TNO 28978 Ixion recorded by Ted Blank in 2020 October 13. The light curve with the blue plus markers at the top is obtained by using *OP*'s photometric reduction method. The red one in the middle with cross markers was obtained with *photutils*, while the green one with dot markers at the bottom was obtained with *PyMovie*. The σ represents the standard deviation in the light curve in the graphs.

et al. 2020) and *PyMovie* were used. The results were compared, using data from the observation of the occultation by Ixion in 2020 October 13,³⁹ and the results obtained with all tools are plotted in Fig. 9. As can be seen in Fig. 9, the standard deviation (σ) of the photometric analysis results is not much different from the others.

Finally, the Occultation Portal runs on Pardus (19.3), a Debian-based GNU/Linux operating system developed by the Turkish Academic Network and Information Center (ULAKBİM). It was in service when the 2002 MS₄ campaign event took place in 2020 August 8. Since the launch of OP, the MTD (Mean Tolerable Downtime) of the system is less than 1 h. The system has been down six times since being in action; however, that was all due to scheduled maintenance.

4 DISCUSSION AND CONCLUSIONS

In this paper, we presented the details of the OP's current system architecture and workflow in detail. The current version of the OP (v2.11-beta) has all the components to support the occultation science on campaign announcement, data collection, archiving, management, and reduction to produce results efficiently. With hundreds of events, it has been demonstrated that the OP efficiently stores observational information while easing data archiving, analysis, and management. On the long run, observational data and database size on OP will increase considerably, and improved data science methods will have to be used to store and process this data effectively and efficiently. Considering the extensive impact of the *LSST* and *Gaia*'s subsequent

releases on occultation observations, it might also be an excellent solution to make data of the OP public later following IVOA standards. (Arviset et al. 2010).

Primarily the OP was a customized platform only for the Lucky Star campaigns; but now, with the implementations made after the participation of the ACROSS project to the OP, any prediction with the *occultation elements file* in the XML format on the OW Cloud can be added/announced on the OP by the authorized users. Yet, the OP can become a common stellar occultation data collection centre of all groups, such as those mentioned in Section 1. Along with a common central server, another plan is to make the source code available under a free software licence (e.g. GNU GPL v3) for the stand-alone server deployments of the OP for other research organizations and teams.

Being the OP served from a single location, the time to upload large-scale observational data will increase for the users on far locations, such as different continents. So, to prevent this and limit the time loss, it has been planned to deploy the on-premise mirror servers located in different zones. Besides, the system will have better high availability and higher fault tolerance. The other option to achieve these goals is to migrate all systems to a Cloud Platform. These plans heavily depend on the continuous funding of the platform, budget, and labour force. Currently, OP only has the prediction service API, but in the future, it is planned to offer all services as API or with a client running on the terminal.

In stellar occultation campaigns, it is obvious that small telescopes make great scientific contributions. Accordingly, OP is a great platform to gather these small telescopes around the world, which can together have an extraordinary impact on citizen science. As a result, with this system, we especially encourage amateur astronomers to use their telescopes for scientific purposes, and thus we offer a

³⁹<https://lesia.obspm.fr/lucky-star/occ.php?p=41312>

non-profit, scientific and time-saving practical portal that effectively brings together both researchers and amateur astronomers.

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DATA AVAILABILITY

All assets, data, and documents used in this article are available on <https://occultation.tug.tubitak.gov.tr/> and <http://occultationportal.org/>. Source code may be shared on reasonable request to the corresponding author.

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APPENDIX A: SUPPLEMENTARY FIGURES

Some screenshots of the *OP* front-end (v2.02-beta) are provided for illustrative purposes to interest the reader.

2010JO179's chord(s)

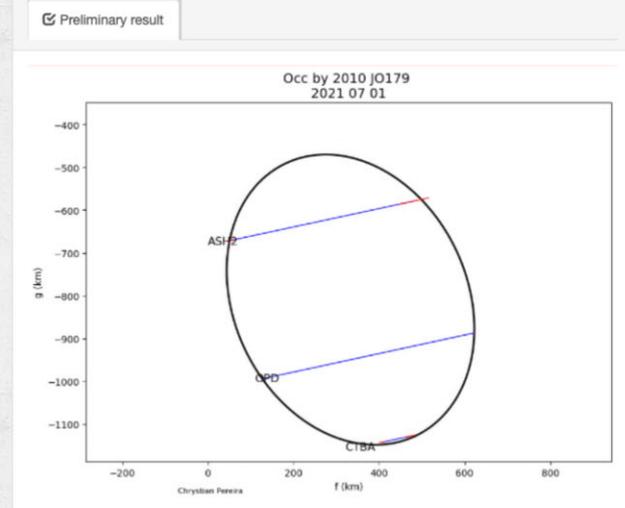
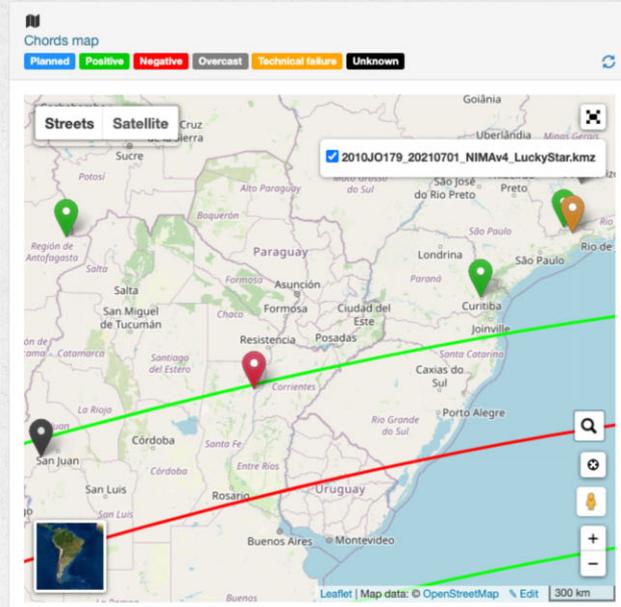
July 1, 2021, 3:03 a.m.

PDF Copy Excel CSV Print Column visibility Search:

Event	Observer(s)	Site	Status	Telescope aperture (mm)	Camera	Exptime (s)
2010JO179	R. Sfair, A. R. Gomes Jr	FEG	Technical failure	406.0	Merlin 247 Raptor	
2010JO179	Nico Morales	Spaceobs San Pedro de Atacama- ASH2	Positive	407.0	SBIG STL11000	5.000
2010JO179	Mario Melita & Luis Mammana	CASLEO	Unknown		SBig	12.000
2010JO179	G. Benedetti Rossi, G. Margoti, C. L. Pereira	Observatorio do Pico dos Dias, Itajuba	Positive	1600.0	Anfor - Ixon	
2010JO179	Felipe Braga Ribas	F10999 - Curitiba	Positive	254.0	QHY174M-GPS	1.500

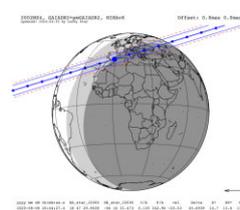
Showing 1 to 7 of 7 entries Previous 1 Next

Total 7 (Planned : 0, Positive : 3, Negative : 1, Overcast : 1, Technical failure : 1, Unknown : 1) chords are listed.



TUG UT FPR
©2022 Copyright: OccultPortal (v2.02-beta)

Figure A1. The front-end of the chords report page. The successful occultation campaign by the TNO (574372) 2010 JO₁₇₉ dated 2021 July 1, is chosen as an example. Each observer can see the information of each reported observation, and can edit his own information previously provided. The lower left-hand panel displays a map showing the positions of the observers across the predicted shadow path with colors representing the reported result. The lower right-hand panel presents an image which can be uploaded by the *staff* or *event responsible*. Usually it presents a preliminary limb fit obtained from that campaign.



**(307261)
2002MS4**

08 Aug 2020 20:44:27
(yucel.kilic) **Yucel Kilic,**
Orhan Erece, Sila
Eryilmaz TUBITAK
National Observatory
(T100)

Status: Negative
Obs. start (UT): 20:32:33
Obs. end (UT): 20:48:29
Telescope: T100 (1000 mm)
Detector: SI 1100 (SOE)
Filter: Clear

[Update Info](#)

[ROI Image](#)

[Occ. Report](#)

Add New Occultation Data
Analyse
Results

Add New Occultation Data

[Upload Data](#)
[Request Event Data](#)

Info! Please consider the explanations below. ✕

- Compress the observational data and calibration data (if any) into a single file (Ex: 20210501_Ixion.zip).
- The file formats allowed to upload are: .zip, .rar, .gz, .7z, .fit(s), .avi, .adv, .aav, .ser formats.
- Please do not close the page before the **uploading progress bar disappears**.
- The upload limit for the video file is **4 GB (4096 MB)**. If you have a larger video file, please send an e-mail to yucel.kilic@tubitak.gov.tr.

PDF
Copy
Excel
CSV
Print
Column visibility

Search:

Actions	Event	File	Image Type	NAXIS
+ Edit ✕ Delete	(307261) 2002MS4	2002MS4_0002_Empty.fits 92.8 KB	Light	211x211
+ Edit ✕ Delete	(307261) 2002MS4	2002MS4_0003_Empty.fits 92.8 KB	Light	211x211
+ Edit ✕ Delete	(307261) 2002MS4	2002MS4_0004_Empty.fits 92.8 KB	Light	211x211
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+ Edit ✕ Delete	(307261) 2002MS4	2002MS4_0018_Empty.fits 92.8 KB	Light	211x211
+ Edit ✕ Delete	(307261) 2002MS4	2002MS4_0019_Empty.fits 92.8 KB	Light	211x211
+ Edit ✕ Delete	(307261) 2002MS4	2002MS4_0020_Empty.fits 92.8 KB	Light	211x211
+ Edit ✕ Delete	(307261) 2002MS4	2002MS4_0021_Empty.fits 92.8 KB	Light	211x211

Showing 1 to 20 of 156 entries
Previous 1 2 3 4 5 ... 8 Next

Total 156 frames are listed.



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Figure A2. A sample report page of an observer who provided data to the observation campaign for the occultation by Ixion in 2020 August 8. On this page, the observer and all authorized users can upload data with the *Upload Data* button, request all reported information and data with the *Request Event Data* button, update information about the observation with the *Update Info* button, view the additional files uploaded by the observer with the *Additional Files* button, and view the status report of the observation in Asteroidal Occultation Report format with the *Occ. Report* button.

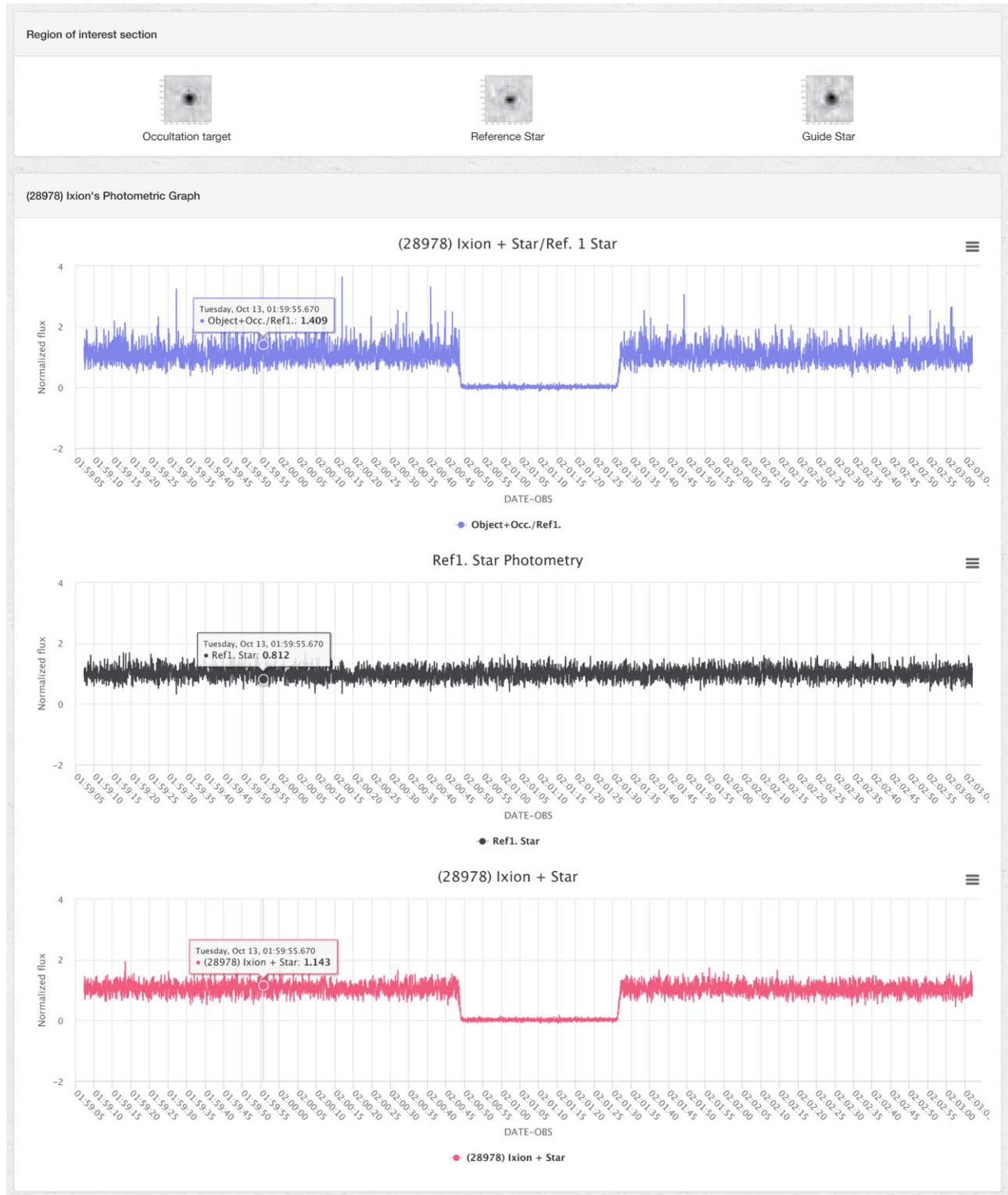


Figure A3. Aperture photometry result page displaying the obtained light curves. The small images at the top of the figure change according to each clicked point on the graphic. Thus, the user can visually examine the occultation event. The blue graph shows the light curve ratio of the ‘target star + Solar System object’ to the reference star, the black graph shows the normalized light curve of the reference stars, and the red graph shows the normalized light curve of the ‘target star + Solar System object’ only.

This paper has been typeset from a $\text{\TeX}/\text{\LaTeX}$ file prepared by the author.