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Parallax in “Pi of the Sky” project

A. Majcher[a,*], M. Sokołowski[b,c,a], T. Batsch[a], A.J. Castro-Tirado[d], H. Czyrkowski[e], A. Ćwiek[a], M. Ćwiok[e], R. Dabrowski[e], G. Kasprowicz[f], A. Majczyna[a], K. Małek[g,h], L. Mankiewicz[g], B.A. de la Morena[i], K. Nawrocki[a], Ł. Obara[e], R. Opiela[g], L.W. Piotrowski[j], M. Siudek[g], R. Wawrzaszek[k], G. Wrochna[a], M. Zaremba[e], A.F. Żarnecki[e]

[a] *National Centre for Nuclear Research, Hoża 69, 00-681 Warsaw, Poland*
[b] *International Centre for Radio Astronomy Research, Curtin University, GPO Box U1987, Perth, WA 6845,Australia*
[c] *ARC Centre of Excellence for All-sky Astrophysics (CAASTRO)*
[d] *Instituto de Astrofísica de Andalucía CSIC, Glorieta de la Astronomia, s/n, E 18080 Granada, Spain*
[e] *Faculty of Physics, University of Warsaw, Hoża 69, 00-681 Warsaw, Poland*
[f] *Institute of Electronic Systems, Warsaw University of Technology, Nowowiejska 15/19, 00 665 Warsaw, Poland*
[g] *Centre for Theoretical Physics, Polish Academy of Sciences, Al. Lotnikow 32/46, 02 668 Warsaw, Poland*
[h] *Institute for Advanced Research, Nagoya University, Furo-cho, Chikusa-ku, 464 8601 Nagoya, Japan*
[i] *INTA-CEDEA, Ctra. de San Juan del Puerto, km 33, 29130 Mazagon, Spain*
[j] *RIKEN Advanced Science Institute, 2-1 Hirosawa, Wako, Saitama 351 0198, Japan*
[k] *Space Research Center, Polish Academy of Sciences, Bartycka 18A, 00 716 Warsaw, Poland*

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Abstract

The main goal of the “Pi of the Sky” project is search for optical transients (OTs) of astrophysical origin, in particular those related to gamma-ray bursts (GRBs). Since March 2011 the project has two running observatories: one in northern Chile and the other one in southern Spain. This allows for regular observations of a common sky fields, visible from both observatories which are scheduled usually 1–2 h per night. In such a case, the on-line flash recognition algorithm, looking for optical transients, can use parallax information to assure that events observed from both sites have parallax angle smaller than the error of astrometry. On the other hand, the remaining OT candidates can be verified against a hypothesis of being near-Earth objects. This paper presents algorithm using parallax information for identification of near-Earth objects, which might be satellites, or space debris elements. Preliminary results of the algorithm are also presented.

Keywords: Space debris; Satellite observations; Optical transients

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1. Introduction

Parallax is the most direct method to determine distances to astronomical objects. There is no need for any assumptions here: one has to know line of sight directions to an object from two different observatories, the angle between them and the distance between these places (called the baseline). The only limitation for this method is an angular resolution, causing that it can be used only for relatively close objects. The parallax angle gets smaller and smaller quickly, when the distance increases. Thus, in order to measure the parallax of objects far away from the observer more powerful telescope or larger baseline is needed.

Nowadays a number of artificial satellites orbiting the Earth increases quickly. In consequence there are more

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* Corresponding author. Tel.: +48 5532284.
E-mail address: majer@cft.edu.pl (A. Majcher).

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and more space debris elements, which can be dangerous for working satellites, spaceships and astronauts in space in case of a collision. Quite a large number of these objects are easy to spot even with a naked eye. Moreover, some of orbiting objects (like ISS or Iridium Satellites), when passing above an observatory can become the brightest objects in the sky (sometimes they are even visible in the broad daylight!). Satellites sending short pulses of reflected sunlight (e.g. due to their rotation) can cause false triggers to observers looking for optical transients (OT), variable stars or other objects changing their brightness in short time scales. An amount of such events depends only on a limiting magnitude and a field of view of a given telescope.

There is a number of other objects, which are able to generate false triggers, like cosmic radiation, meteors, planes, etc., but they are relatively easy to reject. Satellites are much harder to recognize, because when they are in a huge distance from an observer, they look like stars. Thus, in order to reject them, one can consider using observations from a second observatory in some distance from the first one, depending on the angular resolution and field of view of a telescope.

Observations of artificial satellites become more and more important, mainly because geostationary orbit is more and more crowded, and possibility of a collision becomes significant. Different space programmes have to commit huge amount of money and time to finally launch a rocket with their satellite on board, so they have to know detailed orbit parameters for all objects orbiting the Earth or the Sun, which are potentially dangerous for such missions. Thus, several different programmes are being developed, like for instance Space Situational Awareness (SSA), which are designed for identification, tracking and warning about space debris elements before any potentially hazardous situation will occur. It is very important to continuously monitor the whole sky. “Pi of the Sky” project is designed for the same observation mode, meaning that it can be useful also for early identification and alerting about new space debris elements. In this paper, we would also like to demonstrate the advantages of large baseline parallax measurements in general.

2. The Pi of the Sky project

The “Pi of the Sky” project is a scientific cooperation of a few polish institutes, concentrating on a search and investigation of prompt optical counterparts of Gamma-Ray Bursts (GRB). Besides GRBs, we are also interested in other short timescales astronomical phenomena, particularly optical transients. “Pi of the Sky” started in 2004, when the first 2 cameras mounted on equatorial mount were installed in Las Campanas Observatory (LCO) in central Chile. The cameras observed the same part of the sky, which is helpful to reject background events due to cosmic rays hitting CCD chip, hotpixels and other sources of false alerts, which occur in only one camera. “Pi of the Sky” prototype detector worked in LCO until December 2009. The greatest success of the project was an observation of GRB080319B since the very beginning, when gamma-ray emission was still ongoing (Racusin et al., 2008). The burst was optically the brightest GRB ever observed (in its maximum it could had been observed even with the naked eye). “Pi of the Sky” cameras observed the burst position before, during and after the GRB, which allowed us to get limits on possible optical precursor (Piotrowski, 2012).

In December 2009 the telescope finished its operation in LCO and in March 2011 it was re-installed in a private observatory near San Pedro de Atacama (SPdA) in northern Chile. SPdA is located about 740 km north from LCO at 22°57′12″S, 68°10′48′W (Zaremba et al., 2011), thus from this location it is possible to observe a slightly bigger part of the sky.

In the meantime, in October 2010, we commissioned our new observatory in northern hemisphere, at Instituto National de Tecnica Aeroespacial (INTA), near Huelva in southern Spain at 37°6′14″N, 6°44′3″W. A new mount carrying 4 cameras was installed there. The cameras can observe the same or adjacent parts of the sky (Zaremba et al., 2011). In both observatories very similar CCD cameras are used. They carry Canon lenses f = 85 mm, f/d = 1.2, resulting in angular pixel size of 36″ and sky coverage of 20° × 20°. In the future we consider to establishing another observatory in southern Spain, which will work in coincidence with the INTA system. The observatory could be located near Malaga in a distance of almost 240 km from INTA, allowing to use parallax to reject OTs from artificial satellites up to a distance of approximately 1.2 million km.

3. Parallax in Pi of the Sky

The two working observatories in INTA and SPdA allow to observe a parallax of all celestial bodies, which can be observed from both sites simultaneously and pass in proper distance from the Earth’s centre. It can be used in order to distinguish not interesting OTs due to near-Earth object, mostly artificial satellites, from the real OTs coming from distant Universe.

The distance between observatories in Chile and Spain is almost 8500 km (along the Earth’s chord) and the cameras’ field of view spans for 20° × 20° (a half of a diagonal is a bit more than 14°). Assuming, that both telescopes are pointing in the same direction this results in an observable parallax angle for objects, which are in a distance larger than 20,600 km from the centre of the Earth. In the case of closer objects, the parallax angle exceeds the image size, and they cannot be registered in pictures of the same part of the sky taken from both locations.

On the other hand, the smallest parallax which can be observed is 25″ (a half of a diagonal of a pixel), resulting in a distance of almost 38.2 million km. The planet Mars can pass the Earth in a distance of almost 56 million km and Venus - in over 41 million km. So we could not observe the parallax of any planet, even during their maximum close-up to the Earth. But we should be able to measure parallax for all closer object, including geostationary and GPS satellites, near Earth asteroids and comets. However, such asteroids and comets are usually small (their sizes typically do not exceed one kilometre), and therefore reflect small amounts of light, which makes them very difficult or even impossible to be perceived with "Pi of the Sky" cameras. Nevertheless, such observations are possible, an example is the asteroid 2005 YU 55, which passed the Earth a few years ago in a distance smaller than 125,000 km and was observed by our system or recent observation of asteroid 2012 DA14, which passed very close to our planet this year and was tracked by INTA system for about 5 h (2005YU55; 2012DA14).

Once our second Spanish observatory near Malaga will be launched, the parallax baseline will be approximately 240 km (along the Earth's chord). Similar calculations lead to the conclusion, that the two Spanish observatories would allow to observe the parallax of objects in distances between 6800 km and 1.2 million km from the centre of the Earth. This range is populated by many satellites occupying so called Low Earth Orbit (LEO), including ISS, and parallax would help in rejecting optical flashes, which they can produce, when searching for OTs of cosmic origin.

4. Observation's strategy

Due to the large baseline and location of observatories in different hemispheres, we observe the parallax mostly for geostationary satellites, which are located near the celestial equator, because the probability of measuring the parallax of other satellites (e.g. GPS) is much smaller.

Observations of common field are scheduled twice a night, at about 0 UT and 3 UT. Usually, we observe only in one of those time slots, and the choice depends on the observation conditions.

Before the telescope in SPdA starts to observe a common field in the sky, the control computer checks whether the dome in INTA is opened, and system is up and running. The check allows to avoid observations of the field with one system only. Either both telescopes are observing the common field or the system selects different field in the sky, according to strategy of the pointing algorithm. During common-field observations, the flash recognition algorithm looks for optical transients in images collected in both observatories and the lists of flash candidates are used by parallax-finder algorithm as described in the following section.

Observations, which satisfy parallax conditions are listed in a dedicated table in a special website, where we can browse them and check if they are properly recognized as satellites' flashes. An example of such an observation is shown in Fig. 1. The pictures were taken on July 25 2011, about 0:16 UT. The left one was taken by camera cam36 from INTA and the right one - by camera k2a from SPdA. The pictures recorded the group of communication satellites called Hispasat. There are at least 3 satellites visible, which orbit the Earth together. Above INTA the group was visible at coordinates: $\alpha = 18.2$ h, $\delta = -5.8$ deg, while in SPdA $\alpha = 18.8$ h, $\delta = +3.8$ deg. The group is circled in green to be better visible. Sharp black lines visible in the left picture there are features of our INTA cameras matrixes.

5. Determination of the parallax and distance to objects

In order to use parallax to determine distance to an object observed from both observatories, the following information is required: geographical coordinates of the observatories, equatorial coordinates (right ascension and declination) of the observed object and the observation time. The geographical coordinates (longitude and latitude) of both "Pi of the Sky" observatories are known exactly.

The Cartesian coordinates of the observatories in the coordinate system defined in Fig. 2 can be written as:

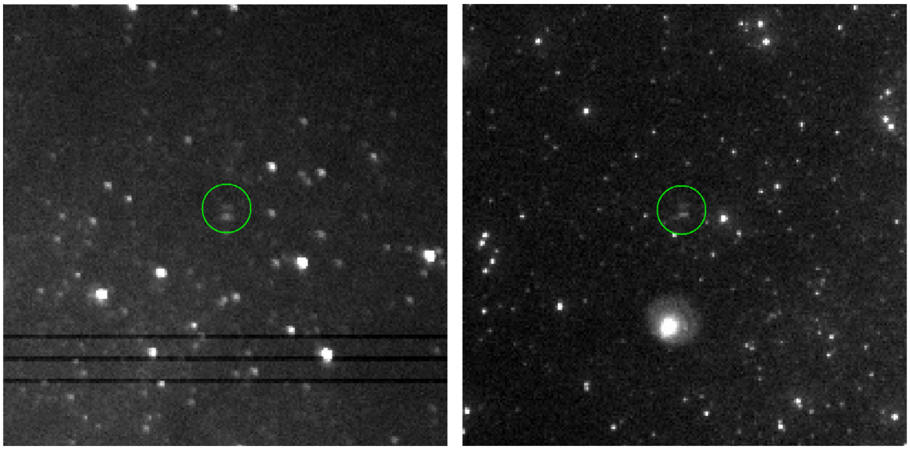

Fig. 1. An example of a simultaneous observation of a parallax in "Pi of the Sky" . Left picture is taken from INTA, and right – from SPdA. Green circles indicate the group of Hispasat communication satellites, for which parallax was measured. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this article.)

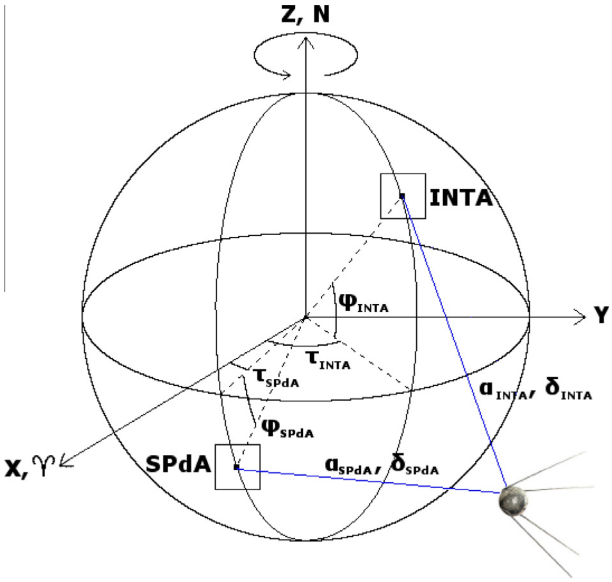

Fig. 2. A scheme of the parallax observations from the two "Pi of the Sky" observatories in Chile (SPdA) and Spain (INTA). The right-handed Cartesian coordinate system *XYZ* is defined with the *X* axis pointing to Vernal Equinox and *Z* axis pointing to the North Celestial Pole.

$$\begin{aligned}\mathbf{r}_{\mathrm{SPdA}}\colon X_{\mathrm{SPdA}} &= R_E \cos\phi_{\mathrm{SPdA}} \cos\tau_{\mathrm{SPdA}}\\ Y_{\mathrm{SPdA}} &= R_E \cos\phi_{\mathrm{SPdA}} \sin\tau_{\mathrm{SPdA}}\\ Z_{\mathrm{SPdA}} &= R_E \sin\phi_{\mathrm{SPdA}}\end{aligned}$$

$$\begin{aligned}\mathbf{r}_{\mathrm{INTA}}\colon X_{\mathrm{INTA}} &= R_E \cos\phi_{\mathrm{INTA}} \cos\tau_{\mathrm{INTA}}\\ Y_{\mathrm{INTA}} &= R_E \cos\phi_{\mathrm{INTA}} \sin\tau_{\mathrm{INTA}}\\ Z_{\mathrm{INTA}} &= R_E \sin\phi_{\mathrm{INTA}}\end{aligned}$$

where: R_E is the Earth's radius, ϕ is the latitude, and τ is the sidereal time in SPdA and INTA respectively.

Satellite candidates are identified by the algorithm looking for optical transients (Sokolowski et al., 2010); moving and flashing satellites can imitate such events and thus are automatically identified as flash candidates. Very similar algorithms are working in both observatories. For every flash candidates its equatorial coordinates are determined as follows: $(\alpha_{\mathrm{SPdA}}, \delta_{\mathrm{SPdA}})$ and $(\alpha_{\mathrm{INTA}}, \delta_{\mathrm{INTA}})$, where α is a right ascension, and δ – a declination of the object in each of the observatories respectively. Converting these positions to Cartesian coordinates, we obtain:

$$\begin{aligned}\mathbf{r}^{\mathrm{SAT}}_{\mathrm{SPdA}}\colon X^{\mathrm{SAT}}_{\mathrm{SPdA}} &= \cos\delta_{\mathrm{SPdA}} \cos\alpha_{\mathrm{SPdA}}\\ Y^{\mathrm{SAT}}_{\mathrm{SPdA}} &= \cos\delta_{\mathrm{SPdA}} \sin\alpha_{\mathrm{SPdA}}\\ Z^{\mathrm{SAT}}_{\mathrm{SPdA}} &= \sin\delta_{\mathrm{SPdA}}\end{aligned}$$

$$\begin{aligned}\mathbf{r}^{\mathrm{SAT}}_{\mathrm{INTA}}\colon X^{\mathrm{SAT}}_{\mathrm{INTA}} &= \cos\delta_{\mathrm{INTA}} \cos\alpha_{\mathrm{INTA}}\\ Y^{\mathrm{SAT}}_{\mathrm{INTA}} &= \cos\delta_{\mathrm{INTA}} \sin\alpha_{\mathrm{INTA}}\\ Z^{\mathrm{SAT}}_{\mathrm{INTA}} &= \sin\delta_{\mathrm{INTA}}\end{aligned}$$

Using the above results and assuming that observations were performed at the same time, it is possible to determine a straight line joining the observatories with the object. The two straight lines can be parameterized as follows:

$$\mathbf{d}_{\mathrm{SPdA}}(p) = \mathbf{r}_{\mathrm{SPdA}} + p \cdot \mathbf{r}^{\mathrm{SAT}}_{\mathrm{SPdA}}$$
$$\mathbf{d}_{\mathrm{INTA}}(q) = \mathbf{r}_{\mathrm{INTA}} + q \cdot \mathbf{r}^{\mathrm{SAT}}_{\mathrm{INTA}}$$

where $p, q \in [0, \infty)$ are parameters defining distance along line of sight. Using the above parameterizations it is possible to parameterize and calculate the distance between these two lines (in kilometres):

$$d_{\mathrm{SAT}} = \frac{\begin{vmatrix} X_{\mathrm{SPdA}} - X_{\mathrm{INTA}} & Y_{\mathrm{SPdA}} - Y_{\mathrm{INTA}} & Z_{\mathrm{SPdA}} - Z_{\mathrm{INTA}} \\ X^{\mathrm{SAT}}_{\mathrm{SPdA}} & Y^{\mathrm{SAT}}_{\mathrm{SPdA}} & Z^{\mathrm{SAT}}_{\mathrm{SPdA}} \\ X^{\mathrm{SAT}}_{\mathrm{INTA}} & Y^{\mathrm{SAT}}_{\mathrm{INTA}} & Z^{\mathrm{SAT}}_{\mathrm{INTA}} \end{vmatrix}}{\sqrt{\begin{vmatrix} Y^{\mathrm{SAT}}_{\mathrm{SPdA}} & Z^{\mathrm{SAT}}_{\mathrm{SPdA}} \\ Y^{\mathrm{SAT}}_{\mathrm{INTA}} & Z^{\mathrm{SAT}}_{\mathrm{INTA}} \end{vmatrix}^2 + \begin{vmatrix} X^{\mathrm{SAT}}_{\mathrm{SPdA}} & Z^{\mathrm{SAT}}_{\mathrm{SPdA}} \\ X^{\mathrm{SAT}}_{\mathrm{INTA}} & Z^{\mathrm{SAT}}_{\mathrm{INTA}} \end{vmatrix}^2 + \begin{vmatrix} X^{\mathrm{SAT}}_{SPdA} & Y^{\mathrm{SAT}}_{\mathrm{SPdA}} \\ X^{\mathrm{SAT}}_{\mathrm{INTA}} & Y^{\mathrm{SAT}}_{\mathrm{INTA}} \end{vmatrix}^2}}$$

which follows from differentiation of $\mathbf{d}_{\mathrm{SPdA}}(p) - \mathbf{d}_{\mathrm{INTA}}(q)$ with respect to p and q. Requiring the result to be zero, allows to find parameters p_0 and q_0 corresponding to the smallest distance d_{SAT} between the two lines. The following formulas for values of parameters p_0 and q_0 are obtained:

$$p_0 = \frac{\left((\mathbf{r}_{\mathrm{SPdA}} - \mathbf{r}_{\mathrm{INTA}}) \cdot \mathbf{r}^{\mathrm{SAT}}_{\mathrm{SPdA}}\right)\left(\mathbf{r}^{\mathrm{SAT}}_{\mathrm{INTA}}\right)^2 - \left((\mathbf{r}_{\mathrm{SPdA}} - \mathbf{r}_{\mathrm{INTA}}) \cdot \mathbf{r}^{\mathrm{SAT}}_{\mathrm{INTA}}\right)\mathbf{r}^{\mathrm{SAT}}_{\mathrm{INTA}} \cdot \mathbf{r}^{\mathrm{SAT}}_{\mathrm{SPdA}}}{\left(\mathbf{r}^{\mathrm{SAT}}_{\mathrm{SPdA}} \cdot \mathbf{r}^{\mathrm{SAT}}_{\mathrm{INTA}}\right)^2 - \left(\mathbf{r}^{\mathrm{SAT}}_{\mathrm{SPdA}}\right)^2\left(\mathbf{r}^{\mathrm{SAT}}_{\mathrm{INTA}}\right)^2}$$

$$q_0 = \frac{(\mathbf{r}_{\mathrm{SPdA}} - \mathbf{r}_{\mathrm{INTA}}) \cdot \mathbf{r}^{\mathrm{SAT}}_{\mathrm{SPdA}}}{\mathbf{r}^{\mathrm{SAT}}_{\mathrm{INTA}} \cdot \mathbf{r}^{\mathrm{SAT}}_{\mathrm{SPdA}}} + \frac{\left(\mathbf{r}^{\mathrm{SAT}}_{\mathrm{INTA}}\right)^2}{\mathbf{r}^{\mathrm{SAT}}_{\mathrm{INTA}} \cdot \mathbf{r}^{\mathrm{SAT}}_{\mathrm{SPdA}}} \cdot p_0$$

Using (p_0, q_0) the position of object (the center of the smallest distance line) can be determined as:

$$\mathbf{R}_{\mathbf{calc}} = \frac{\mathbf{d}_{\mathrm{SPdA}}(p_0) + \mathbf{d}_{\mathrm{INTA}}(q_0)}{2}.$$

Its length (in kilometres) will be denoted as R_{calc}. The angular distance between the two straight lines can be determined as:

$$\Delta = \frac{d_{\mathrm{SAT}}(p_0, q_0)}{R_{calc}} \text{ (in radians).}$$

6. Results

For every pair of flash candidates from both observatories a value of Δ is calculated and when it is smaller than certain limit, the pair is considered as observations of a near Earth object. The limiting value was initially set to

180″ (5 pixels), roughly corresponding to 10 times the astrometric error of the survey. The algorithm checks every pair of flash candidates from SPdA and INTA, and logs those which satisfy condition $\Delta < 180$ to the dedicated log file. The whole procedure will be referred to as parallax-finder procedure.

On the other hand, it is possible to use databases of Two Lines Elements (TLE), available on the Internet (NORAD; IDB), which contains orbital elements of most of the satellites (typically around 13,000 objects). Every evening, such a database is automatically downloaded, and is later used during the observations to verify every flash candidate. For every image, positions of all objects from the TLE database are first calculated. Then, every flash candidate found on a particular image is verified against the list of positions of all satellites that can be observed on this image. When a satellite is closer than 1000″ from a position of flash candidate, such an event is flagged as a satellite, and satellites' parameters are logged into the log file; the event candidate is also rejected from the list of astrophysical OTs (Sokolowski, 2008).

The TLE information is also used by the parallax finder procedure, and TLE parameters of events marked by the algorithm as satellites are also saved to the log file. Using this information, it is possible to verify which satellites found by the parallax-finder procedure are known TLE satellites and thus assess the algorithm's efficiency.

In Fig. 3 a distribution of the differences ΔR between satellites' distances from the Earth centre taken from TLE database and determined by the described algorithm versus distances taken from TLE database is shown. Vertical line at $R_{TLE} \approx 42{,}000$ km corresponds to geostationary satellites, which constitute to the majority of our sample. The distance difference $\Delta R = R_{calc} - R_{TLE}$ is also presented in Fig. 4.

As one can see for most cases our position estimates are in good agreement with the TLE database, and the obtained distance precision is of the order of 50 km. Most of events, where significant deviation is observed are caused by misidentification of satellite in TLE database, probably due to limited accuracy of our observations (both in space and time).

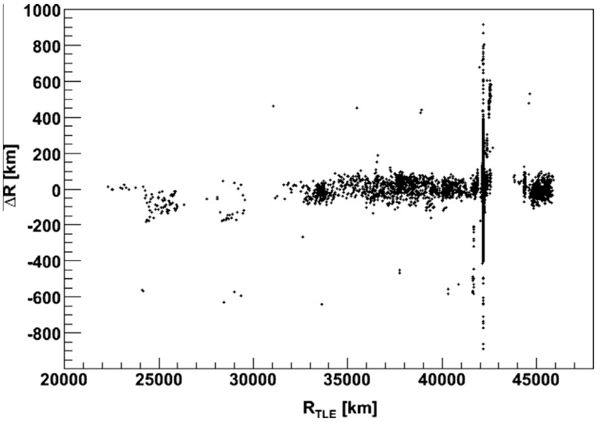

Fig. 3. A distribution of difference (ΔR) between satellites' distance taken from the TLE database (R_{TLE}) and determined by the described algorithm (R_{calc}) vs. R_{TLE}.

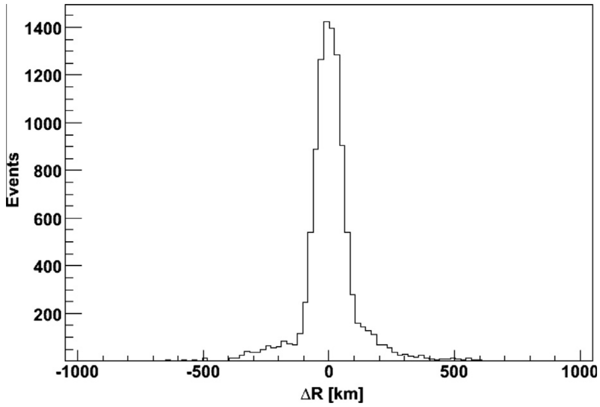

Fig. 4. An example of distribution of difference between satellites' distance taken from the TLE database (R_{TLE}) and determined by the described algorithm (R_{calc}). There is a correction to Earth's radius and 1000 km cut.

7. Summary

Since March 2011 "Pi of the Sky" project includes two observatories working: one in Chile and one in Spain. With this systems we are able to observe a parallax of geostationary or GPS satellites, and Near Earth Objects at orbits higher than 20,600 km. In the future, with considered second observatory in Spain, we will able to observe a parallax of LEO objects. Each cloudless night we record almost 3000 different satellites with known orbit, and many others, which orbits are not found in the TLE database. Parallax allow us to identify object between the Earth and the Moon or even further, although distant objects shine too weak to our cameras and are beyond our reach in most cases. Nevertheless, we developed algorithms for parallax determination and satellite identification as a next generation "Pi of the Sky" apparatus, which is currently being designed, will have much bigger sensitivity. Results presented in this paper demonstrate, that long-baseline parallax measurements are a unique tool for precise studies of NEO orbits.

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