Searching for Space Debris Elements with the "Pi of the Sky" System

M. Sokołowski, M. Należyty, A. Majczyna, R. Wawrzaszek, P. Wajer

Abstract

The main purpose of the "Pi of the Sky" system is to investigate short timescale astrophysical phenomena (particularly gamma-ray bursts, optical transients and variable stars). Wide field, short exposures and full automation of the system, together with effective algorithms, give good prospects for effective identification of space debris elements. These objects can be a great danger for current and future space missions, and should be continuously monitored and cataloged. Algorithms for identifying optical transients (OT), designed for the "Pi of the Sky" experiment enable moving objects like planes, satellites and space debris elements to be identified. The algorithm verifies each OT candidate against a database of known satellites and is also able to automatically self-identify moving objects not present in this database. The data collected by the prototype in the Las Campanas Observatory enabled us to obtain a large sample of observations of moving objects. Some of these objects were identified as high-orbit geostationary (GEO) satellites, which shows that it is possible to observe even distant satellites with small aperture photo lenses. The analysis of the sample is still going on. The preliminary results and algorithms for automatic identification of moving objects will be described here.

Keywords: space debris, robotic telescopes, satellite observations, satellite tracking, optical transients.

1 Introduction

Space debris consists of objects originally launched by humans, which now orbit the Earth but are no longer in use. They can be upper stages of rockets, dead satellites, engine modules of geostationary satellites, remnants from satellite collisions, etc. Collisions of these elements moving at a speed of several km/s can destroy active satellites and can in the worst case be dangerous for astronauts on missions (spacecraft or space stations). This problem was spectacularly demonstrated in reality on 12 February 2009, when the Irridium 33 and Cosmos 2 251 satellites collided over northern Siberia at relative speeds of about 11 km/s. The crash produced thousands of new pieces of space junk, which can be dangerous for other satellites. Such elements should be cataloged and continuously monitored to enable satellites and spacecraft to avoid them.

Most space debris elements populate Low Earth Orbits (LEO), but the number of objects near to geostationary orbit (GEO) is constantly growing. There are about 13 000 artificial objects in the Earth's orbit, fewer than 800 of which are active satellites, while more than 12,000 are space debris elements larger than 10 cm. In principle, the only way to avoid collisions with potentially dengerous space debris elements (larger than 1 cm in size) is by manoeuvering spacecraft. However, in order to do this, space junk elements must be continuously monitored and cataloged. Efforts are being undertaken by national and international space agencies to discover and monitor space debris elements. The largest existing catalog of objects in the Earth orbit is the Space Object Catalog, provided by NORAD (North American Aerospace Defense Command), which is based on a network of optical and radio telescopes of various apertures. Systems like NORAD typically work in two modes. In wide-field mode they can discover new space debris elements, which are later precisely tracked by narrow field instruments. Long term narrow mode observations enables precise determination of orbital parameters. The orbital elements are stored in the Two Line Elements (TLE) format which, besides identifiers, consists of ten parameters fully describing the object's orbit [1]. There are also initiatives in Europe to create a system similar to NORAD. One of the ideas is the Space Situational Awareness program (SSA). The first stage of such a system is the European Space Surveillance System (ESSS) [2], which was proposed for automatic detection and identification of space debris pieces, and for determining orbital elements. It will track objects from LEO orbits and predict their movements. Natural candidates to join such a system are robotic telescopes. These instruments work automatically with almost no human attention. They also perform automatic data analysis, which is expected in the ESSS. In many cases they run algorithms very similar to those required for discovering space debris. Examples of European telescopes already tracking elements in the Earth orbit are TAROT (FOV of $2^\circ \times 2^\circ$) and Starbrook (FOV of $10^\circ \times 6^\circ$) [2].

Another component of this system will be wide-field optical systems like "Pi of the Sky". The purpose of this study is to verify the ability of the "Pi

Parameter	Prototype	Final
focal length	85 mm	85 mm
focal ratio	1.2	1.2
CCD Sensor brand	Fairchild	STA
CCD size	$2\,048 \times 2\,048$ px	$2\,048 \times 2\,048$ px
FOV	$20^\circ \times 20^\circ$	1.5–2 steradians
CCD pixel size	15×15 μm	15×15 μm
time of exposure	10 s	10 s
relative accuracy of shutter synchronization	20 ms	20 ms
limiting magnitude for stationary objects	12^m	12^m
average accuracy of astrometry	10arcsec	10arcsec
# of CCD cameras	2	2×12 (goal 2×16)
# of mounts	1	2×3 (goal 2×4)

Fig. 1: Basic parameters of "Pi of the Sky" telescopes. The image on the left shows the prototype system installed in the Las Campanas Observatory in Chile between 2004 and 2010

of the Sky" system to observe and automatically discover objects in the Earth's orbit (satellites or space debris).

2 "Pi of the Sky" system

The "Pi of the Sky" system [3, 4] was originally designed for observing short timescale optical events, particularly optical counterparts of gamma-ray bursts (GRBs), optical transients, and to monitor variable objects (stars, blazars etc.). The system is remotely controlled, fully automatic, to a large degree autonomous, and performs automatic data analysis. Special algorithms were designed and developed in order to automatically discover optical transients and discover new objects in the sky [5, 6, 4]. The final version of the system is currently under construction. The prototype system was installed in the Las Campanas Observatory in Chile (Figure 1) between 2004 and 2010. The prototype consists of two cameras, which observe the same field in the sky and collect images in synchronized mode. Besides its primary scientific goals, the data from the prototype has allowed to study the potential of the system for discovering and identifying space debris. The final system will have a substantially larger FOV (the final goal is 2 steradians), which will allow the system to look for new pieces of space debris more effectively (more information can be found in [3]). The data from the prototype verified the system capabilities, and further developed the algorithms and software tools for space debris oriented analysis. Figure 1 gives a summary of the parameters of the prototype and the full version of the system.

3 Satellites in "Pi of the Sky" data

The algorithms designed for identifying the short optical transients in the "Pi of the Sky" data are described in detail in [6]. The on-line algorithm analyses images while they are being collected by the camera, and looks for new objects appearing in the sky. In the first step, the algorithm finds objects which appear in the new image, but were not present in previous images. After this step, a list of flash candidates is created, then further cuts are applied in order to reject the background (mostly cosmic rays hits, hot pixels, sky background, star fluctuations etc.). One of the most important cuts at this stage is the coincidence of two cameras, requiring the optical transient to be visible in two cameras. This cut eliminates cosmic rays striking one of the CCD chips. After the coincidence cut, a list of real flashes from the sky is obtained. Most of them are due to moving objects, e.g. planes, satellites, and perhaps space debris elements. The primary goal of the algorithm is to identify OTs from natural astrophysical sources, so such objects must be identified, flagged, excluded from the sample of OT candidates, and saved to log files. Then another algorithm can simply be used to analyze the objects in detail and look for space debris elements.

In order to reject most of these events, databases of orbital elements in Two Lines Element (TLE) format are retrieved from the Internet (mainly from the NORAD website) every evening. They are combined into a single large database containing $\approx 13\,000$ or-

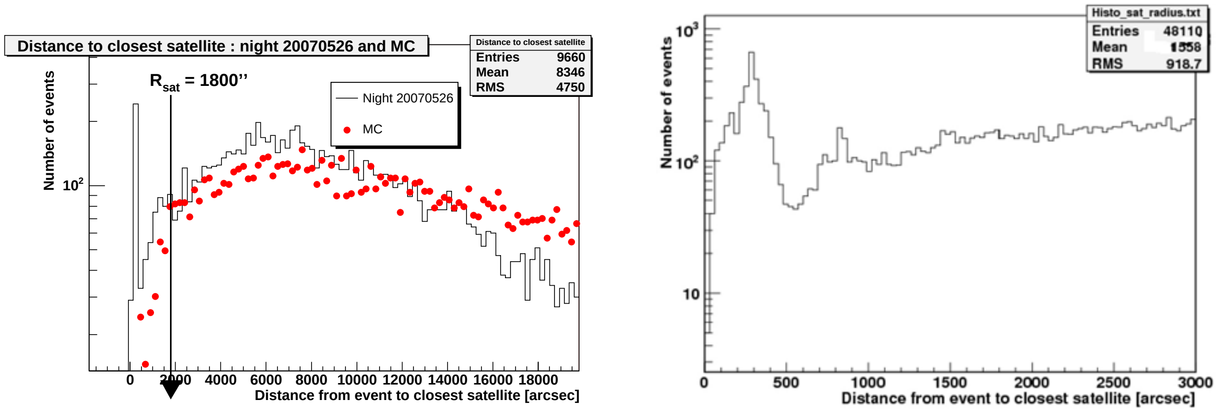

Fig. 2: The image on the left shows the distribution of the distance from a flash event candidate to the closest satellite from the catalog, for events found by the coincidence algorithm during night of 2007.05.26/27. For comparison, distances from randomly generated flashes to the nearest satellite are shown as red dots — the combinatorial background is nicely reproduced. For the purposes of this analysis, the signal threshold was decreased to have more accidental coincidences. The image on the right shows the distribution of the distances from real data zoomed in the range $[0, 3000]$ arc sec only

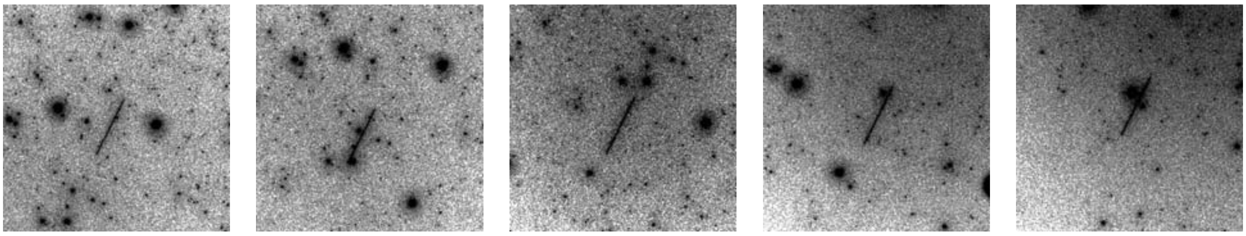

Fig. 3: Five subsequent 10s exposures showing fast, low orbit satellite SL-12 observed by the "Pi of the Sky" prototype

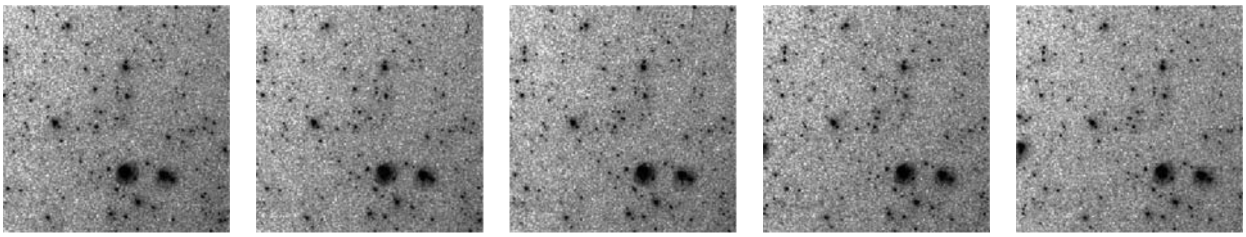

Fig. 4: Five successive 10s exposures showing geostationary satellite XM-4 BLUES observed by the "Pi of the Sky" prototype. The satellite is a large object, with solar panels exceeding 10 m

bital elements. For each image, the positions of all satellites in the database are calculated (using the predict package [7]), each flash candidate is verified and, if it is closer than $R_{sat} = 1\,000$ arc sec from any of the satellites, it is flagged and excluded from further OT analysis. This rejection radius was determined according to the distribution of angular distances from flashes to the closest satellite from the database, which is clearly peaked around zero (Figure 2).
The red dots on the plot represent the distance distribution for randomly generated flashes to the closest satellite from the catalog, and illustrate the size of the combinatorial background.

The satellites identified according to the TLE database are mostly LEO and GEO satellites. Images of low orbit satellite SL-12 are shown in Figure 3. There are also many geostationary satellites in the sample (mostly large, with solar panels exceeding 10 m). However, these observations show that it is possible to observe even geostationary objects with the small aperture (70 mm) instrument. Images of geostationary satellite XM-4 BLUES are shown in Figure 4.

The orbital element databases are not complete, and many satellites are not included in them. In order to identify them, event candidates are examined against track criteria. There are currently two procedures for track identification:

- **Normal track** — tries to form a track out of events from different images, it finds slowly moving satellites (like the geostationary satellite in

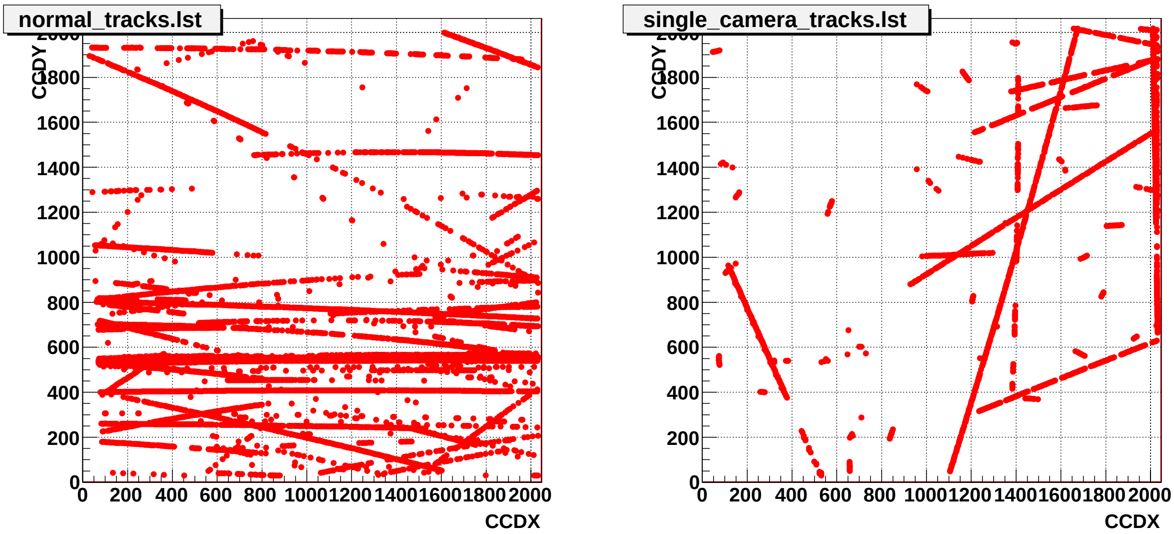

Fig. 5: Tracks identified by the two algorithms described in the text during the same night. The image on the left shows 160 `normal tracks` and the image on the right presents 40 `single camera tracks`

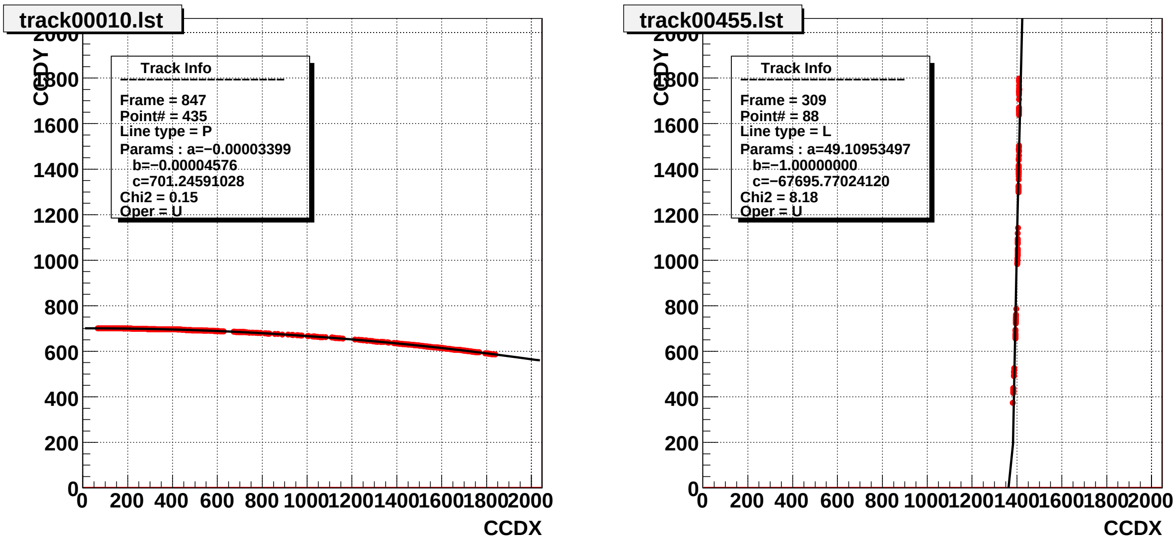

Fig. 6: An example of a `normal track` with a fitted parabola (left image) and a `single camera track` with a fitted straight line (right image)

Figure 4). If it is possible to fit a track to a set of events from different or same images and the velocity of the object is approximately constant, all events matching the track are flagged as moving objects. An example of 160 normal tracks fitted during a single night is shown in Figure 5.

- **Single camera tracks** — identify tracks using events identified by a single camera. The tracking starts with events from a single image, and requires at least 5 events in a track. If a new `single camera track` is identified, it is matched to earlier tracks of the same type. If they match each other, the earlier track is extended by the new one and a single larger track is formed. This procedure rejects fast satellites (or planes) which produce "long line" signatures in a single image (Figure 3). An example of 40 normal tracks fitted during a single night is shown in Figure 5.

In the initial version only straight lines were fitted. For many moving objects, however, FOV of $20^\circ \times 20^\circ$ is large enough to observe significant curvature of the track. Thus, in order to make the fit procedure more efficient, a parabolic curve is now also fitted. If the track consists of at least 20 events

```
# ------------------- PI DATA SECTION -------------------
# OBSERVATION DATA :
# UT_DATE_TIME TIME_UT RA[deg] DEC[deg] CCDX CCDY DIST[arcsec] FRAME
20091108_082417 08:24:17 61.81529167 31.55470000 1184.00 869.00 901.16 732
20091108_082430 08:24:30 62.16020833 31.02470000 1155.00 922.00 589.26 733
20091108_082443 08:24:43 62.58359850 30.31565747 1119.92 993.14 -1
20091108_082455 08:24:55 62.98895660 29.60273621 1084.85 1064.28 -1
20091108_082508 08:25:08 63.38844575 28.88884172 1049.78 1135.42 -1
20091108_082520 08:25:20 63.78219174 28.17424364 1014.71 1206.57 -1
```

Fig. 7: Example of a text file containing satellite observational data

and $\chi^2_{par}/\chi^2_{line} < 2$, parabolic fit parameters are chosen. Examples of a straight line and parabolic tracks are shown in Figure 6. The efficiency of identifying moving objects by the `normal track` procedure was studied by checking how many of the satellites identified in the TLE database were later identified in the track procedure. The procedure is already very efficient and 99 % of objects that are moving objects according to the TLE database were also identified by the `normal track` procedure.

Software tools were created in order to obtain the positions and times of all observations of the given TLE-satellite. The observational data (right ascension, declination, time and some additional information) is saved to text files (Figure 7). Optionally, the data may be saved to the database in order to allow for fast searches of multi-night observations of satellites. `Php` scripts were developed to access the data via the web browser. For example, it extracts all observations of the given satellite (from multiple nights).

The data was later used to fit the orbital parameters. Two programs were tested: FindOrb [8] and the custom developed `orbfinder` software. Preliminary tests show that it is possible to fit orbital parameters using "Pi of the Sky" data if at least 0.7–1.0 % of the whole orbit is observed.

4 Conclusions

The data from the prototype "Pi of the Sky" system was used to study the capability of the system to discover space debris elements. Preliminary estimates show that the system is able to observe at least half of the objects from the NORAD database. It is even possible to observe large and bright satellites on the geostationary orbit. Algorithms for automatic identification of moving objects were developed, tested and seem to be efficient. The analysis is still going on, but it seems that a wide field system like "Pi of the Sky" could be used successfully for survey tasks for discovering and calculating the orbit of large and easy targets.

Acknowledgement

We are very grateful to G. Pojmanski for giving access to the ASAS dome and for sharing his experience with us. We would like to thank the staff of the Las Campanas Observatory for their help during installation of the apparatus. This work was financed by the Polish Ministry of Science from 2005 until 2010 as a research project.

References

[1] Website *The Source for Space Surveillance Data*, http://www.spacetrack.org/tle_format.html

[2] Klinkrad, H., et al.: Europe's Eyes on the Skies — The Proposal for a European Space Surveillance System, *ESA Bulletin* **133** (2008).

[3] Żarnecki, A. F., et al.: Improving photometry of the Pi of the Sky, *this journal*.

[4] Małek, K., et al.: Pi of the Sky Detector, *Advances in Astronomy*, Volume **2010** (2010), Article ID 194946, 9 pages, http://www.hindawi.com/journals/aa/2010/194946.html

[5] Sokolowski, M.: *Investigation of astrophysical phenomena in short time scales with Pi of the Sky apparatus*, PHD thesis, Institute for Nuclear Studies, Jan 2008, http://arxiv.org/abs/0810.1179

[6] Sokołowski, M., et al.: Automated Detection of Short Optical Transients of Astrophysical Origin in Real Time, *Advances in Astronomy*, Vol. **2010** (2010), Article ID 463496, 11 pages, http://www.hindawi.com/journals/aa/2010/463496.html

[7] *Web page of Predict package*, http://www.qsl.net/kd2bd/predict.html

[8] *Web page of FindOrb package*, http://www.projectpluto.com/find_orb.htm

M. Sokołowski
E-mail: msok@fuw.edu.pl
The Andrzej Soltan Institute
for Nuclear Studies
Hoża 69, 00-681 Warsaw, Poland

M. Należyty
University of Warsaw Astronomical Observatory
Al. Ujazdowskie 4, 00-478 Warsaw, Poland

A. Majczyna
The Andrzej Soltan Institute
for Nuclear Studies
Hoża 69, 00-681 Warsaw, Poland

R. Wawrzaszek
Space Research Center of the
Polish Academy of Sciences
Bartycka 18A, 00-716 Warsaw, Poland

P. Wajer
Space Research Center of the
Polish Academy of Sciences
Bartycka 18A, 00-716 Warsaw, Poland