PROBLEMS OF THE CATALOGUE MAINTENANCE FOR FAINT GEO OBJECTS

V. Agapov (1), V. Biryukov (2), S. Kamensky (3), Z. Khutorovskiy (4), I. Molotov (5), V. Rumyantsev (6), A. Sochilina (7), V. Titenko (8)

(1) Keldysh Institute of Applied Mathematics, Miusskaya Sq., 4, Moscow, Russia, 125047
Space Informatics and Analytical Systems (KIA Systems JSC), Gzhelsky Lane, 20, Moscow, Russia, 107120
(2) Crimean Astrophysical Observatory, Nauchny, Crimea, Ukraine, 98409
Crimean Laboratory of Sternberg Astronomical Institute of Moscow State University, Nauchny, Crimea, Ukraine, 98409
(3) Space Informatics and Analytical Systems (KIA Systems JSC), Gzhelsky Lane, 20, Moscow, Russia, 107120
(4) Vympel Corporation, 4th of March 8th Str., 3, Moscow, Russia, 125319
Space Informatics and Analytical Systems (KIA Systems JSC), Gzhelsky Lane, 20, Moscow, Russia, 107120
(5) Central (Pulkovo) Astronomical Observatory, Pulkovskoe chaussée, 65/1, St. Petersburg, Russia, 196140
Keldysh Institute of Applied Mathematics, Miusskaya Sq., 4, Moscow, Russia, 125047
(6) Crimean Astrophysical Observatory, Nauchny, Crimea, Ukraine, 98409
(7) Central (Pulkovo) Astronomical Observatory, Pulkovskoe chaussée, 65/1, St. Petersburg, Russia, 196140
(8) Keldysh Institute of Applied Mathematics, Miusskaya Sq., 4, Moscow, Russia, 125047

ABSTRACT

Under order of the Russian Academy of Sciences’ Center on collection, processing and analysis of information on space debris operated at the Keldysh Institute of Applied Mathematics (KIAM) group of researchers developed the program of search, tracking and analysis of orbital evolution of faint objects of space debris in the geostationary region (GEO), presumably from events of fragmentation of some resident GEO objects. Search fields were calculated by use of the various approaches, each of which is briefly described in this paper. The search in the calculated fields and their vicinities was carried out on many nights in October - December, 2004 and January-August, 2005. Almost two dozen faint objects were discovered. These objects were detected repeatedly at the nearest possibility (sometimes in 2-3 weeks and more of an interruption in observations because of an unfavorable weather). All detected objects were tracked continuously during several subsequent nights. The accuracy of astrometric positions (ε=1") achieved has allowed not only to construct accurate orbits, but also to improve the estimation of the solar radiation pressure coefficient value for each object. It was revealed that at least for 3 objects the solar radiation pressure is a very essential factor, causing strong evolution of eccentricity and argument of perigee of the object’s orbit. Further analysis has shown, that the eccentricity of one of objects changes 5 times during just one half-year.

The discovered objects raised serious problems for GEO catalogue maintenance. They are significantly different in evolution from other GEO population members, so making decision solutions as applied previously for objects identification, tracking etc. are not always applicable.

The detailed results of research are presented in this paper. The work is carried out at partial support of the grant INTAS 2001-0669.

1. INTRODUCTION

The center on collection, processing and analysis of information on space debris of the Russian Academy of Sciences (RAS), developed and operated on the basis of the Ballistic Center at the Keldysh Institute of Applied Mathematics (KIAM), carries out works aimed at systematic research of a population of small-sized high altitude objects and their properties. Under order of the Center, the group of the researchers from KIAM, KIA Systems, Central (Pulkovo) astronomical observatory of the RAS, and Crimean astrophysical observatory (CrAO, Nauchny, Ukraine) carry out the special program of search, tracking and analysis of orbital evolution of faint (fainter than 15m at phase angles 20°-30°) objects in the geostationary region (GEO). The program is aimed at reaching of the following purposes:

- Improvement of application of the various methodical approaches of calculation of observation fields for search of objects in the GEO region
- Detection of faint objects in the GEO region
- Tracking of the detected objects
- Determination of trajectory parameters and analysis of evolution of orbital elements
- Estimation of area-to-mass ratio (AMR) value for tracked objects
- Studying catalogue maintenance problems for this class of objects

General statement of the task, processing of measurements, analysis of orbital evolution, estimation of area-to-mass ratio values, calculation of ephemerides for observations, and interpretation of results were carried out by the KIAM team. The Pulkovo observatory team was responsible for the calculation of fields for search of fragments produced as a result of supposed explosions, independent analysis of measurements for increase of reliability of results, and
also for identification of observed objects with the probable "parent body". The CrAO team performed a search for faint objects in the calculated fields using the selected strategy of objects search, repeated detection and tracking of the rediscovered objects, and implemented the techniques of processing of CCD-frames obtained with integration time up to 20 sec. The KIA Systems team performed implementation of an improved version of GEO catalogue maintenance procedures in order to take into account peculiarities of newly discovered objects.

After obtaining the first results, the research group has addressed the request to some observatories for scheduling and realization of several sessions of follow-up observations with the purpose of confirmation of the results reliability. Observations were carried out at Mondy (Sayan observatory of the Institute of Solar-Terrestrial Physics of the Siberian Department of the RAS), Zimmerwald (Astronomical Institute of University of Bern), PIMS (Observatory Sciences Ltd.), and Xinglong (China) observatories.

On the basis of the obtained sets of astrometric positions the KIAM and KIA Systems teams carried out the precise determination of orbit parameters, researched orbital evolution, obtained the estimation of the area-to-mass ratio value, carried out studies of a series of measured values of a visual magnitude of objects.

This work is a further development of the regular IADC GEO survey campaigns and its results are an essential addition to understanding the real properties of a population of objects of space debris in the GEO region. Moreover, this work is the first attempt to include faint GEO objects in the process of regular catalogue maintenance with all appropriate tasks to be solved.

2. OBSERVATION TOOLS

The main tool for realization of the observation program is the AT-64 telescope (D = 64 cm, F = 90 cm), established in the CrAO. The telescope is equipped with the ST-8 (KAF-1600) CCD-matrix. The field of view with the given CCD-matrix makes 53x34 arcmin. The limiting magnitude of the instrument is 20m in integral light at the integration time of 120 sec. This mode of observation can be used to search for asteroids. For Earth-orbiting objects of space debris in the GEO region the limiting magnitude is 17,5m-18m with an integration time of 15 sec.

The given telescope permits the tracking of objects having an angular rate up to 4 arcmin per sec. The exterior of a telescope is shown in Fig.1.

Since March, 2005 use of the second telescope for observations of small-sized high altitude objects - ZTSh (D = 260 cm, F = 1000 cm) also established in CrAO - is started. CCD-camera IMG-1001E (KAF-1001E) was specially purchased and installed at the telescope to provide support within the frame of the described observation program developed under the order of the Center at KIAM. The field of view is 8.5x8.5 arcmin. Since the telescope has not yet the capability of auto tracking of fragments of space debris (the necessary adaptations are carried out), the observations are made with a fixed telescope and periodic manual repositioning at the time of exit of an observable object from the boundary of a field of view. The exterior of the telescope site is shown in a Fig. 2.

Figure 2. ZTSh telescope site at CrAO

A Zeiss-600 telescope equipped with S1C (Electron) CCD-matrix of 1024x1024 pixels in size was used for observations in Sayan observatory. The field of view is 7.5x7.5 arcmin, limiting magnitude – 18m.

Observations at Zimmerwald observatory were carried out with 1m-class telescope equipped with 2048x2048 pixels CCD-matrix. The field of view is 20x20 arcmin, limiting magnitude – 19m.

PIMS observatories are equipped with 40 cm aperture robotic telescopes having CCD-matrix of 1024x1024 pixels in size installed. The field of view is 40x40 arcmin, limiting magnitude – 17m.

Xinlong observatory has used a 60/90 Schmidt telescope with Ford 2048x2048 CCD-matrix. Field of view of the instrument is 58x58 arcmin.

3. OBSERVATION STRATEGIES AND CCD-IMAGES PROCESSING

3.1. Observation strategies

One of key elements of this work is the observation strategy from the point of view of two aspects: search for new objects and repeated detection of earlier observed ones.

One of the approaches used to search for new objects in the GEO area is well known. It is widely used in the coordinated IADC GEO survey campaigns. According to the IADC WG1 recommendations, the strategy in this case is to point the telescope to a given right ascension (RA) and Declination (DECL), and then take images as
quickly as possible. Thus, the effective limiting detectable size is constant for each night. The sky coverage is continuous within each declination band, so there are no gaps. This search fence is solid in RA (east-west direction), but leaky in DECL (north-south direction). All of the data are then collected at the same solar phase angle. There is no time lost due to telescope motion. To provide optimal observation conditions search fields are placed close to the antisolar point (i.e. to the point with minimal phase angle that as a rule corresponds to maximal brightness of searched objects) taking into account that it should avoid the shadow of the Earth covering some part of the GEO region during the period close to spring and autumn equinoxes. Moreover, search fields sometimes are placed at areas where the apparent density of the catalogued GEO objects in the RA-DECL-space is maximal.

The second approach is developed specially for search of fragments of supposedly exploded GEO objects. A list of some objects supposed to explode was given in (Agapov et al., 2003). The developed theory of evolution of geostationary satellite orbits (Kiladze et al., 2003) allows determining RAAN ($\Omega$) and inclination ($i$) for all simulated explosion fragments with high accuracy on intervals of 40-50 years. Calculating RA ($\alpha$) and DECL ($\delta$) for cross points ($S$) of orbits of fragments with the orbit of the exploded parent satellite on long time frames, it is possible to determine geocentric coordinates of the parent object orbit’s segment, on which cross points with orbits of all fragments are distributed with a minimum dispersion (Sochilina et al., 2003). Fig. 3 demonstrates the geometry of the discussed case.

As the planes of the orbits of the considered object and its fragments are intersected in two points, the coordinates on cross points $S$ will differ by $180^\circ$ in $\alpha$. The value of $\delta$ will have the inverse sign.

Figure 3. Geometry of relative position of orbits of a parent satellite and a fragment of its explosion

The results of the simulation for supposed fragmentation of some Transtage-type and Ekran-type objects are presented at Fig. 4. Tiny blue dots represent trajectories of catalogued GEO objects in geocentric RA-DECL-space as of Feb 09, 2005. Green lines represent conditional boundaries of the galactic equator and solid black line represents the Earth shadow boundary. Magenta and yellow solid lines represent trajectories of supposedly exploded ‘parent’ objects. Solid circles on these trajectories mark segments where cross points with orbits of all simulated fragments are distributed with a minimum dispersion.

Figure 4. Position of segments of cross points of orbits of fragments with the orbit of some supposedly exploded parent objects, where cross points distribution dispersion is minimal as of Feb 09, 2005. Transtage-type parent object orbits are shown in yellow.

Figure 5. Trajectories of Ekran 1979-087A satellite and its explosion fragments as of Feb 09, 2005.

For repeated observation of the earlier detected objects the planar along-trajectory search strategy was realized. While using this strategy it is important to properly estimate the error of the object’s predicted position. If the error is insignificant in comparison with the size of the field of view of the telescope, the object at once falls in the field of view and the special search is not required. Otherwise, it is necessary to conduct a search.

As a rule, for the newly detected objects optically observed on a short time interval, an ellipse of errors of the predicted position has a strongly prolate form, thus its semimajor axis is oriented approximately in parallel to the trajectory of the object’s motion. It allows to use a simple search method - "waiting in a point ". Let the predicted right ascension and declination of object at the moment $t$ be $\alpha$ and $\delta$ respectively. The method of search consists in observation of a point with coordinates ($\alpha, \delta$)
The projection of the ellipsoid of errors is better understood in (Hour Angle-Declination) or (Azimuth-Elevation) space due to the specific motion of the GEO objects. So, it is very useful to calculate the appropriate values of errors and to develop telescope pointing software, which can use this representation of the search field for calculation of the search strategy. Several search fields should be covered as a rule, after the initial orbit determination based on a short arc.

### 3.2. CCD images processing

Since the purpose of the work was the observation of faint objects, to obtain the image of a moving object in the star background with a telescope AT-64 CCD-matrix, it is necessary to increase the exposure time. In this case stars look like points and the object looks like a trail. The problem of an accurate estimation of the astrometric properties of trail objects from a single observation is important for predicting its positions at the next time of observation. It is necessary to increase the probability of repeated detection of the object. To solve the problem some limited estimates based on Cramer-Rao theorem about minimum variance bound are used in the processing algorithm.

Another situation takes place when the telescope control system permits to trace the object of interest, if it’s predetermined trajectory is known. In that case stars smear to trails on the “moving frame” associated with the moving object. Then the problem is to precisely estimate the CCD-frame position relative to the star-trails, and calculate coordinates of the point-like (or slightly smeared) object on the CCD-frame. Fig. 6 shows an example of a CCD-frame, obtained in tracking mode, of one of the discovered objects. The high density of stars is clearly visible.
The Hough transform technique is used for processing such images in the case of the absence of a-priori information about star trails direction and length. But usually the telescope control system provides such information. In this case cross correlation algorithms are used for selection of star trails and their characteristics estimation. Finally, more precise estimations of star positions are obtained with the assumption that the track is a pixel detector image of a segment blurred by a 2-D Gauss point spread function (PSF). The finite size of the pixels takes into account, what the model image is calculating and the PSF is integrating inside of each pixel by analytical calculation. Parameters of the model are estimated with the maximum likelihood method. The combination of approximate, heuristic methods and algorithms on the initial stage of processing and more exact estimation on the final stage allows to achieve good outcomes.

3.3. Positional measurements processing

The refinement of the orbit was conducted with the use of the numerical motion model, which is taking into account the following essential perturbations:

- Earth gravity field (EGM-96 model truncated down to 16x16)
- the Moon gravity (DE-403)
- the Sun gravity (DE-403)
- direct solar radiation pressure (along the object-Sun direction component) in view of the Earth shadow passages

The calculation of derivatives in the model of the orbit determination depends on analytical relations, the integration of the equations of motion implements a modified Runge-Kutta method of the 8-th order (Stepaniants et al., 2000).

Already right at the beginning of activity, in November, 2004, in processing of measurements of two objects detected in the middle of October, rediscovered after a two weeks observation interruption due to weather, the following fact was obvious. For both objects the RMS value of residuals has several times exceeded that expected after refinement of the orbit parameters and the solar radiation pressure coefficient estimation. The external accuracy of single measurements was rated before, on the basis of large statistics accumulated on rather bright unknown objects in the GEO region (Agapov et al., 2005). The value of solar radiation pressure coefficient has appeared extremely large compared to the known usual GEO population representatives. Originally, even the supposition was considered that different objects on very close orbits actually were observed. However, further analysis has confirmed the obtained estimations of the solar radiation pressure coefficient. So some other explanations have to be found for the observed measurements inconsistency. There are the following possible explanations:

- variation of the solar radiation pressure coefficient due to complex object tumbling is not taken into account in the motion model
- two other components of direct solar radiation should be taken into account
- Moon shadow transitions should be added into the motion model, since any time interval without solar radiation influence may result in changes in evolution of orbit for objects with high AMR values

4. RESULTS

As of Aug 20, 2005 orbits of 9 fragments were studied in detail. Object 43022 was first discovered at Zimmerwald observatory and then tracked at CrAO. The orbital parameters are summarized in Table 3. The orbital elements are given in the J2000 reference frame at the epoch provided in the appropriate column.

Table 4 contains values of the standard visual magnitude of the objects (mean and 1 sigma RMS value), estimations of the area-to-mass (A/m) ratio value, and the most probable source of the object (“parent” object).

The values of the standard magnitude are reduced to distance 37000 km and a phase angle 90° according to the well known formula (McCue et al., 1970):

\[
m = -26.58 + 2.5 \log \left[ \frac{\pi}{3} \gamma \right] + \log \left( \frac{A \gamma F(\phi)}{R^2} \right)
\]

where

- \( A \) – area of reflected surface, sq. m
- \( \gamma \) – reflectivity coefficient
- \( \phi \) – phase angle (the Sun–object–observer angle)
- \( F(\phi) \) – function of phase angle
- \( R \) – range between observer and an object

The value of the standard visual magnitude should be considered as the first order estimation, since it was calculated assuming the phase angle function as the one for a diffuse Lambertian sphere:

\[
F(\phi) = \frac{2}{(3\pi^2)} \left[ (\pi-\phi) \cos \phi + \sin \phi \right]
\]

Fig. 7 shows measured values of visible magnitude of these and a few other objects in integrated light.
Table 3. Orbital parameters of detected and tracked faint objects

<table>
<thead>
<tr>
<th>Object</th>
<th>Nights/positions</th>
<th>Observation interval</th>
<th>Orbit epoch</th>
<th>Nodal period, min</th>
<th>a, km</th>
<th>e</th>
<th>i, °</th>
<th>( \Omega, ° )</th>
<th>( \omega, ° )</th>
</tr>
</thead>
<tbody>
<tr>
<td>90003</td>
<td>7/577</td>
<td>18.10.04-10.01.05</td>
<td>2005/01/10 11:08:49</td>
<td>1370.55</td>
<td>40868.21</td>
<td>0.0331042</td>
<td>11.350</td>
<td>337.942</td>
<td>345.7792</td>
</tr>
<tr>
<td>90004</td>
<td>4/294</td>
<td>14.10.04-13.01.05</td>
<td>2005/01/13 15:25:41</td>
<td>1482.82</td>
<td>43075.92</td>
<td>0.0172312</td>
<td>07.464</td>
<td>67.385</td>
<td>43.7397</td>
</tr>
<tr>
<td>90005</td>
<td>4/158</td>
<td>07.11.04-10.04.05</td>
<td>2005/04/10 11:35:33</td>
<td>1428.34</td>
<td>42012.69</td>
<td>0.0605817</td>
<td>14.493</td>
<td>2.432</td>
<td>79.1740</td>
</tr>
<tr>
<td>90006</td>
<td>45/527</td>
<td>17.12.04-17.08.05</td>
<td>2005/09/05 21:12:21</td>
<td>1434.54</td>
<td>42137.74</td>
<td>0.0012055</td>
<td>14.596</td>
<td>356.476</td>
<td>21.4741</td>
</tr>
<tr>
<td>90008</td>
<td>4/205</td>
<td>09.01.05-04.03.05</td>
<td>2005/09/03 18:56:01</td>
<td>1436.50</td>
<td>42175.82</td>
<td>0.0044647</td>
<td>14.340</td>
<td>2.169</td>
<td>89.6021</td>
</tr>
<tr>
<td>90009</td>
<td>10/166</td>
<td>15.03.05-01.04.05</td>
<td>2005/04/01 10:27:27</td>
<td>1441.71</td>
<td>42275.74</td>
<td>0.0030073</td>
<td>14.636</td>
<td>4.472</td>
<td>344.2044</td>
</tr>
<tr>
<td>9010</td>
<td>2/126</td>
<td>08.07.05-13.07.05</td>
<td>2005/09/06 02:08:35</td>
<td>1463.62</td>
<td>42711.46</td>
<td>0.0253512</td>
<td>13.296</td>
<td>12.173</td>
<td>263.4078</td>
</tr>
<tr>
<td>43022</td>
<td>4/51</td>
<td>09.08.05-12.08.05</td>
<td>2005/09/14 19:54:09</td>
<td>1508.38</td>
<td>43604.12</td>
<td>0.5383407</td>
<td>13.859</td>
<td>324.807</td>
<td>163.6123</td>
</tr>
</tbody>
</table>

Table 4. Some characteristics of detected and tracked faint objects

<table>
<thead>
<tr>
<th>Object</th>
<th>Standard visual magnitude</th>
<th>A/m, m²/kg</th>
<th>Probable origin source of object (“parent” object)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90003</td>
<td>16.91 ±0.66</td>
<td>2.23-2.58</td>
<td>03432/1968-081, TRANSTAGE</td>
</tr>
<tr>
<td>90004</td>
<td>17.56 ±0.99</td>
<td>0.33-1.08</td>
<td>03432/1968-081, TRANSTAGE</td>
</tr>
<tr>
<td>90005</td>
<td>17.66 ±0.79</td>
<td>0.69-0.71</td>
<td>11273/1979-015A, EKRAN</td>
</tr>
<tr>
<td>90006</td>
<td>17.53 ±0.74</td>
<td>0.006-0.014</td>
<td>11273/1979-015A, EKRAN</td>
</tr>
<tr>
<td>90007</td>
<td>18.36 ±0.86</td>
<td>0.92</td>
<td>10365/1977-092A, EKRAN</td>
</tr>
<tr>
<td>90008</td>
<td>17.34 ±0.70</td>
<td>0.001-0.019</td>
<td>10365/1977-092A, EKRAN</td>
</tr>
<tr>
<td>90009</td>
<td>17.78 ±0.96</td>
<td>0.009-0.012</td>
<td>11273/1979-015A, EKRAN</td>
</tr>
<tr>
<td>9010</td>
<td>18.16 ±1.01</td>
<td>1.20-1.41</td>
<td>10365/1977-092A, EKRAN</td>
</tr>
<tr>
<td>43022</td>
<td>17.73 ±0.68</td>
<td>5.06-5.42</td>
<td>03432/1968-081, TRANSTAGE</td>
</tr>
</tbody>
</table>

It is not unexpected that 5 of the 9 objects are preliminarily identified with two EKRAN and one Transtage as possible “parent” objects. This is due to search fields that had been chosen for modeled explosion fragments trajectory crossing areas for these objects.

The following features of the detected objects are well visible from the given data.

Two of objects, 90003 and 43022, have the area-to-mass ratio (AMR) values 2.23-2.58 and 5.06-5.42 m²/kg respectively, that is usual for materials used in manufacturing of a multi-layer thermal insulation of spacecrafts. As a result, its orbit experiences strong disturbances on the part of direct solar radiation. Fig. 8 shows evolution of an eccentricity of the object 90003. It is clearly visible, that for 7 months its value changes by 5.9 times. Thus, the maximum orbital altitude changes more than 2500 km (from 35000 up to 37550 km). The eccentricity changes due to direct solar radiation pressure influence with a period of approximately one year. During this period the object reaches a protected region of functioning GEO spacecrafts (altitude of 36600 km), and within 7.5 months intersects this region, and then for 6 months...
leaves the protected region.

Eccentricity (as well as argument of perigee and inclination) of 43022 has evolved even more dramatically. It’s clearly visible that at present this object has orbital energy corresponding to the usual GEO objects drifting above the operational GEO altitude. But the eccentricity is equal to 0.538! This fact can be explained by strong solar radiation pressure perturbations due to the high AMR ratio value of the object.

![Figure 8. Eccentricity evolution for object 90003.](image)

The second interesting feature of object 90003, as well as objects 90006 and 90008, is the absence of the obviously expressed relation of brightness from the value of a phase angle in the range of phase angles 12°-80°. This result is rather unexpected and requires close detailed learning. Taking into account the initial supposition on the phase angle function, one can conclude that 90003, 90006 and 90008 are more close in shape to spheres. But this will not explain variations of the AMR ratio for 90003.

For objects 90004 and 95024 the variability of brightness is visible at different phase angles, as well as a strong dependence of brightness on a phase angle value. Such behavior is characteristic for objects such as a plate, flat cover, etc.

5. CONCLUSIONS

The results of the research of faint objects in the GEO area have allowed to reveal a number of features of such objects. In particular, the objects with large area-to-mass ratio values are discovered. It confirms a stated earlier hypothesis about an incorrectness of the supposition of a zero eccentricity at statistical processing of measurements obtained within the framework of the IADC GEO survey campaigns. Direct solar radiation pressure has an essential influence on orbit evolution for these objects. In view of fast changes of eccentricity and argument of perigee of such objects, the statistical samplings of measurements obtained on various nights, even with a difference of a few months, can contain measurements of the same object, where the eccentricity of the orbit has undergone significant change. The result of calculation of a quantity of objects in such a sampling can appear uncertain, if the changes of eccentricity are not taken into account.

Some of the objects do not have the obviously expressed relation of the value of a brightness to a phase angle in the range of phase angles 12°-80°. The obtained results can be used for refinement of models of a density function of objects in the GEO region, and also can serve as a starting point for organization of constant monitoring of the GEO region with the purpose of obtaining the maximum reliable information about a true population of objects in it.

The authors would like to acknowledge James Dick, Phil Herridge, Thomas Schildknecht, Zhou Xu, Pavel Papushev, and Oksana Yurysheva for the rendered support in realization of additional observations of the detected objects. The work is carried out at partial support of the grant INTAS 2001-0669.

6. REFERENCES

Agapov V., Khutorovsky Z., Boykov V., Sbytov N., Samotokhin A., Experience Of Formation Of The GEO Orbital Information Archive Based On Different Data Sources, Proceedings of the 5th US-Russian Space Surveillance Workshop, 24-27.09.2003, Pulkovo, St. Petersburg, Russia


McCue, Gary A., Williams, James G., Morford, Joan M. Optical characteristics of artificial satellites. SD 70-55. 1 July 1970, Space Division, North American Rockwell
