Features of detection and orbit determination of uncatalogued space debris

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Abstract

Expansion of the observational opportunities, tracking, and cataloguing of the small-sized space debris (SD) is becoming one of the topical tasks of spaceflight safety. The experts estimate that the number of potentially tracking debris can achieve several hundred thousand in the future. Observation and cataloguing of such a quantity of objects is a complex scientific and technical problem, and its solution is connected, in particular, with the improvement of technologies and algorithms applied now.

The factors influencing the efficiency of optical sensors and the solution of the tasks of cataloging small-sized SD are considered. The basic attention is focused on the features of measurement correlation, orbit updating, detection of uncatalogued objects, and organization of purposeful observations to improve the precision of the determination and cataloging of their orbits.

Introduction

No doubt the world has made rapid progress in the last 10-15 years in the fields of optics, electronics, computers, and communication technologies. The practical applications of these state-of-the-art scientific and technical achievements allow to improve significantly the opportunities and to increase the contribution of optical-electronic sensors to solving the space surveillance tasks. It is sufficient to note that a few years ago the time interval between the optical observations and digitization of results was from a day to a month; nowadays, the required time is comparable with the characteristics of radars. Thus, the optical angular measurements of space objects can be accessible for processing in near real-time.

Using of the CCD-matrices with their opportunities to store and digitize the images and then process the data allows a range of sensitivity for optical-electronic sensors. During last decades, the limiting magnitude was about 14-15, but at present it achieves 18-19 mags.

The accuracy of optical-electronic sensors has also increased by an order. For many years, the errors of optical measurements were about several arcsecs. At present, these values are reduced to a tenth of an arcsecond.

Over 15 years the performance of optical-electronic sensors has improved dramatically by one-two orders. It is worth pointing out that at the end of 1999 the U.S. Space Command's optical-electronic sensors were able to produce more than 200,000 measurements per month [1].The search rate of the celestial sphere for these sensors lies between 600 and 4000 sq. degrees per hour now. It requires less than 20 minutes for a single cover of the geostationary area. [2, 3]. Russian optical sensors show similar characteristics [4, 5]. First of all, this is due to the creation of wide-field survey telescopes, revolutionary development of computational and informational technologies, and automation of observational process. The robotic technologies of viewing and searching for the uncatalogued debris, including the small-sized ones, have become widely used. [4, 5, 6, 7, 8, 9]. As a result, the surveillance of the entire geostationary belt is being carried out now on a regular basis, but not rarely and selectively as before.

The mainstream of further development and application of optical-electronic sensors is an expansion of their opportunities on observation, tracking and cataloguing of small-sized SD [4]. At least there are three known directions for effectiveness increase for optical observations [10, 11, 12]:

- reduction of the time required for viewing one field
- application of the effective search strategies
- on-line detection and orbit determination of uncatalogued SD.

In this paper the issues of detection and orbit determination of uncatalogued SD are discussed. Let's consider at first the significance of this task in a common process of observation.

Organization of observational process

The workflow of SD observations for a state-of-the-art robotic optical sensor is shown in Figure 1. It includes:

- observation planning and guidance
- telescope pointing
- execution of a series of exposures and readout data from a CCD-matrix,
- astrometric data processing,
- on-line processing of angular measurements.

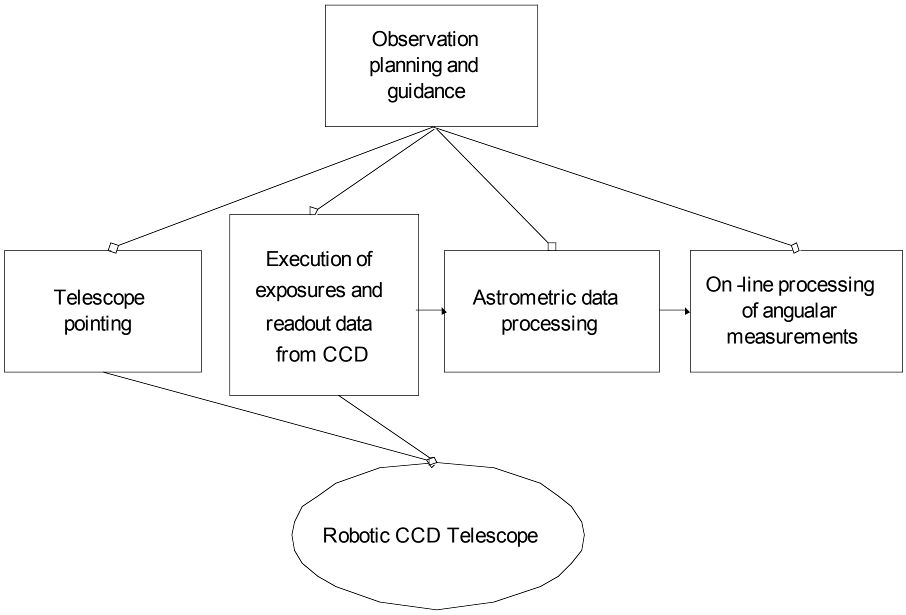

Figure 1. The workflow of observations

The main operating mode of a survey optical sensor consists of a consecutive scanning of the fields in the search zone in accordance with the used algorithm. To realize this process the planning and guidance software is used. For each field in the search area of scanning, the planning and guidance software determines the current conditions of optical visibility and takes into account the observational phases, lunar "keep-out" zone, and current cloudiness from the meteorological station, etc. At favorable conditions for observations the next field for survey is chosen and the telescope is pointed to this field. Then a series of exposures of this field and readout of the CCD-frames are carried out. After that the CCD-images are processed in order to detect space objects and to generate their angular measurements and brightness estimates. Having finished a series of exposures the planning and guidance software sends a command to the pointing system in order to re-point the telescope to the other chosen field. At the same time the on-line processing of measurements obtained for the observed field is carried out. The aims of this processing are:

- correlation of obtained measurements

- updating catalog orbits using correlated measurements
- on-line detection of uncorrelated objects to acquire the "follow-up" observations
- on-line orbit determination of uncorrelated objects when a sufficient number of measurements is obtained.

After successful correlation the software for processing the trajectory measurements carries out the orbit improvement of catalogued objects using the measurements. If it is impossible to correlate the measurements with any catalogued objects, the message is generated for the planning and guidance software to organize the priority "follow-up" observations. The task consists in acquiring sufficient observations for an uncatalogued object during one night to determine its orbit.

The features of the on-line processing of trajectory measurements

Thus, in this scheme the on-line processing of trajectory measurements includes the correlation of measurements, orbit updating for catalogued objects, data collection and orbit determination of the uncatalogued SD during the one night session. It is noted that the reliability of correlation of measurements has an influence on the sensor's survey performance. Really, if the measurements of a catalogued space object will not be correlated, the data collection for this space object as on uncatalogued SD will be mistakenly switched on, and it does not allow observing the priority objects. In the case of a mistaken attribution of measurements of uncatalogued debris to any catalogued space object, the new object will remain undetected.

With the beginning of the observation and cataloging of small-sized SD, the problem of reliability of correlation of optical measurements will become more intensively. There are the following reasons for this:

1. The number of the observable and catalogued objects will essentially increase and that will complicate the correlation of angular measurements of optical sensors.

2. There will be large gaps in the observations due to the dependence of optical sensors on the weather conditions, faintness, and variability of brightness of small-sized SD. This will be a reason for additional difficulties in tracking of small-sized SD and the correlation of measurements.

3. Due to the influence of solar radiation, the motion of a majority of the small-sized SD will be poorly predicted even in short time intervals. This influence is dominant for space objects with large area-to-mass relations. The skill of observations and maintenance of such "exotic" debris shows that the errors of predictions are too large for the common space objects [13, 14]. Taking into account that the area-to-mass relation increases inversely to the cross-section of the space object, the unpredicted perturbation of solar radiation will make an impact on the reliability of the correlation of optical measurements.

4. The evolution tendency of space technology shows that groups of microsatellites will be orbiting the Earth in the near future. A microsatellite is a small-sized spacecraft with a mass of up to several hundred kilograms. Due to the modern level of science and technology, it is possible to mount on such spacecraft all on-board systems, like on a big-sized satellite: orientation (passive and active), power, positioning, radio, and also computational complex. The microsatellites can solve a wide range of the tasks: communication, remote sensing, photo surveying, scientific research, technological experiments, etc. The small sizes of microsatellites and the opportunity of their maneuvering and creating compact orbiting groups will be a reason for additional difficulties, both for the correlation of optical measurements and their tracking.

5. There is a process of clustering in the geostationary belt, when a few active satellites are located at the same longitude. Figure 2 shows a histogram for distribution of longitudes for active geostationary satellites, to illustrate this fact. At present, the groups of European satellites ASTRA, EUTELSAT, HOT BIRD, American DIRECT TV, Spanish HISPASAT and SPAINSAT, Indian INSAT, Japanese B-SAT are the examples of clusters. Due to frequent orbit corrections, it is difficult to discern the satellites in clusters and almost impossible to do this without regular observations.

6. In a few years the first space objects, launched into the geostationary orbits, will naturally begin returning to the orbital planes of functioning spacecrafts (see Figure 2). The distribution of orbit inclinations and longitudes of right ascending node of catalogued space objects with respect to the Laplace plane (Figure 3) shows that the density of space objects in this area will begin gradually growing. It will become one more reason for making the surveillance of the geostationary belt difficult.

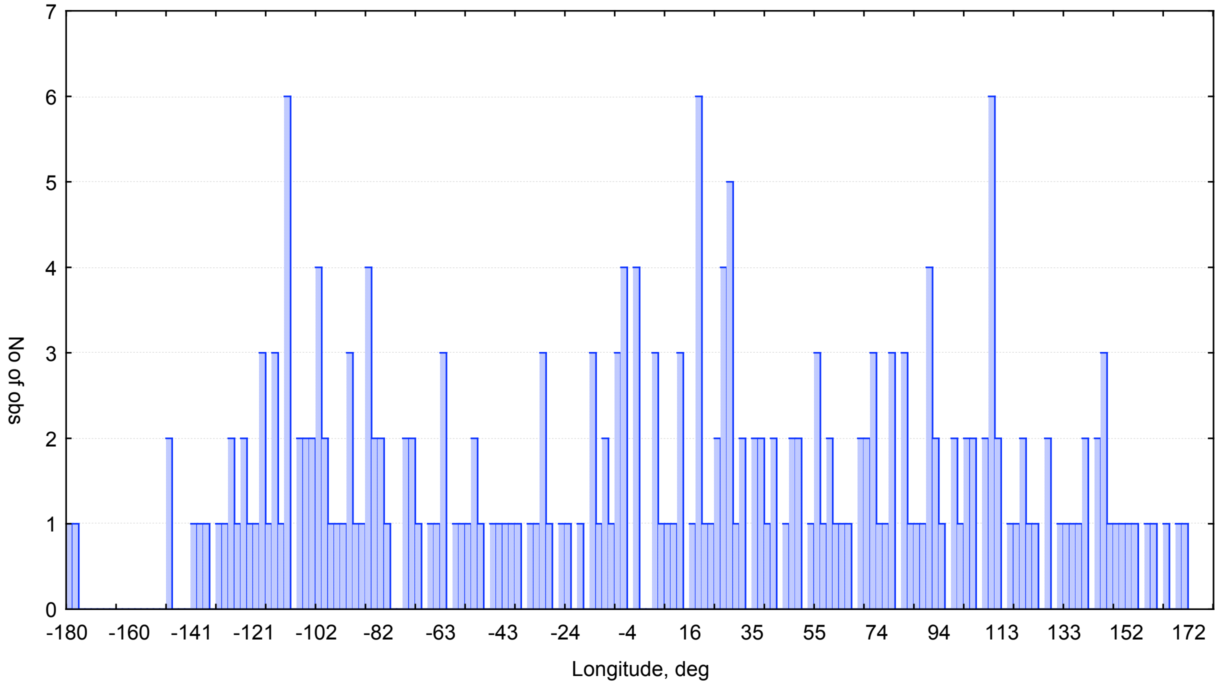

Figure 1. Distribution of longitudes of active GEO satellites

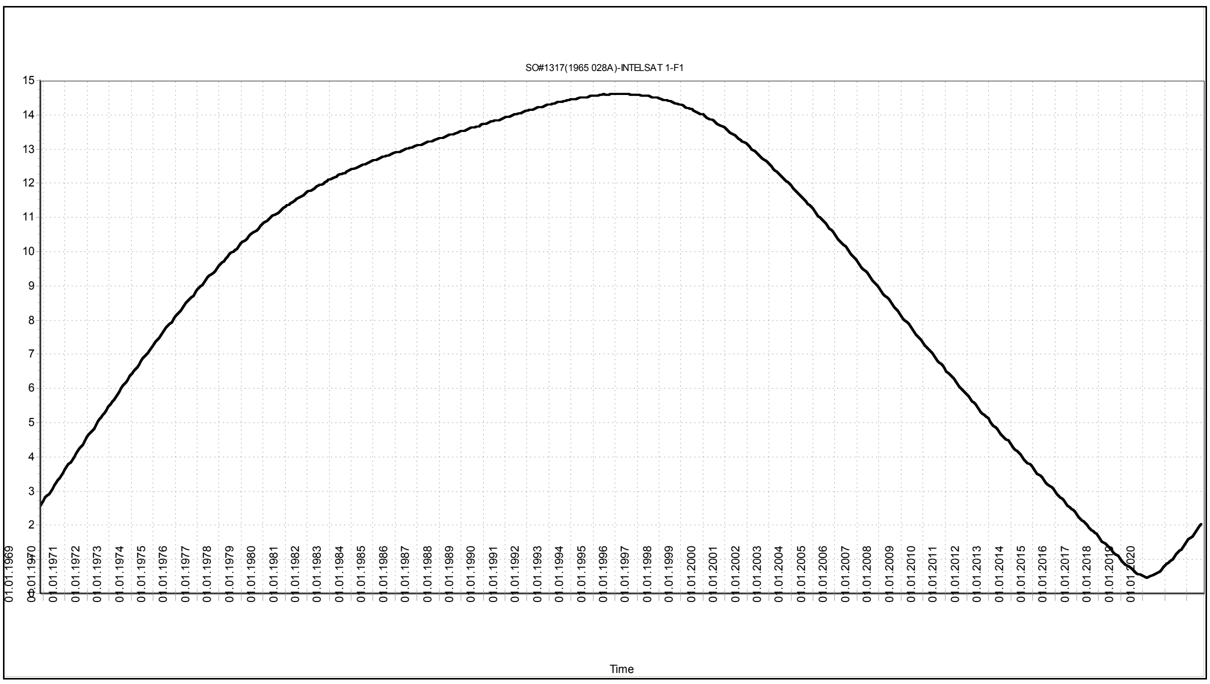

Figure 2. Evolution of orbit inclination of INTELSAT 1-F1

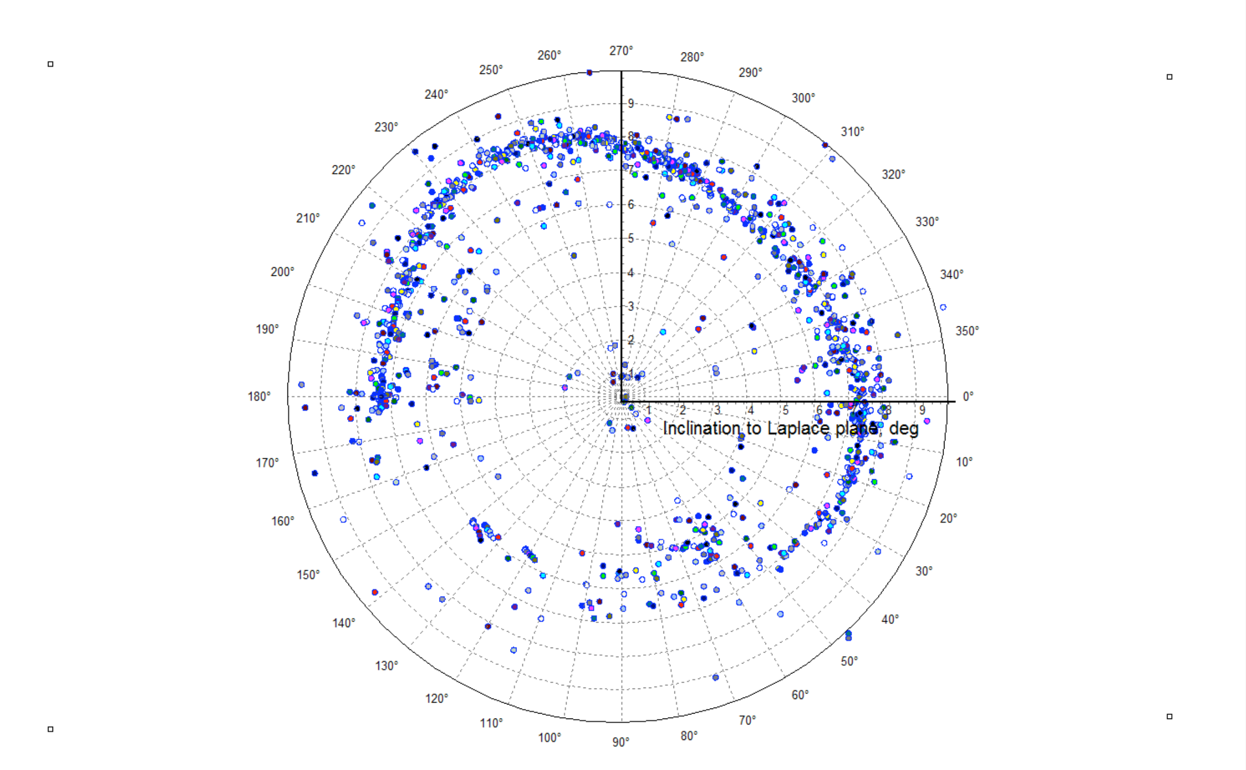

Figure 3. Evolution of orbit inclinations and longitudes of the ascending node
with respect to the Laplace plane

On-line detection and orbit determination of uncatalogued SD

Initially, the processing of angular measurements from the optical sensors took place centrally in the processing center, collecting the data from sensors after night observations have been finished. At the same center the correlation of all measurements and the joint data processing were carried out. As a result the catalog orbits were updated and new objects were detected. If necessary, the updated catalog was sent to the sensors.

During the last decade the decentralized scheme has become more frequently used. In this case the on-line processing of trajectory measurements is carried out directly on the optical survey sensors. Such a technique was proposed for the first time and carried out for monitoring the geostationary area, where there are a majority of closely located satellites and an increased concentration of observed SD [6, 11, 12]. Let's consider the main features of this technology, realized on the optical survey sensors.

The catalog of space objects is used for the on-line correlation of measurements of space objects, which is constantly updated using data of processing centers and the sensor's own measurements.

The correlation of measurements is carried out in a few stages. The first stage is a calculation of ephemeredes of catalogued space objects for a forthcoming session of observations. On the second stage, a subset of space objects – candidates for correlation – is singled out from the comparison of measured coordinates and ephemeris data. The third stage is the decision-making about the correlation, when the hypothesis of the measurements belonging to one or other space object is tested. This decision is based on the analysis of results of orbit updating of candidates using all received measurements. The passive and maneuvering motion takes into account the orbit determination of active geostationary satellites [15]. The successful measurements correlation is finished by attributing the new measurements to the catalogued space objects and recording the updated orbit in the catalog.

The results of correlation are sent to the planning and guidance software. If it is impossible to correlate the measurements with any catalogued objects, the planning and guidance software automatically organizes a priority observation of such space debris. For this purpose a tasking telescope (if exists) may be used. The telescope's pointing, for acquiring a new series of measurements for uncatalogued SD is carried carries out by extrapolation of the received parameters of its apparent motion.

When the new series of uncorrelated measurements are obtained, the task of orbit determination for the new space objects is running. The orbit determination for the new space objects consists in a search of several uncorrelated short track measurements belonging to the same space object, orbit determination and recording of this orbit into the catalog. The solution of this task is carried out by the following steps (see Figure 4).

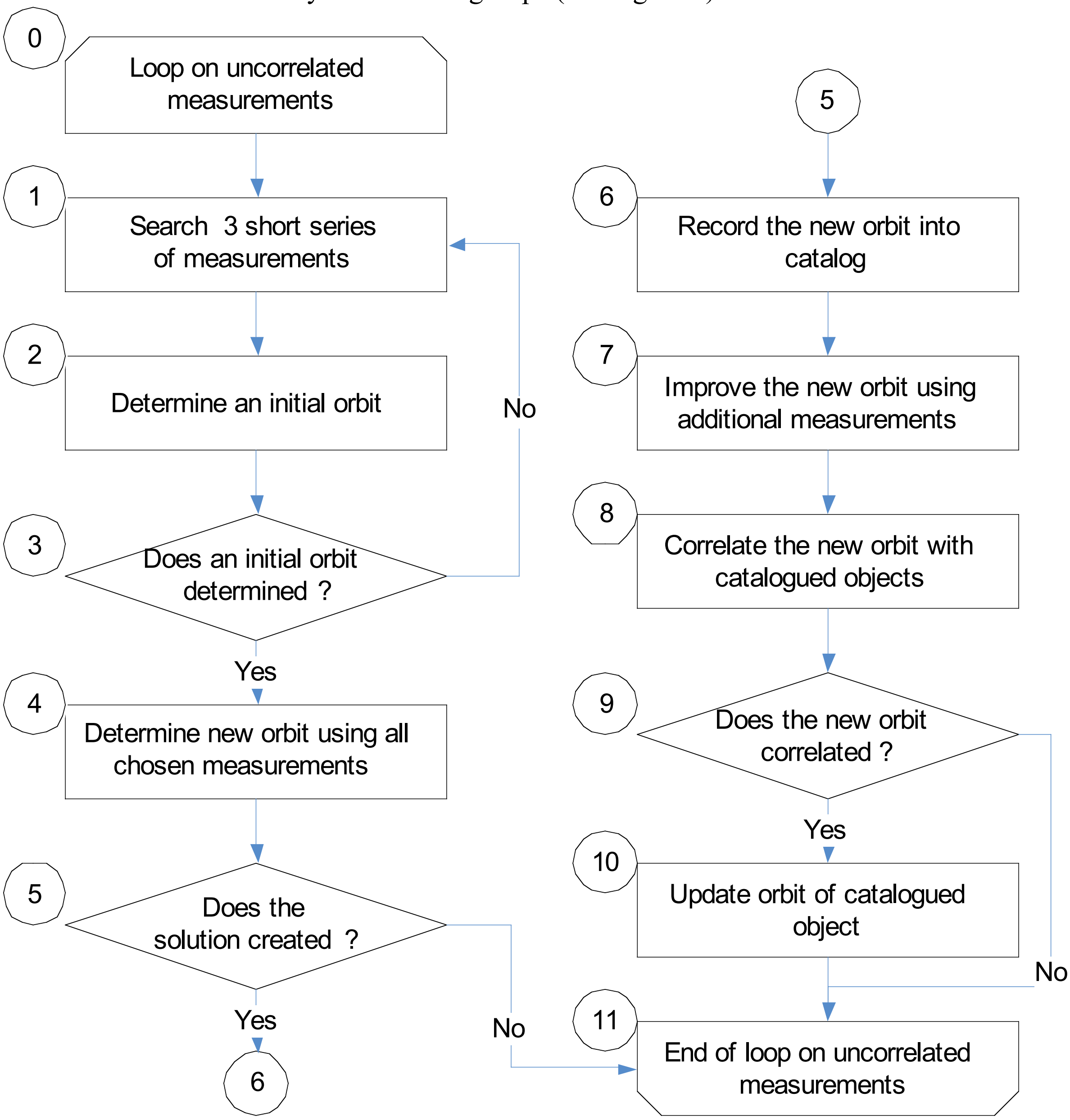

Figure 4. Flowchart of a new orbit determination task

1. Search of a short series of measurements and choose three series, which are allocated in time and presumably related to one space object.
2. Carry out an attempt to determine the initial orbit by using the chosen measurements. For this purpose three sets of angular measurements, belonging to different short series, are used. To create the initial orbit the well-known methods (Gauss, Laplace, r-iteration and their modification) are used [16].

3. Choose the next three series of uncorrelated measurements, if the initial orbit can not be created.

4. Determine the least-square solution for the new orbit by using all chosen three short observation series, and the initial orbit as a first approximation.

5. Choose the next three series of uncorrelated measurements, if the least-square method can not provide a solution.

6. Record the new orbit into the catalog, if the least-square solution is obtained.

7. Correlate the uncorrelated measurements with the new determined orbit and then carry out the orbit improvement using the additional measurements.

8. Correlate of a new orbit and catalogued space objects. There are some reasons why a short series of measurements can not correlate with the catalogued objects. For example:

- orbit correction of the active satellites has been done
- for any of several reasons the catalogued space object was not observed by any sensor for a long time and its orbit has become outdated
- the catalogued object's motion is under the strong influence of unpredictable perturbations.

At this stage, an attempt to find the object in the catalog, to which a new orbit and its appropriated correlated measurements could belong to is done.

9. Choose the next three series of uncorrelated measurements, if the new orbit is not correlated with catalogued objects.

10. Attach the new measurements to the catalogued space object and update its orbit, if the new orbit was correlated with the catalogued space object. Otherwise, a record with the new orbit remains in the catalog and it will be equivalently used in the further on-line data processing together with the other catalogued orbits. This orbit is used also for the ephemeris calculation in the further processing of measurements gathered for the newly detected object.

11. Choose the next three series of measurements, if the set of uncorrelated measurements is not empty.

Conclusions

The beginning of the regular observation and cataloguing of small-sized SD will require a modification of applied techniques and algorithms of data collection and processing. One of the directions of this work is to increase the efficiency of optical sensors, which play a significant role in the observation of small-sized objects. In the paper the methodical and problem questions, connected with the on-line detection and orbit determination of uncatalogued space debris, are considered. The on-line measurements processing allows:

- to increase the reliability of measurements correlation
- to find the uncatalogued space objects and organize their purposeful observations during the a one-night session
- to joint the different short arc of measurements obtained for the same space object during one-night session
-to increase the performance of the survey optical sensor.

The described approach used for the GEO survey can be expanded in the future for monitoring SD on the other classes of orbits.

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