THE *SSOS* PIPELINE: IDENTIFICATION OF SERENDIPITOUSLY OBSERVED SOLAR SYSTEM OBJECTS IN IMAGES OF GROUND-BASED OBSERVATORIES

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Abstract

Discovery and identification of Solar System Objects (SSOs) are necessary preceding steps to their characterization. We present here a versatile minor planet detection pipeline to search for asteroids in public image archives. The *ssos* pipeline is able to identify both known and unknown minor planets in astronomical images primarily based on their apparent motion. Its foundation on the widely-used SExtractor and SCAMP software as well as a high degree of configurability make it applicable to almost any type of observation campaign.

We outline the methodology of the pipeline and present the results of its application on images acquired by GTC/OSIRIS (DR1), OAJ/T80Cam (DR1), and UKIRT/WFCAM (WST), including the detection of about 6,000 SSOs in 45,000 images. About 5,000 of these objects could be linked to known objects, from close near-Earth asteroids to distant objects of the Kuiper Belt.

1. Introduction

Serendipitous observations of Solar System Objects (SSOs) are a common by-product of astronomical imaging campaigns. The astrometry and photometry of these chance encounters help discovering new objects, refining orbit calculations, and physically characterizing and grouping them. The minor planets community has made extensive use of these observations, recovering the visible and near-infrared colours and albedos of hundreds of thousands of SSOs e.g. in 2MASS [1], SDSS [2], NEOWISE [3], and VISTA-VHS [4].

However, while the data comes at no additional cost in observation time, the development of a recovery pipeline to automatically extract the astrometry and photometry can require extensive time and funding investments. Observational campaigns led by smaller institutes may not be able to expend these efforts and the possible science is archived without being used.

We present here the *ssos* pipeline, a versatile minor planet detection pipeline developed with a focus on ease-of-use and minimal requirements to the imaging data. With it, we aim to lower the threshold of asteroid detection projects and allow a robust recovery for all observation campaigns.

2. Pipeline

A broad outline of the detection principle and the practical application of *ssos* are given here. Please refer to [5] for details.

2.1 Theory

The basic principle of the *ssos* pipeline is based on the blinking method which has already been used for decades to discover minor planets. In essence, the changes in position of each source over the observation epochs is evaluated. If sources move fast and in a linear fashion, they are likely SSOs. Basing us on this principle only, we achieve a pipeline with the minimal requirement of three consecutive images of an overlapping area in the sky to to identify SSOs.

To translate this principle into a robust algorithm, in a first step, all sources in all input images are registered and catalogued using SExtractor, a widely-used software part of the AstrOmatic software suite [6]. The output catalogues are input into SCAMP, which is part of the AstrOmatic software as well. Using a reference catalogue such as Gaia DR2, the sources registered in different images at different epochs are cross-matched against each other. By evaluating the differences in the positions of overlapping detected sources in pairs of images, SCAMP accounts for shifts, rotations, and distortions between the images and assigns source detections belonging to the same source a unique source ID. Refer to [7] for a detailed explanation of the process.

At this point in the pipeline, we differentiate the SSOs from the stars, galaxies, and other sources in the images much like it is achieved using the blinking method: we evaluate the apparent motion based on its absolute value and linearity. In addition, several other filter algorithms like the number of minimum detections and a bad-pixel rejection are implemented to reject artificial sources arising e.g. from cosmic rays.

2.2 Practice

The practical application of *ssos* was set-up with a simple and straight-forward approach in mind, while closely mimicking the command line interfaces of the underlying AstrOmatic software. The user adjusts the settings of SExtractor, SCAMP, and *ssos* itself to the images at hand, while *ssos* handles the image and catalogue dependencies. The online documentation at [8] contains detailed instructions on how to set-up the pipeline and find the right settings.

ssos is written in python3 and can be retrieved from the Python Packaging Index using

$ `pip install ssos` (1)

from the command line. Note that the python version must be >= 3.6 and the package dependencies such as numpy and astropy should be the latest versions.

To dump the default configuration to the current working directory, use

$ `ssos --default` (2)

After adjusting the configuration files of SExtractor, SCAMP, SWarp, and *ssos*, the pipeline is run using

$ `ssos path/to/images` (3)

The input are images in FITS format.

3. Applications

3.1. OAJ/T80Cam: J-PLUS DR1

We applied the *ssos* pipeline to the first public data release of the J-PLUS survey executed at the Observatorio Astrofísico de Javalamabre. J-PLUS images are acquired with the T80Cam, a camera covering a 1.4 x 1.4 degree field-of-view covered with 9,500 x 9,5000 pixel CCD. A total of 6,132 images split up into 511 tiles covering in total 1,020 square degree of the sky was searched with *ssos*.

We recovered 34,014 detections of 4,606 unique SSO candidates, with an estimated false-positive rate of about 2%. Using the IMCCE SkyBoT service, we cross-matched our output sample with the known SSOs within a radius of 10 arcseconds and thus identified 3,932 objects, including three Near-Earth Asteroids (NEAs) and one Trans-Neptunian Object (TNO). Please refer to [5] for details.

3.2. GTC/OSIRIS: Broad Band DR1

The minimal requirements of *ssos* on the imaging campaigns means that we can apply it not only to survey data, but also PI-led campaigns, such as executed at the Gran Telescopio Canarias (GTC). The OSIRIS camera covers a field-of-view of 7.8 x 7.5 arcminutes.

The varying exposure cadence and durations of the observation campaigns, aiming to observe anything from SSOs to galaxy clusters and gamma-ray bursts, can be accounted for by adapting the *ssos* pipeline parameters at runtime based on the image metadata, which is particularly helpful when associating source detections with SCAMP.

In the 8,096 images of the GTC OSIRIS Broad Band DR1, we recovered 2,828 minor planet detections belonging to 204 unique objects. Again relying on the SkyBoT service, we identified 63 of them as known objects. Please refer to [5] for details.

3.3. UKIRT/WFCAM: WTS

The WFCAM Transit Survey (WTS) aimed at finding exoplanets transiting cool dwarf stars using the WFCAM at the United Kingdom Infrared Telescope (UKIRT). The field-of-view of the WFCAM is split into four parts, covering 13.65 x 13.65 arcminutes each.

30,558 images were searched using *ssos*. We detected 1,165 distinct SSOs with a total of 9 897 detections. 983 SSOs were identified as known objects using SkyBoT. Please refer to [8] for details.

4. Conclusion and Outlook

Our application highlights the potential of this method and harvesting public image archives for SSO detections. Identifying the vast amount of asteroids hidden in these archives can greatly reduce the ephemeris uncertainties and add valuable photometric measurements for spectral classification, a fundamental tasks in their characterization.

We are improving *ssos* with every new application. A major improvement will be an increased completion by using the SkyBoT cross-match information already at the phase of SSO differentiation from the other sources in the images.

5. References

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