Performing Automated, High-Speed Photometry on Occulting, Small Outer Solar System Bodies

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Abstract

Monitoring stellar occultations provides a powerful means to measure the shapes and sizes of small Solar System bodies, but produces large quantities of image data which can be laborious to analyse. An automated Python-based software, `occ_find`, was written for performing high-speed aperture photometry on `spool` files packed with large volumes of images from the 1.54m Danish Telescope. `occ_find` processed 11 `spool` files at a maximum rate of around 4-6 minutes per `spool` file, without image reduction. From these files, 3 occultation events were detected. The measured chord lengths are consistent with prior size measurements of these small bodies.

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Introduction

Of the many small bodies that exist in the Solar System, there is an enormous variety in their shapes and sizes, and there exists a plethora of methods for measuring them, as well as looking for the presence of rings and/or satellites. Such methods include spacecraft visits, radar observations, and lightcurve shape modelling; that is using changes in the brightness of the body with time to model its approximate shape (Kaasalainen *et al.* 2001a,b).

Stellar occultation events provide another means of measuring the shapes and sizes of small bodies. A stellar occultation is where a small body within the Solar System passes through the line of sight to a background star, causing it to be blocked momentarily. Since the stars are significantly further from the observer than the occulting body, the rays of light emitted can be approximated as parallel. Therefore, the shadow the body casts on the Earth will be the same size and shape as the body. By measuring the duration of the occultation, t_{occ}, and the orbital speed of the body relative to Earth, v_{rel}, the length of the occulting body in the direction of travel at a particular point on the Earth – referred to as the 'chord' of the occultation, l_{chord} – can be calculated:

$$l_{\mathrm{chord}} = v_{\mathrm{rel}} t_{\mathrm{occ}} \tag{1}$$

Measuring at least 3 well separated chords (that is, the chords are measured from points on the Earth with sufficiently different latitudes) sampling the same aspect of the body is sufficient to determine it's size assuming an ellipsoidal shape, true of large Trans-Neptunian Objects (TNOs) and dwarf planets. Furthermore, multiple chords allow us to accurately constrain the shape of smaller, more irregular bodies such as (486958) Arrokoth (Lissauer *et al.* 2019; Buie *et al.* 2020).

Stellar occultation measurements have led to several major Solar System discoveries such as the discovery of ring systems around the planets Uranus and Neptune (Elliot *et al.* 1977; Reitsema *et al.* 1981), and more recently, the centaur (a type of small body inhabiting the region between the orbits of Jupiter and Neptune) (10199) Chariklo, along with numerous other small bodies since then (Braga-Ribas *et al.* 2014; Ortiz *et al.* 2017; Pereira *et al.* 2023). Occultation measurements also revealed the presence of

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the Neptunian satellite Larissa (Hubbard *et al.* 1986), its existence later confirmed by Voyager 2 (Smith *et al.* 1989).

Monitoring stellar occultation events presents a number of technical challenges – rapid imaging (10 Hz frame rate in this work) of the target star is required to accurately capture the drop-off in stellar flux, resulting in a large volume of image data ($\sim 10^3$ images or $\sim$1 GB of data for a typical observation). Because of this, without some sort of automation: analysis of these images is a very laborious and time-consuming task. Furthermore, due to uncertainty in the predicted size, shape, and path of the body, there is no way to guarantee in advance that an occultation will be observed at a particular location on the Earth. Therefore, a set of images from an observation is not guaranteed to yield a chord.

Automated photometric pipelines provide a convenient solution to some of these challenges (Assafin *et al.* 2011; Anderson 2019; Pavlov 2020). These pipelines allow for rapid processing and analysis of image data, which provides a tool for the observer to determine whether or not an occultation was detected immediately after an observation is made. Furthermore, this allows for quick identification of occultation events from large archives of observational data spanning many years. The processed data can then be used to assist the efforts of groups monitoring occultation events (LESIA 2022; IOTA 2024).

In this work, I wrote a Python software package called `occ_find` to extract and analyse image data from an archive of `spool` files taken by the Lucky Star Project using the Two Colour Instrument (TCI) on the 1.54m Danish Telescope at La Silla, Chile. The TCI supplies HDF5 (Hierarchical Data Format) `spool` files containing image data. HDF5 is a compact data file format allowing storage of large volumes of image data (and associated metadata) from each observation. Following extraction, aperture photometry – the measurement of flux from a source within a fixed region of the image – was performed on all detected stars in each image. The software returns a lightcurve, a plot of the stellar flux against time, for each star in the images. The lightcurves can be manually inspected for occultation events (see Results and Analysis section). The lightcurves, photometry, and time data was also saved in multiple formats to enable further processing by the user if required. `occ_find` was tested on an archive of 11 `spool` files, and the chord lengths calculated from any detected occultation events were compared with past size measurements of the target bodies.

Methods

The `occ_find` package consists of three Python scripts:

1. `h5_unpack` – for extraction and conversion of datasets from the HDF5 file to either `.fits` (image data) or `.txt` (metadata) file format.
2. `reducto` – for image reduction to account for instrumental errors and biases; optional, see below.
3. `occ_find` – for detecting stars in the images and plotting their lightcurves.

The HDF5 `spool` files must first be unpacked for analysis; when `h5_unpack` is called, the files are saved into a `spool` directory, with all image data saved into its own sub-directory called `images`. At this point, the software `reducto` can be called to perform image reduction using bias and flat-field images supplied within the `spool` files, if required. Image reduction with `reducto` is not essential if the user simply wishes to process a large archive to quickly find occultation events, however, reduction is recommended if any further analyses are to be performed. `occ_find` opens the first `.fits` image from the `spool` and uses a star-finding routine to detect the sources within it (Bradley *et al.* 2023). If sources are found, `occ_find` proceeds to perform aperture photometry at their pixel coordinates in every `.fits` image extracted from the `spool` file, recording the photometry results in a `.txt` file. Finally, the lightcurves are plotted from this data and the time data (extracted from the `spool` file by `h5_unpack`).

Results and Analysis

11 `spool` files (with a typical size of $\sim$1.5 GB) were processed using the `occ_find` package on a Dell Latitude E7450 laptop with an Intel i5-3500 processor. 3 occultation events were detected from the TNOs: (278361) 2007 JJ_{43}, (28978) Ixion, and (120347) Salacia. Their lightcurves, as shown in Figures 1a-c, display a very sharp drop in stellar flux during the occultation, unlike a null result as shown in Figure 1d. In Figure 1d, the variation in stellar flux is due to changing observing conditions. The

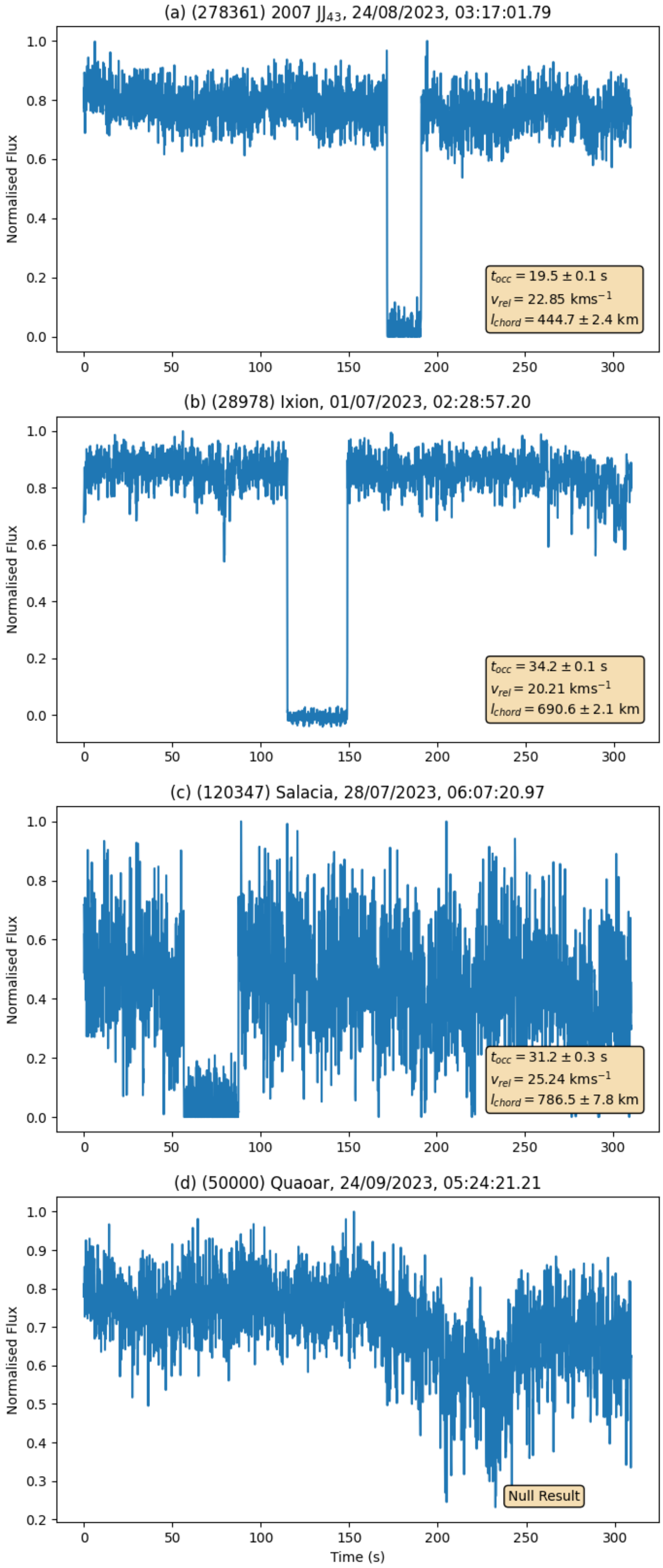

Figure 1: Lightcurves with date and start time of the observation, in UTC, for: **(a)** (278361) 2007 JJ_{43}, **(b)** (28978) Ixion, **(c)** (120347) Salacia, and **(d)** no occultation event (the occulting body targeted was (50000) Quaoar). The relative velocities are taken from the predictions for each event (Lucky Star Project 2023a,b,c).

chord lengths of these bodies calculated using equation (1), and the relative velocity predictions for these events (Lucky Star Project 2023a,b,c), are between 400 and 800 km. This is consistent with prior size measurements of these bodies in literature (Barry *et al.* 2015; Pál *et al.* 2015; Brown *et al.* 2017; Grundy *et al.* 2019; Rommel *et al.* 2020; Levine *et al.* 2021).

The total runtime of the code was on average, ∼4-6 minutes per `spool` file, without image reduction. Adding image reduction increased the runtime by a factor of ∼3, but reduction is not essential for detecting occultations given the significant drop in flux during an event. Without automation, measuring the fluxes of each star in each image using a software such as GAIA (Currie *et al.* 2014) would be prohibitively laborious.

`occ_find` does possess some limitations – it cannot account for any telescope movement throughout the course of the observation (e.g "dither"), which may lead to inaccuracies in the photometry, nor is it well optimised for detecting fainter sources or poor observing conditions, leading to false source detection amongst background noise. Fortunately, false sources are easily distinguished from true lightcurves and occultation events by manual inspection.

Conclusions

Overall, the code allows for rapid processing of large archives of `spool` files to find occultation events, though there are some limitations and scope for improvement. Future work will include updating the code to account for false sources, telescope dither, and to remove null-results. Furthermore, I aim to test of the software on a wider range of `spool` files to further analyse it's performance. In summary, `occ_find`, and photometric pipelines like it, yield the opportunity to monitor occultation events, accurately measure the shapes and sizes of many small bodies, and build a better understanding of their size and shape distribution throughout the Solar System as a whole.

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This work made use of Photutils, an Astropy package for detection and photometry of astronomical sources (Bradley *et al.* 2023).

Software Availability

The code written for this project is available at: `https://github.com/BenAttwood449/occ_find.git`.

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