Analysis of Situation in GEO Protected Region

Vladimir Agapov
Keldysh Institute of Applied Mathematics, Russian Academy of Sciences, Moscow, Russia, avm@kiam1.rssi.ru
Igor Molotov
Keldysh Institute of Applied Mathematics, Russian Academy of Sciences, Moscow, Russia, molotov@kiam1.rssi.ru
Zakhary Khutorovsky
ISC "Vympel", Moscow, Russia, hzn40@mail.ru

ABSTRACT

Protected GEO region is defined by boundaries in inclination (-15° … +15°) and orbit radius (± 200 km with respect to true GEO height). There are nearly 390 operational satellites with orbits inside of this zone. In addition, there are nearly 280 officially catalogued objects with orbits completely inside of the protected zone and nearly 180 catalogued GEO satellites with orbits crossing the protected zone. Research made by the ISON network revealed more than 250 of new previously unknown objects in GEO region with orbits crossing the protected zone. Thus we already have significant amount of accurate information about real population of artificial objects in the most valuable part of GEO space. Based on information obtained by the ISON network we will describe up to the date situation with distribution of GEO objects inside the protected zone. Groups of operational satellites owned by different operators and working in close proximity will be characterized with examples constructed on the base of real measurement data. Uncontrolled objects (both large and small) crossing GEO protected region will be classified by long term evolution peculiarities. Special case of objects with high area-to-mass ratio will be discusses. Importance of more comprehensive deterministic study of the GEO protected region will be shown in our paper.

INTRODUCTION

International Scientific Optical Network (ISON) is a project initiated by the Keldysh Institute of Applied Mathematics (KIAM) of the Russian Academy of Sciences (RAS) joined then by Pulkovo Astronomical Observatory of the RAS.

Initially it was a project aiming to establishing of regular observations of GEO region in order to obtain enough data to confirm the theory of evolution of fragment clouds created in explosions of old GEO resident objects. Another goal was to support radar experiments with additional tracking data using for determination of orbital parameters precise enough to properly point narrow radar beams on selected objects.

First trial experiments are conducted in 2001. The general idea of the project had been presented to the public for the first time in 2003 at the conference conducted by the ISTC[1] [1]. Since May 2004 close cooperation started with colleagues from the Great Britain (former Observatory Sciences Ltd. operated PIMS optical network) and a few months later, in August 2004, with colleagues from Switzerland (Astronomical Institute of the University of Bern, AIUB) and ESA/ESOC (Tenerife/Teide space debris telescope. First results of the new cooperation had been presented at the 4th European Conference on Space Debris in April 2005 [2],[3].

Initial efforts on the ISON development had been supported by the INTAS[2] grants and the special grant by the Russian Ministry of education and science.

Since the end of 2004 the project is concentrated on developing and operating of the international network of optical instruments capable to search and track faint space debris objects on higher geocentric orbits. The aim is improving of our knowledge about pollution of unique regions of the near-Earth space (first of all, GEO) due to launches, on-orbit operations, explosions, deterioration of the spacecraft outer surfaces in time etc. Like for LEO, it is important to understand which sources of space debris exists in that orbits, which explosion events already occurred, how the

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[1] ISTC – International Science and Technology Center, an intergovernmental organization dedicated to the nonproliferation of weapons and technologies of mass destruction

[2] INTAS – ***Int***ernational ***As***sociation for the Promotion of Co-operation with Scientists from the New Independent States (NIS) of the Former Soviet Union, unfortunately not functioning anymore

overall debris population is growing and evolutioning. This knowledge helps us to develop reliable model for the prediction of the future state of higher Earth orbits and to understand better ways for preserving them for the humanity.

The work of the ISON is conducting in full compliance with the recommendations of the UN General Assembly Resolution 62/217 (1 Feb 2008) according to which the General Assembly "*calls … for the development of improved technology for the monitoring of space debris and for the compilation and dissemination of data on space debris*". Overall coordination of the ISON work as well as analysis of obtained results is performed by KIAM.

Interest to ISON capabilities and results started to grow quickly during this year. This can be easily understood if one take into account numerous orbital events happened recently. Operators of GEO satellites realized that they need to have more precise and more up to date orbital information than they have using till now. And this information is required not only for officially catalogued relatively large and easy to track spacecraft and upper stages but also for any other objects surrounding their space assets and creating potential hazard for them. Moreover, data required by operators should contain not just six classical orbit parameters but also information on accuracy of those parameters. All mentioned requirements are obvious but very strong if applied to GEO region due to some problems we discuss in this paper. Right now we do not have even reliable statistical estimation of GEO population for objects larger than 0.1-0.2 m. In contrast, for LEO we have more or less reliable deterministic data for almost complete population of objects with average size (derived from radar cross-section) larger than 10 cm. As for GEO, just a few years ago we were happy to play with measurements for only those objects that have average brightness not fainter than 16^{th} magnitude corresponding to linear size of order 0.8 m if standard albedo assumed. This is mainly due to that primary source of information about GEO region is network of ground optical sensors having numerous constraints (daylight, weather, moonlight, elevation of observed object, limiting magnitude for moving objects observations, geographical distribution etc.).

ISON network, though also consisting of ground optical sensors, gives partial solution of existing problems thanks to wide geographical distribution of facilities, involvement of several dozens of instruments of different class (with aperture between 22 cm and 2.6 m) capable to observe relatively bright (7^{th} – 15^{th} magnitude) as well as very faint (down to 20^{th} magnitude) objects in GEO region, operating several facilities in the same region to ensure minimization of weather dependence. During just a few recent years known population of objects in GEO region increased more than 35 per cent thanks to the scientific work performed within framework of the ISON project (see [4], [5]). More than 150 unknown relatively bright GEO objects are discovered as well as more than 100 unknown HEO (on different orbit types) objects and nearly 450 earlier unknown faint (fainter than 15^{m}) GEO and GTO space debris fragments. Some of the results are publishing annually in issues of "ESOC Classification of Geosynchronous Objects" (see [6] as the most recent published one).

In this paper we discuss ISON capabilities and obtained results on monitoring of the most valuable part of GEO space – so called GEO protected region, one of two protected regions around the Earth introduced in documents at the United Nations level (Fig. 1). GEO protected region is defined by boundaries in inclination (-15°…+15°) and orbit radius (± 200 km with respect to true GEO height 35785 km) and hosts operational spacecraft keeping their station in appropriate orbital slots or performing movement between slots.

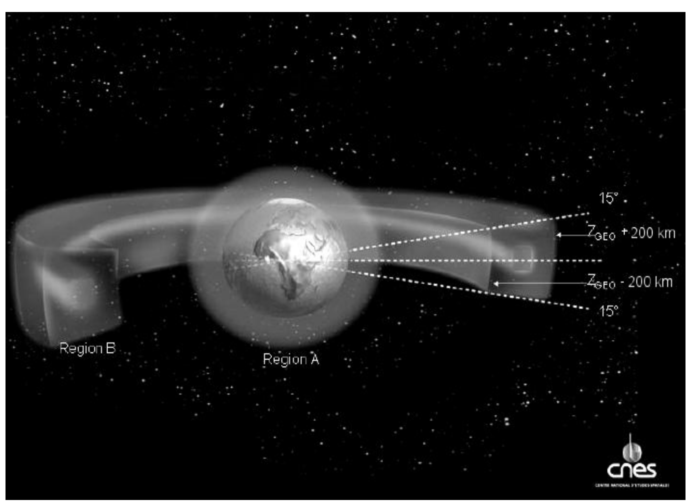

Fig. 1. Defined protected regions around the Earth (Region A – LEO, Region B – GEO)

WIDE SURVEYS AS PRIMARY SOURCE OF OBSERVATIONS OF GEO OBJECTS

By present global GEO coverage capability is achieved by ISON. There are no longitude gaps in the coverage though not all longitudes are observing with multiple instruments yet.

Because objects in GEO region are distributed across wide stripe (as it looks for ground observer) and their number is large (more than 1000) then it is needed to decide which strategy of observation should be applied depending of solving tasks. It is possible to perform observations in two primary modes – continuous survey or object-to-object rounds. From the point of view of new objects discovery and lost objects reacquisition the second mode is much less efficient, especially in case when observing instrument does not have large enough field of view (FOV). This is due to it does not guarantee complete coverage of whole visible part of GEO region. But rounds can be efficiently performed by larger and more sensitive telescopes having smaller FOV for collecting observations for faint space debris in GEO or performing local search around trajectory of the lost object. Some combination of these two modes can result in very efficient strategy of observation data collection.

Object-to-object rounds mode was implemented first in the ISON project. But resulting output was not very significant from the point of view of the project primary goal to estimate real GEO population. Since Jun 2007 wide GEO survey mode is implemented for longitudes 31.5W to 90E in a zone ±16° with respect to the "true" GEO ring. Partial (mostly due to not yet finished work on automation of the telescope mounts) GEO survey mode is implemented for other longitudes.

Wide surveys are performing with 22cm-class Richter-Slevogt-Terebizh (RST-220) optical design instruments specially developed and produced for the ISON project. Depending of the CCD-camera used the FOV of the instrument is varying between 2.8° by 2.8° and 5.5° by 5.5° (optical FOV of the instrument itself is a circle with diameter of 6°). Achieved sensitivity for integration time 10-12 sec is 16.5^m. Metric accuracy of raw measurements depends of the angular velocity of observed object and the mode of survey used. For standard GEO observation mode it is usually better than 2 arcsec. 9 standard instruments of 22-cm class are operational already.

Main instrument performing GEO surveys for 30W-90E arc is PH-1 RST-220 type telescope installed in Nauchny observatory in Crimea (Fig. 2).

Fig. 2. PH-1 (RST-220) telescope in Crimea

Work performed by observers in Nauchny proved that even small class instrument is capable to obtain outstanding results in studying of GEO region. There are 203384 measurements in 28299 tracks collected with PH-1 telescope in 2008 and 203097 measurements in 25473 tracks – in 2009 (as of Aug 19). Measurements obtained in 2008 are identified with 1243 objects, including newly discovered ones. 646 one-night tracks (around 2.3% of overall amount of data obtained in 2008) are not correlated between each other and with any of objects recorded in the KIAM database. Increased output in 2009 is achieved thanks to development and implementation of improved strategy of GEO surveys. Idea of this new strategy is illustrated by Fig. 3 (survey performed on May 19, 2009). There are two main goals driving the survey strategy changing. The first one is fulfilment of a requirement to maximize overall time length of each single-night track in order to increase reliability of one night track correlation with objects in the database and achieve better accuracy in orbit determination. The second one is attempt to increase reliability of correlation of tracks obtained on different nights and belonging to new, earlier unknown, objects. In fact, implementation of the new survey strategy resulted in decreasing of number of uncorrelated tracks in 2009 to less than 1%. Moreover, it becomes possible to correlate tracks and thus to discover earlier unknown fast objects in GEO region having drift rate of order 20-90 deg/day.

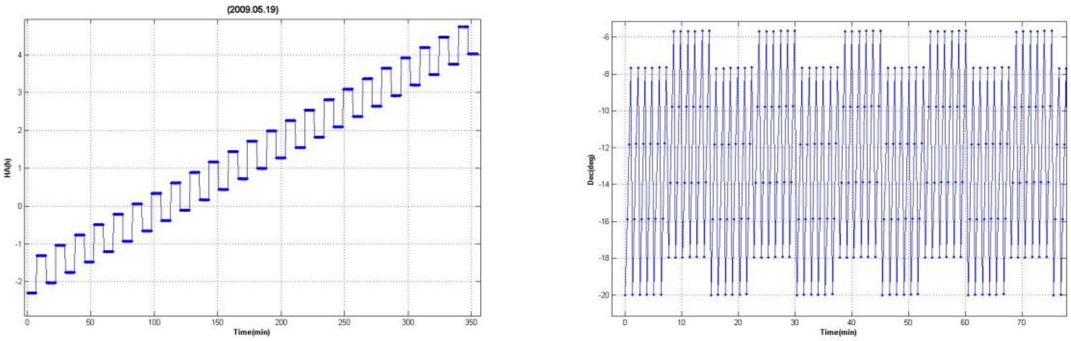

Fig. 3. New strategy of GEO survey developed and implemented in Nauchny observatory (Crimea)

As an example, Fig.4 [7] demonstrates coverage of GEO region in all PH-1 surveys during 2008. Each mark corresponds to one short track. Dense area in the middle of covered region corresponds to 'true' GEO arc where operational satellites maintaining both longitude and inclination are located.

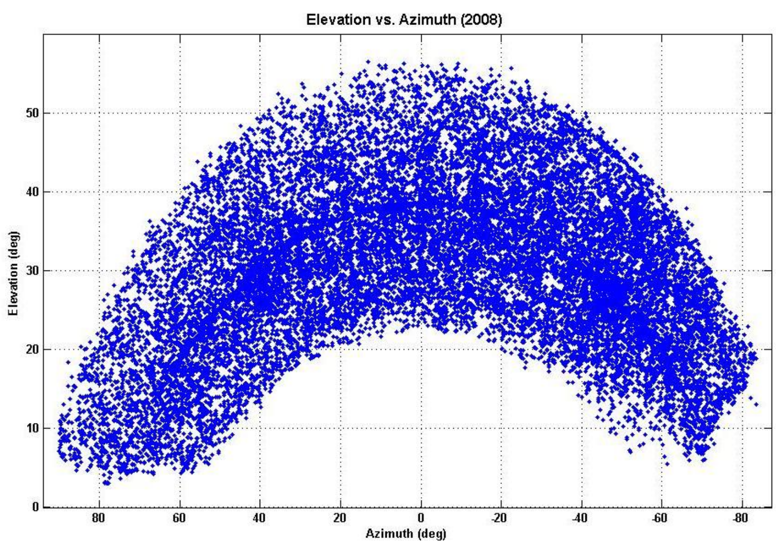

Fig. 4. PH-1 telescope coverage during GEO surveys in 2008.

Collected measurements are used to maintain KIAM database of space objects. As of Aug 20, 2009 the database contains 1441 objects with orbits maintaining on a regular basis (comparing to 1004 ones for which the U.S. SSN provides official orbital information via SpaceTrack Web-site). This number includes 886 spacecraft, 259 upper stages and AKMs and 296 fragments and objects of undetermined type. Analysis of measurement information shows that 391 of 886 spacecraft are maintaining their orbits with periodical corrections.
Distribution of 1441 GEO region objects containing in the KIAM database is shown on Fig. 5. Distribution of the same group of objects by RAAN and inclination is shown on Fig. 6.

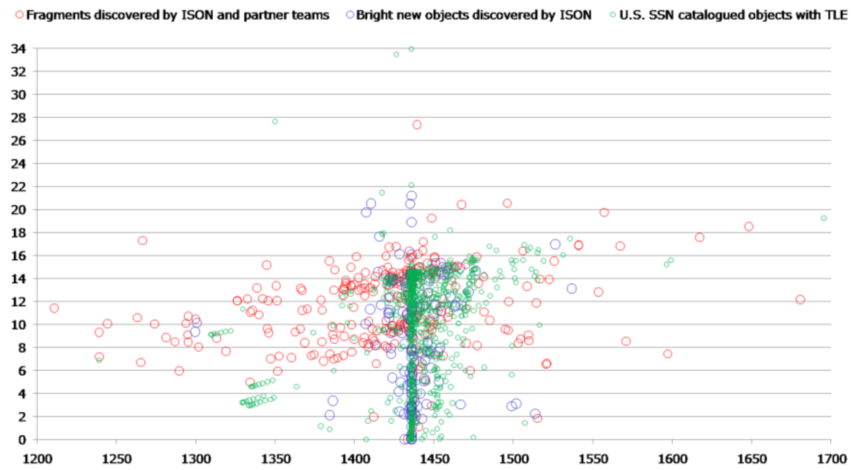

Fig. 5. Distribution of 1441 objects in GEO region (inclination,° vs. period, min)

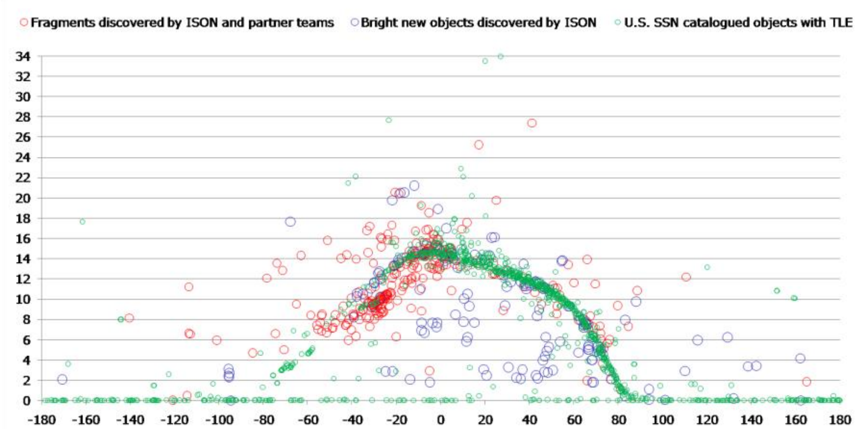

Fig. 6. Distribution of 1441 objects in GEO region (inclination,° vs. RAAN,°)

It should be noted that there are dozens of high altitude high (of order 15-30 sq.m/kg) area-to-mass (AMR) fragments discovered by ISON and partner teams. Many of these objects have orbital period that puts them into GEO class but their eccentricity is significantly varying during evolution due to strong solar pressure perturbations. Because eccentricity values can be as large as 0.6-0.7 those objects can not be considered as belonging to GEO population. We call them GEO-like objects and count separately. These objects are not included into the analysis of situation in GEO protected region.

RESULTS OF ISON RESEARCH OF GEO PROTECTED REGION POPULATION

As it is mentioned earlier, GEO protected region is defined by boundaries in inclination (-15°…+15°) and orbit radius (± 200 km with respect to true GEO height 35785 km). Given orbit radius range corresponds to periods between 1425.6 and 1446.7 min for circular orbits. Objects having eccentricity less than 0.0002, period in given range and relatively low AMR are always staying in GEO protected region. But if the eccentricity is not zero then object may cross GEO protected region. Analysis of orbital information in the KIAM database revealed following current picture of the GEO protected region population (Table 1).

It is seen from Table 1, that operational spacecraft represent 35.6% of overall number of GEO objects permanently staying or periodically crossing GEO protected region. If one takes into account just satellites permanently staying in GEO protected region then operational spacecraft represent 57.2% of the population. Those non-functional objects permanently staying in GEO protected zone pose the most significant danger for GEO operational spacecraft.

Table 1. Distribution of objects in GEO protected region (as of end of Aug, 2009)

Object type	**Overall number**	**Inclination range, °**	**Eccentricity range**	**Period range, min**
Operational spacecraft	391	0.0-16.3	0.0000-0.1067	1435.52-1436.14
Non-operational spacecraft	282	0.3-21.1	0.0000-0.1804	1197.7-1458.2
including permanently staying in GEO protected zone	*212*	*0.8-15.3*	*0.0000-0.0039*	*1430.4-1445.2*
Spent upper stages and AKMs	174	0.2-23.1	0.0003-0.1784	1197.6-1766.0
including permanently staying in GEO protected zone	*67*	*1.2-15.3*	*0.0003-0.0044*	*1428.9-1444.1*
Fragments and objects of unknown type	250	0.2-20.6	0.0009-0.2045	1161.2-1617.3
including permanently staying in GEO protected zone	*13*	*10.9-14.4*	*0.0009-0.0042*	*1433.1-1439.7*
Total	**1097**	**0.0-23.1**	**0.0000-0.1784**	**1197.6-1766.0**
including permanently staying in GEO protected zone	***683***	***0.0-15.3***	***0.0000-0.1067***	***1428.9-1445.2***

Note. Period range for operational spacecraft is given for satellites on-station. Periods of those operational spacecraft drifting at present between orbital slots or permanently drifting around GEO are not taken into account for determining of this period range.

In order to estimate current capabilities of ISON to determine accurate orbits of potentially dangerous objects and to predict possible close encounters with high level of reliability special research is made. It is revealed that, in general, threats for operational GEO spacecraft can be divided into two groups: creating by other operational spacecraft located in close proximity (for example, sharing the same orbital slot) and created by non-functional objects.

Threat existing for particular operational spacecraft in GEO from other operational spacecraft exists mainly due to different strategies using for GEO satellite position maintenance and lack of co-ordination between different satellite operators. In order to better understand this kind of threat orbital motion of all operational GEO spacecraft have been studied using large amount of measurements produced by ISON network. Analysis of accumulated orbital archive has permitted to propose new classification of orbits for GEO operational spacecrafts comparing to that one used in “Classification of Geostationary Objects” issues by ESOC [6].

New classes of operational GEO spacecraft include [8]:
C1 – satellites maintaining longitude and near-zero inclination,
C2 – satellites maintaining longitude only,
C3 – satellites maintaining longitude and non-zero inclination,
C4 – satellites maintaining orbital period different then ‘true GEO’ and near-zero inclination while remaining in GEO region,
C5 – making manoeuvres on orbit with period different of 'true GEO' one (including graveyard one) while remaining in defined GEO region.

Each class can be divided into two subclasses:
E1 – orbits with eccentricity less than 0.001,
E2 – orbits with eccentricity between 0.001 and 0.15.
This classification gives new view on ‘operational zone’ of GEO.

Following pictures demonstrate peculiarities of orbital motion of some GEO spacecraft belonging to different operational classes. Each circle corresponds to updated orbital parameters set obtained after processing of ISON measurements.
Fig. 7 shows typical pattern of orbit inclination maintenance for satellites of the C1 class (Intelsat 904 is given as an example).
Fig. 8 shows typical pattern of longitude maintenance for satellites of the C2 class (spacecraft with ISON number 95151 is given as an example).

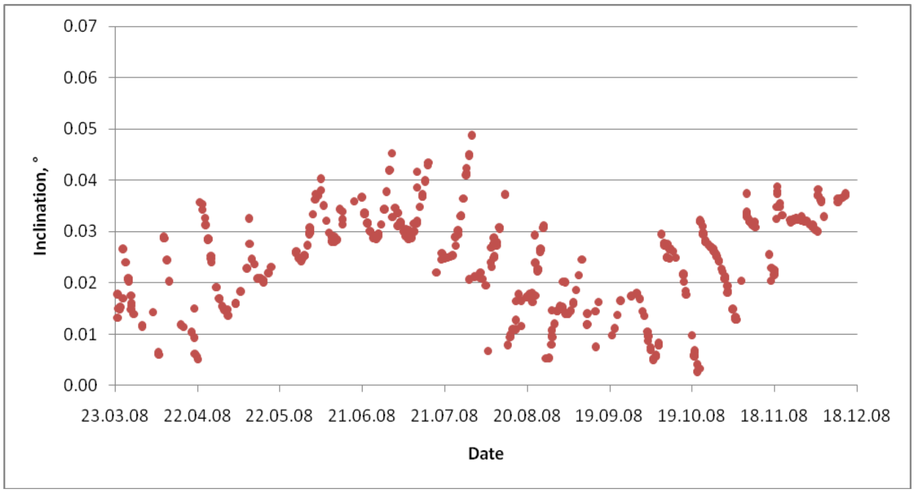

Fig. 7. Orbital inclination maintenance for the C1 class of orbital motion GEO spacecraft (27380 INTELSAT 904)

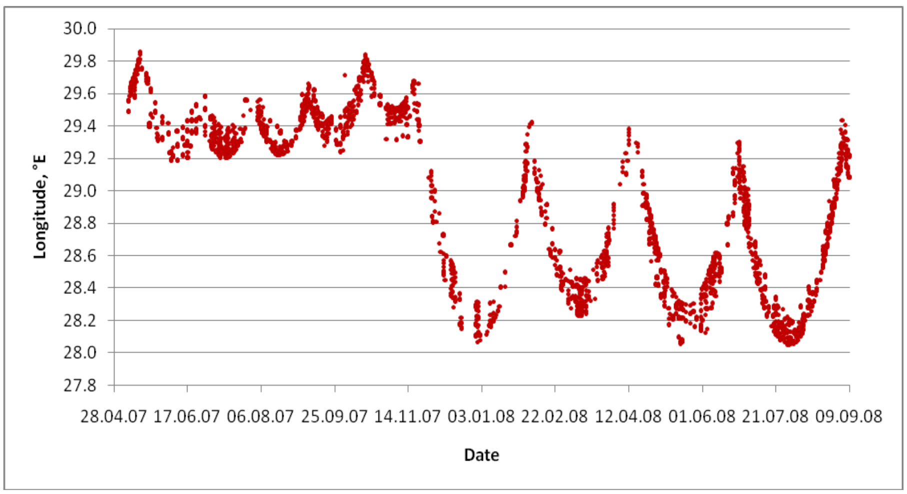

Fig. 8. Longitude maintenance for the C2 class of orbital motion GEO spacecraft (ISON number 95151)

Fig. 9 shows typical pattern of inclination maintenance for satellites of the C3 class (spacecraft with ISON number 95162 is given as an example).

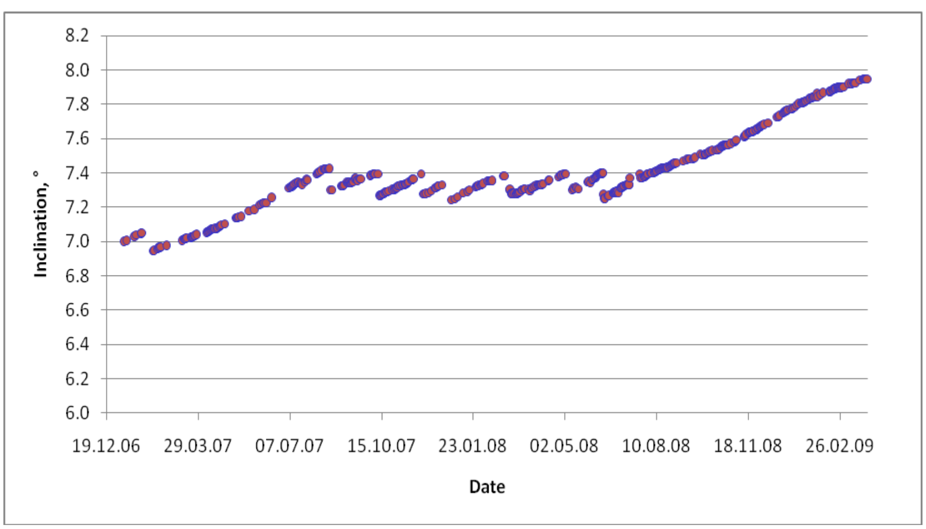

Fig. 9. Inclination maintenance for the C3 class of orbital motion GEO spacecraft (ISON number 95162)

Fig. 10 shows typical pattern of orbit maintenance operations for satellites of the C4 class (spacecraft with ISON number 95010 is given as an example).

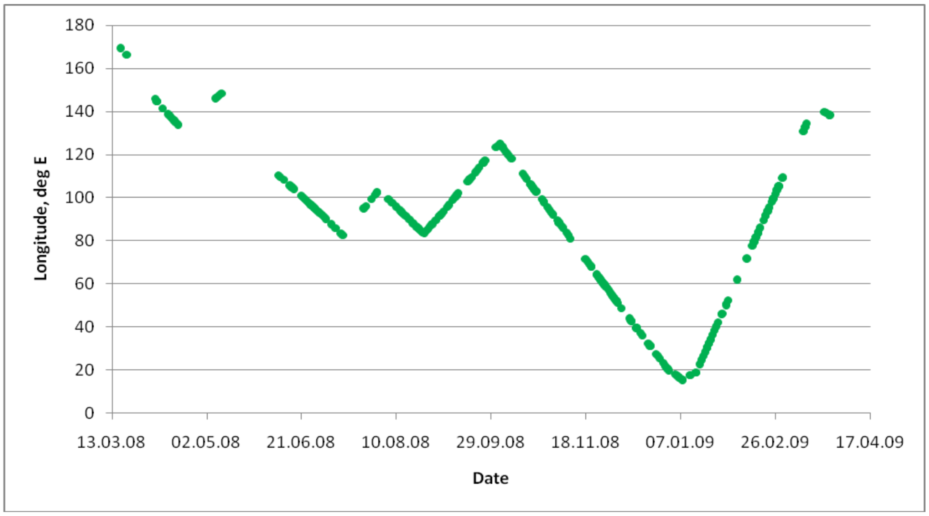

Fig. 10. Orbit maintenance for the C4 class of orbital motion GEO spacecraft (ISON number 95010)

One can expect that different strategies of orbital maintenance in case of absence of coordination between operators may result in creation of potentially dangerous situations. As an example, Fig. 11 shows history of longitude for two satellites (27380 INTELSAT 904 and spacecraft with ISON number 95198) co-located in 60E orbital slot. One can see that till the beginning of 2009 longitude position of object 95198 have been close periodically to longitude position of INTELSAT 904. During those periods of time when this situation have been happening very close coordination between operators have been required in order to avoid any troubles. It seems that early 2009 Intelsat and operator of 95198 have agreed to keep position of their spacecraft in such manner that would permit to avoid close encounters between their assets.

Similar situation exists in 70E where there are two co-located satellites – 32373 COSMOS 2434 (C1 class of orbital maintenance) and spacecraft with ISON number 26880 (C2 class of orbital maintenance). Analysis of recent measurement data obtained by ISON revealed series of close encounters between these two satellites happened between Aug 25 and Aug 28, 2009. The closest one took place at 01:20:35 on Aug 28. Miss-distance in radial, in-track and cross-track directions was 4.1, -5.2 and 0.17 km correspondently that is comparable with orbit determination errors.

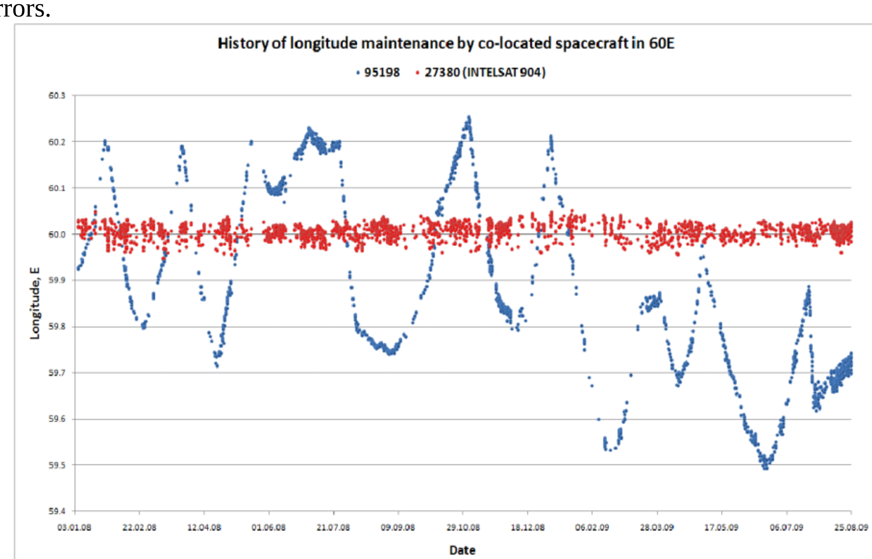

Fig. 11. History of longitude maintenance by co-located spacecraft in 60E

Accurate analysis of possible close encounters between two operational spacecraft is a complex task due to periodical manoeuvres performing by them. The task becomes even more complex in case of absence of precise orbital information from operators. Scheduling of ISON surveys and object-by-object rounds takes this into account in order to obtain the best result we can produce.

Other threats to operational GEO spacecraft are created by non-functional satellites – dead spacecraft, spent upper stages and AKMs and fragments of different kind (operational or fragmentation related). Potentially the most dangerous of them are those located on so called librating orbits. These satellites are moving very slowly along GEO ring at heights where operational spacecraft are located. Those of them having normal AMR value are usually well predictable in motion though there are some exceptions. But fragments having high and variable AMR value are very hard from the point of view of close encounters search due to large errors of prediction of their motion caused by numerous uncertainties.

To demonstrate (based on recent ISON data) typical close encounter of operational GEO spacecraft and non-functional object permanently located in GEO protected zone following situation have been found. Object with ISON number 95061 (supposedly – operational fragment) is located at orbit with parameters: period – 1434.1 min, eccentricity – 0.001445, inclination – 14.45°. AMR for this object is of order 0.005-0.009 sq.m/kg. It was found that on Sep 1, 2009 at around 20:31:59 UTC 95061 will pass close to INTELSAT 902 (Fig. 12). Predicted radial, in-track and cross-track components of miss-distance are following: -13.6 km, 0.99 km and 0.13 km respectively. Relative velocity at the time of encounter is 774 m/s. Interval of prediction is less than 1 day since the last orbit determination for each satellite. Such encounter should be considered dangerous due to very small miss-distance in radial and cross-track directions. Relatively large along-track miss-distance should not be assumed safe because even small orbital correction planned by Intelsat operators without information on possible encounter can dramatically change whole situation.

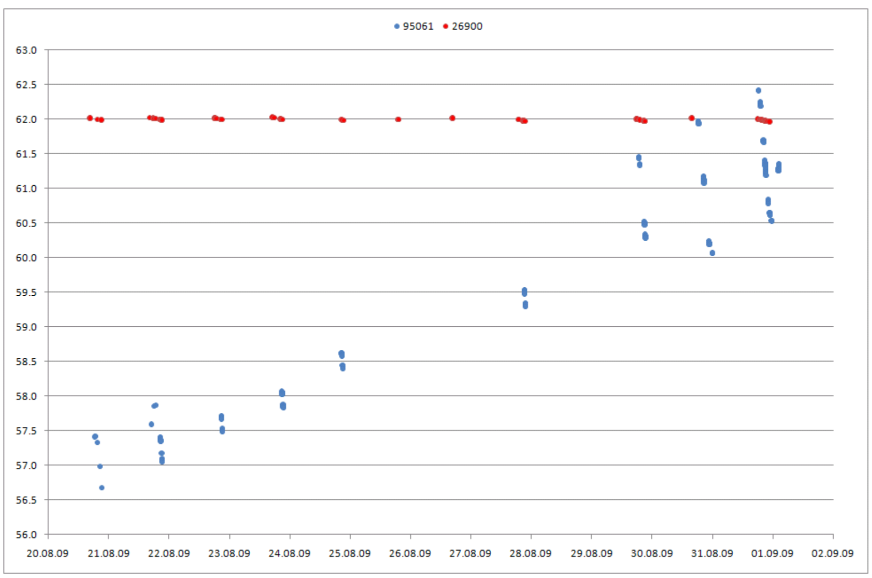

Fig. 12. Position of objects 95061 and 29600 (INTELSAT 902) at the time of observation by ISON network during Aug 20-31.

CONCLUSIONS

Thank to the developing and implementation of the ISON project new level of quality of GEO region research is achieved. At present full GEO arc coverage is established, regular wide surveys are carried out. For the first time our knowledge of true GEO population of objects brighter than 15^m can be considered as very close to complete.

Analysis of obtained measurements and orbits revealed that GEO protected zone is highly populated both operational spacecraft (391 as of end of August 2009) and non-functional satellites, including dead spacecraft, spent upper stages and AKMs, fragments and objects of undetermined type (706 as of end of August 2009).

New classification of operational spacecraft orbits has been developed. This classification can be taken into account in observation planning as well as in process of search of potential close encounters between operational satellites and other objects in GEO protected zone. Also, it can be used by satellite operators for better understanding of overall situation around their space assets.
In order to improve quality of obtained orbital information and to fulfill requirements of accuracy at close encounters analysis new survey strategy has been developed and implemented. In addition, implementation of this strategy resulted in decreasing of number of uncorrelated tracks.

The ISON have developed new level of international cooperation in very complex research area. It is an open scientific structure and all nations are welcome to participate.

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