Conjunction assessment for GEO satellites: ISON experience of using orbital data produced from own measurements

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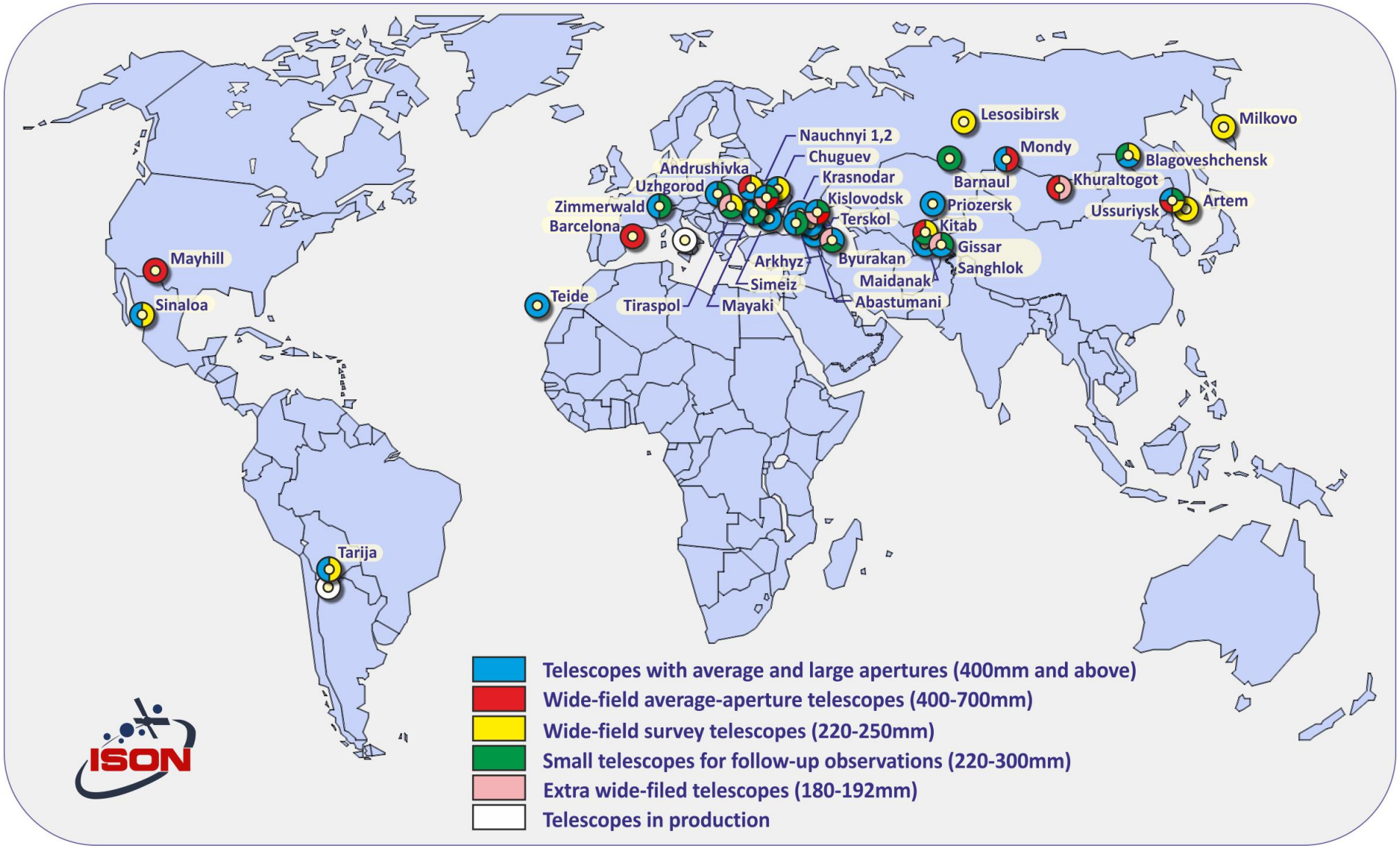
International Scientific Optical Network (ISON)

- ISON is an open international project developed to be an independent source of data about natural and artificial space objects for scientific and applied purposes
- ISON is a worldwide network coordinated by Keldysh Institute of Applied Mathematics of the Russian Academy of Sciences (KIAM)
- ISON is cooperating with 35 optical observatories and observation facilities operating at present 84 telescopes in 15 countries
- ISON promotes enhancing the international collaboration between observatories in developing countries and scientific organization in industrialized countries in the filed of optical observation of natural and man-made celestial objects

ISON observatories location



Network of Roscosmos observation instruments (complimentary to ISON)

Provides measurements to support ASPOS OKP functions by KIAM Space Debris Center

This single instrument have providing up to 18500 observations for up to 560 objects per night

KIAM Space Debris Data Center Overview

- KIAM space debris data center is established in 2003 as a central information node to perform space debris research in RAS and to support ISON development and operations
- Key solving tasks
  - Maintenance of the ISON master database on space objects, related events (launches, fragmentations, re-entires etc.), measurement data and derived products (orbits etc.)
  - Development and implementation of optical observation strategies
  - Daily scheduling of the ISON sensors for routine and special survey and tasking observations of GEO, HEO and MEO regions of the near-Earth space
  - Collecting and processing of the ISON produced optical measurements on objects in the near-Earth space, determination of parameters of orbits and their accuracy estimation for each observed object
  - Evaluation of physical characteristics of observed objects
  - Search and analysis of probable close conjunctions at GEO, HEO and MEO
  - Processing customer's requests and preparing output products (conjunction assessment messages, raw measurements, orbital data/ephemerides etc.)

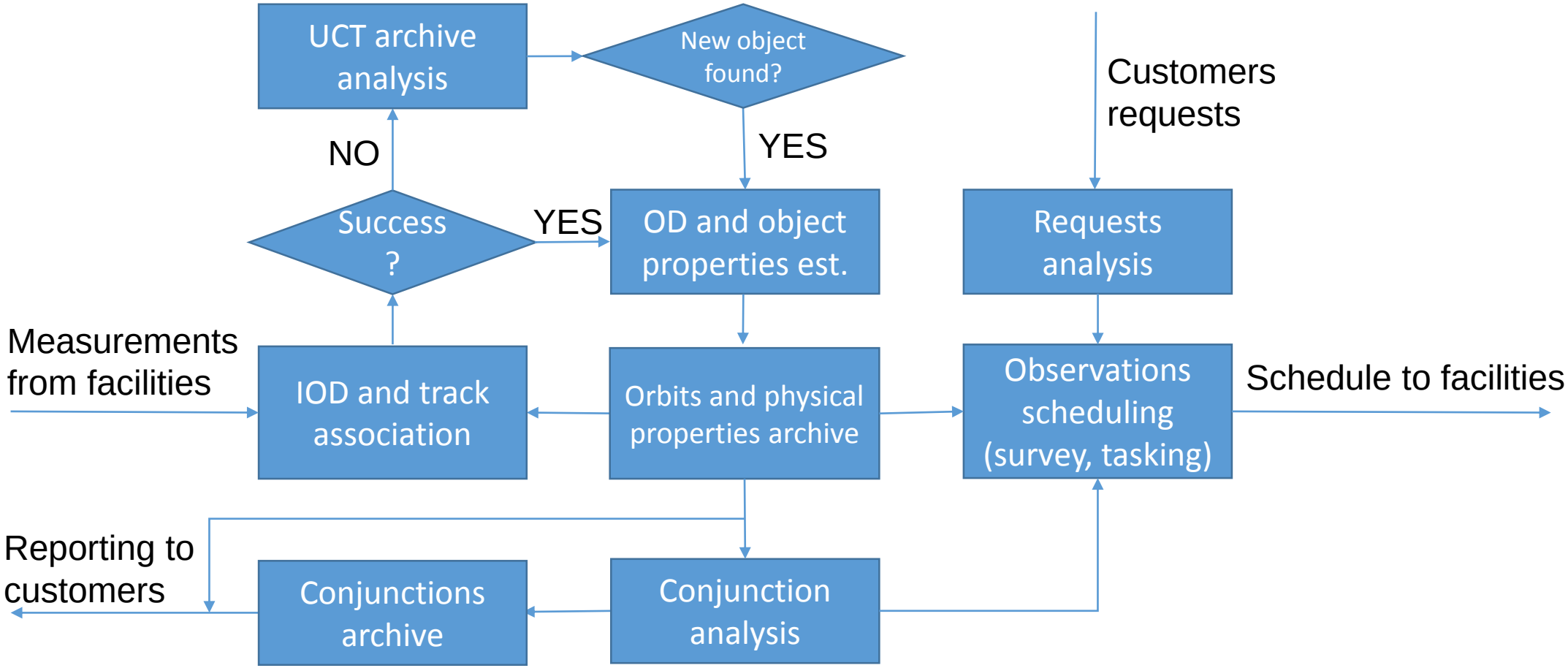
Data Center Current Operational Characteristics

- Daily processing up to 90000 optical measurements
- Daily updating orbital data for nearly 2000 high altitude space objects
- Daily conjunction analysis for >50 operational spacecraft, including analysis of motion for co-located GEO active spacecraft operated by non-cooperating entities
- Daily scheduling of 20 survey and 15 tasking sensors
- Scheduling and processing dedicated observations of objects as part of launch operations support (HEO, MEO, GEO)
- Storing original CCD images obtained by ISON instruments
- Required number of personnel for operation – 3 people in a shift

The Center's Master Database

Objects and events	Sensors	Observations and derived data	Customer's data
Master registry of orbital objects	Optical instruments properties	Raw measurements archive	Archive of data on customer's objects
List of space launches	Archive of calibration data	Processed measurements archive	Customer requests archive
List of on-orbit fragmentations	Obs schedules archive (survey, tasking)	Archive of orbits	Output reports archive
Archive of external data on objects and events in space	Archive of data on meteo and sky conditions	Archive of estimated physical properties of objects	
		Conjunctions archive	

Simplified operational flow chart of measurement processing and conjunction analysis



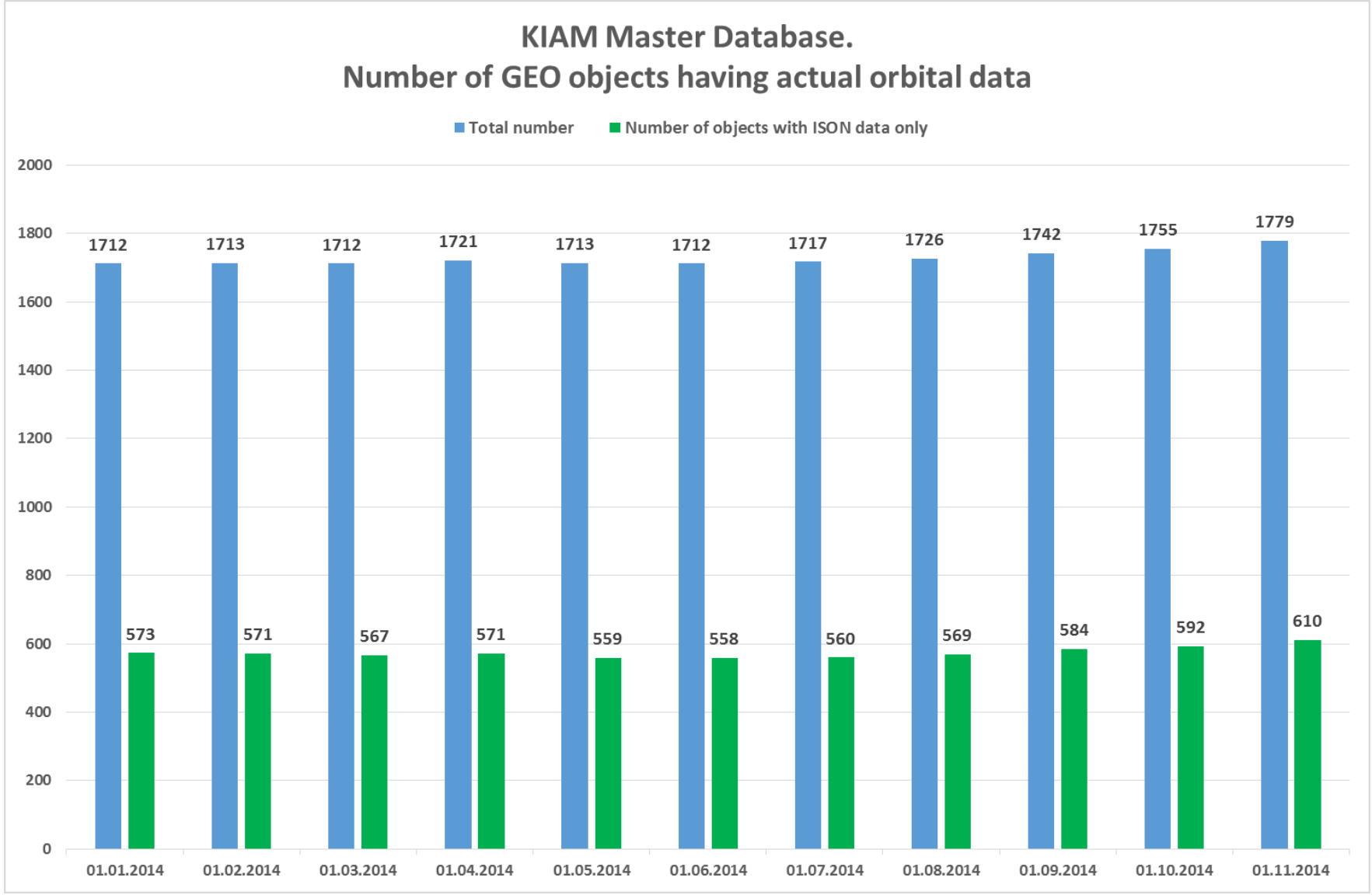
Customers of the KIAM Space Debris Data Center

- ASPOS OKP - Automated system of warning on dangerous situations in space developed and maintained for ROSCOSMOS
- Industry entities
  - Vimpel Interstate Corporation
  - Information Satellite Systems – Reshetnev Company
  - Gazprom Space Systems
  - Lavochkin Research and Production Association
- RAS research institutes

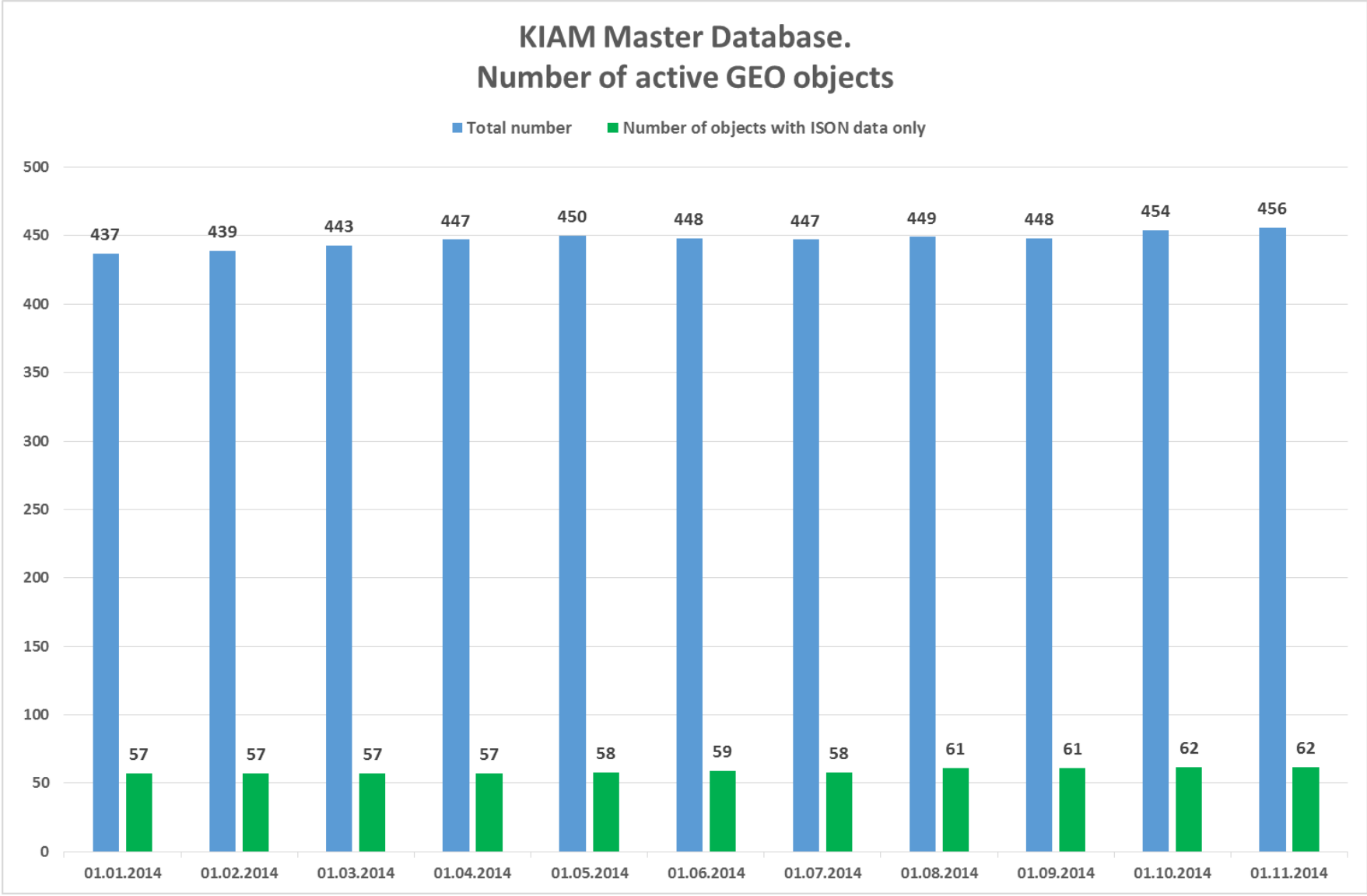
Key Requirements Arising from Conjunction Assessment

- Completeness of a catalogue
- Accuracy of the orbital data taken for conjunction assessment:
  - some ‘average’ level for each and every object – for conjunctions screening
  - the best possible for objects in predicted conjunction – for detailed analysis and decision making
- Estimation of reliability of the conjunction assessment results
- Understanding orbital ‘behaviour’ of each object (based on analysis of information archive) for proper interpretation of predictions for orbits and conjunctions:
  - manoeuvering spacecraft (including customer’s objects)
  - special kinds of non-active objects (e.g., HAMR debris, objects with low perigee)
  - other non-active objects
  - newly discovered objects (including objects associated with new launches)
- Consistency of the conjunction assessment procedure timeline with time constraints existing in the customer’s spacecraft flight control procedures

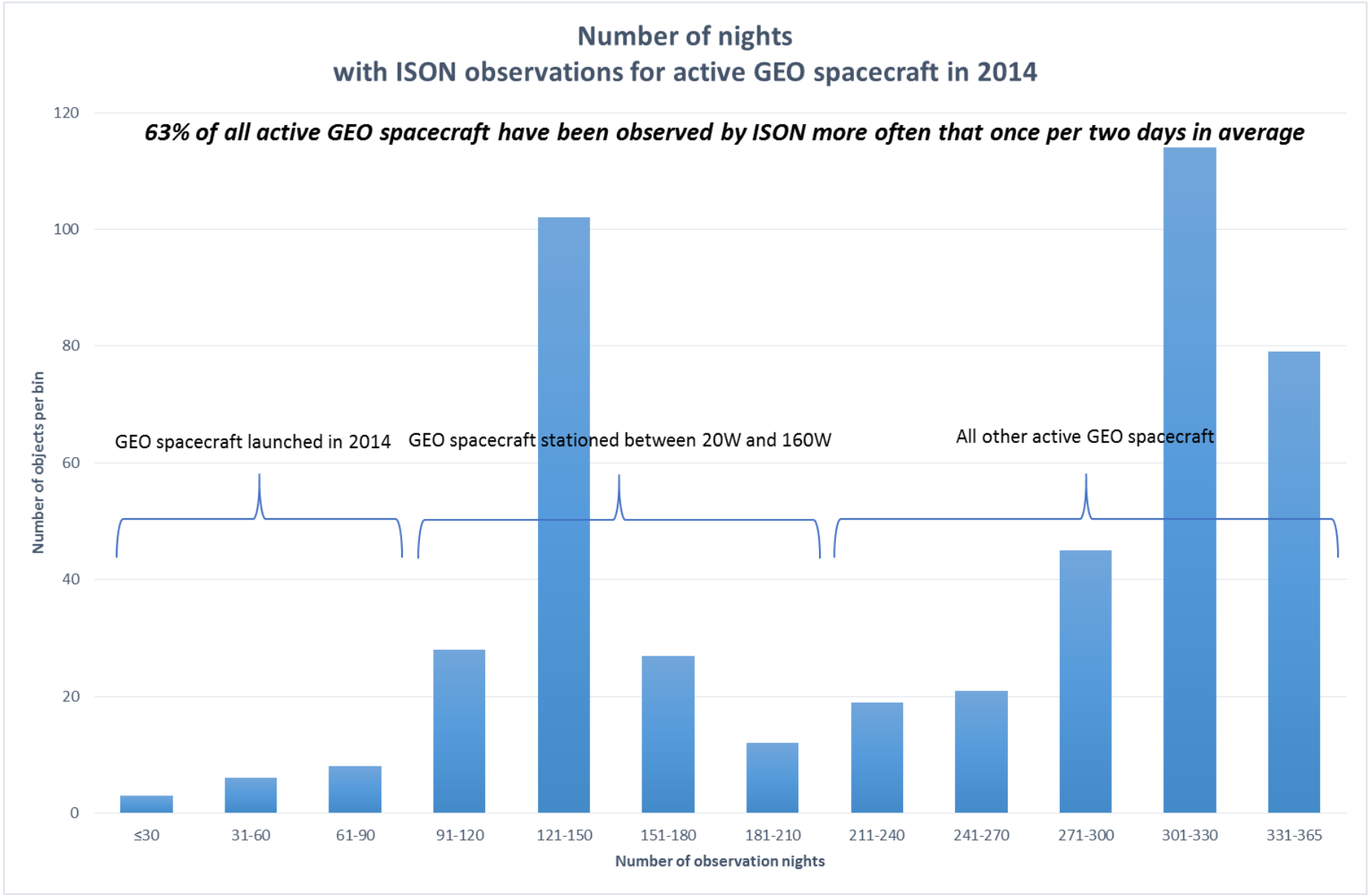
Completeness of the ISON catalogue for GEO and frequency of observations



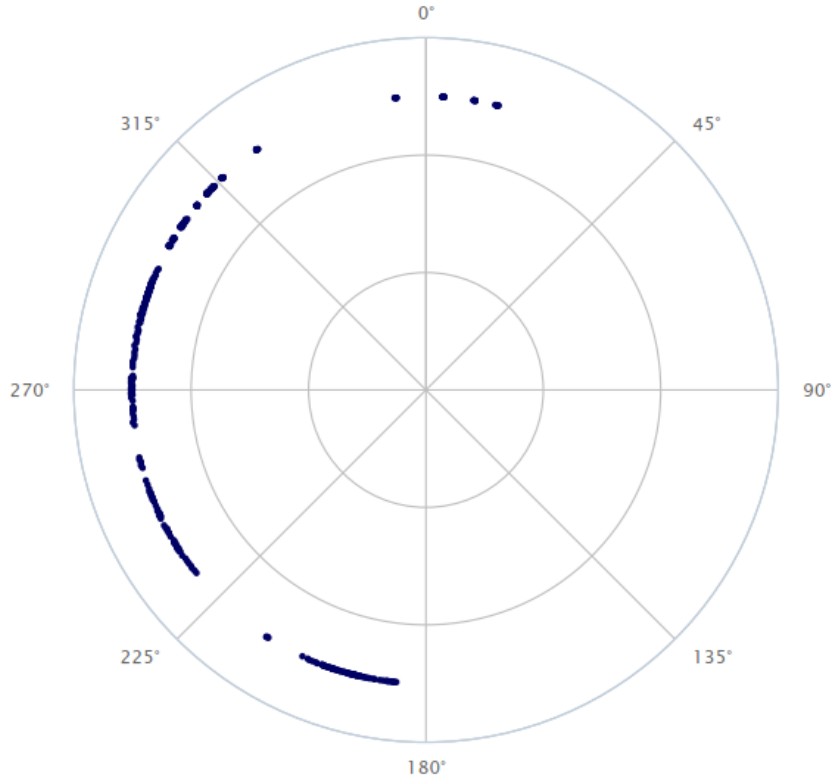
34% of objects tracked by ISON in GEO region (*defined by following constraints: period between 1100 and 1800 min, eccentricity is less than 0.3, inclination is less than 30°*) have orbital data derived only from ISON measurements

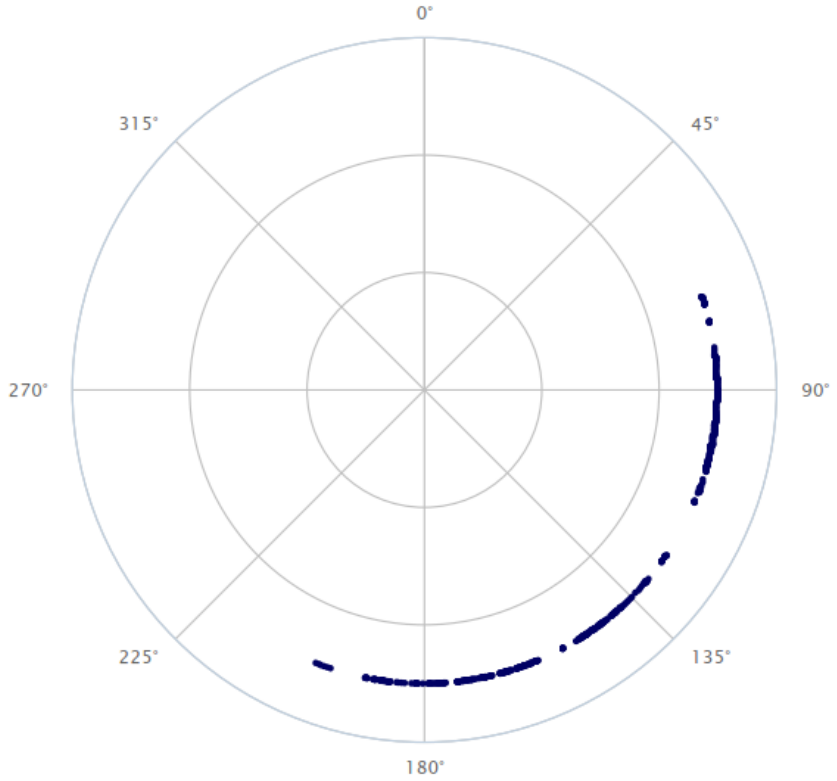


13.6% of active objects in GEO region have orbital data derived only from ISON measurements



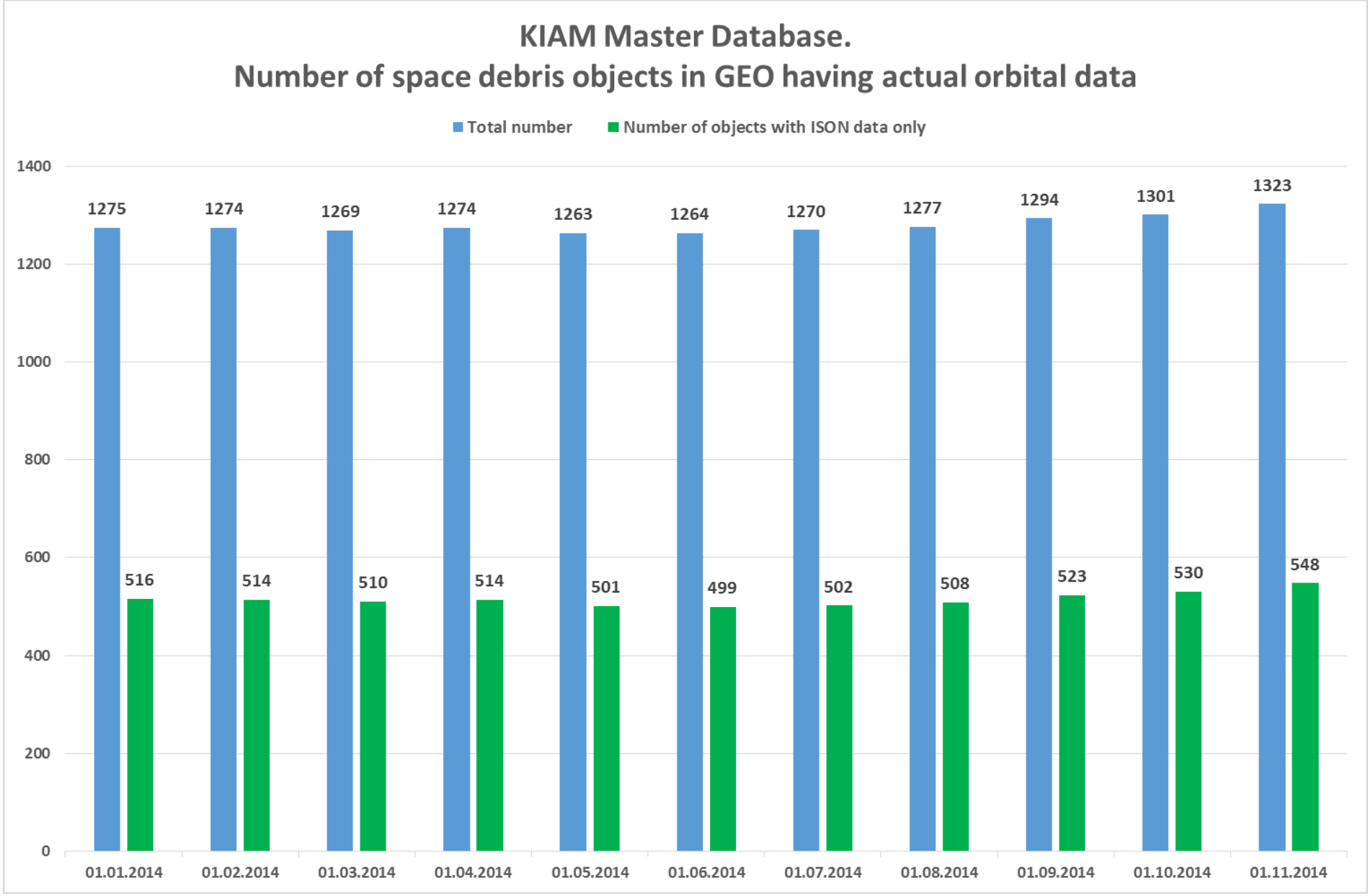
Observations frequency and overall orbit coverage arc for OD are the most critical requirements for active S/C



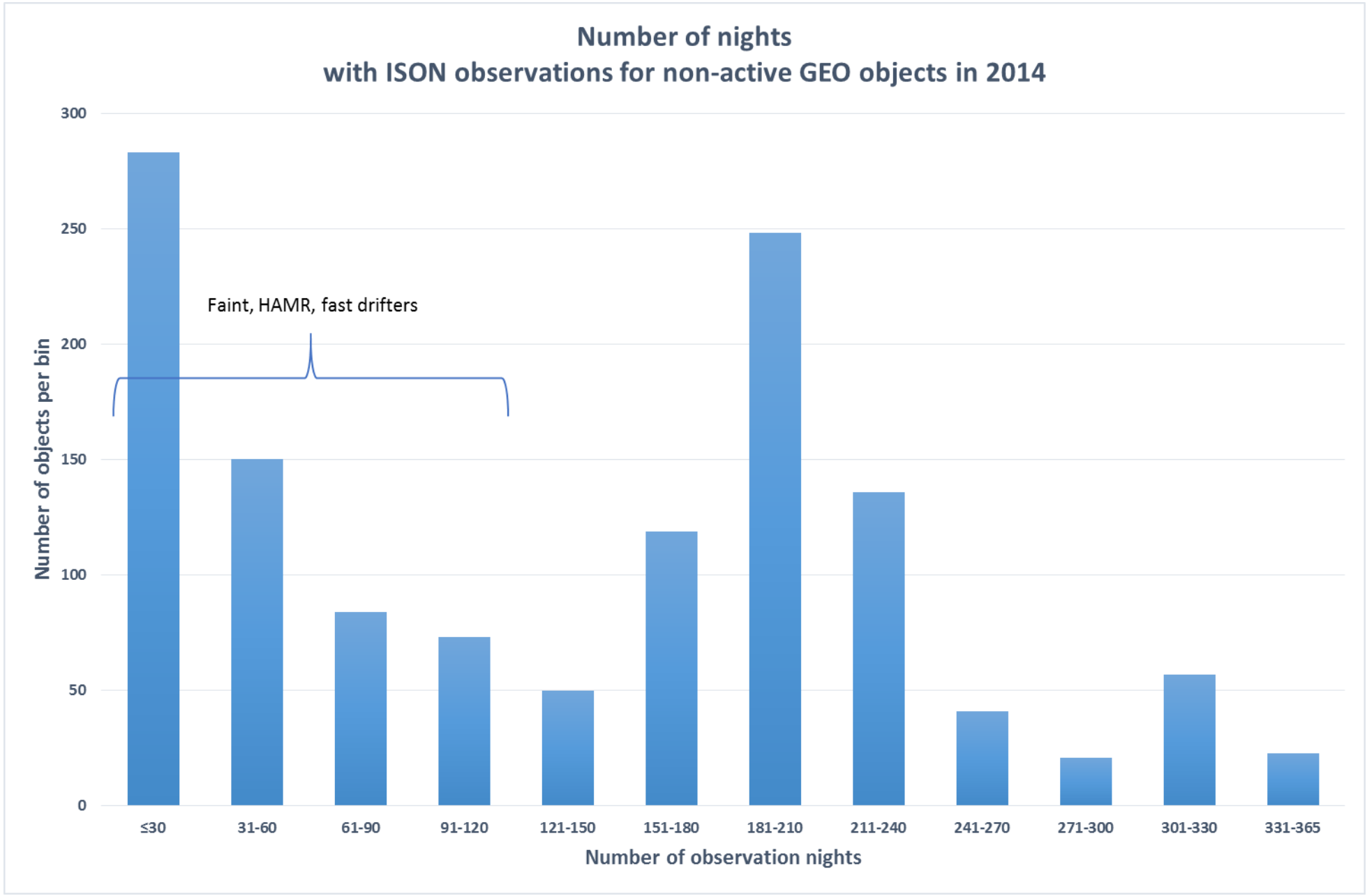


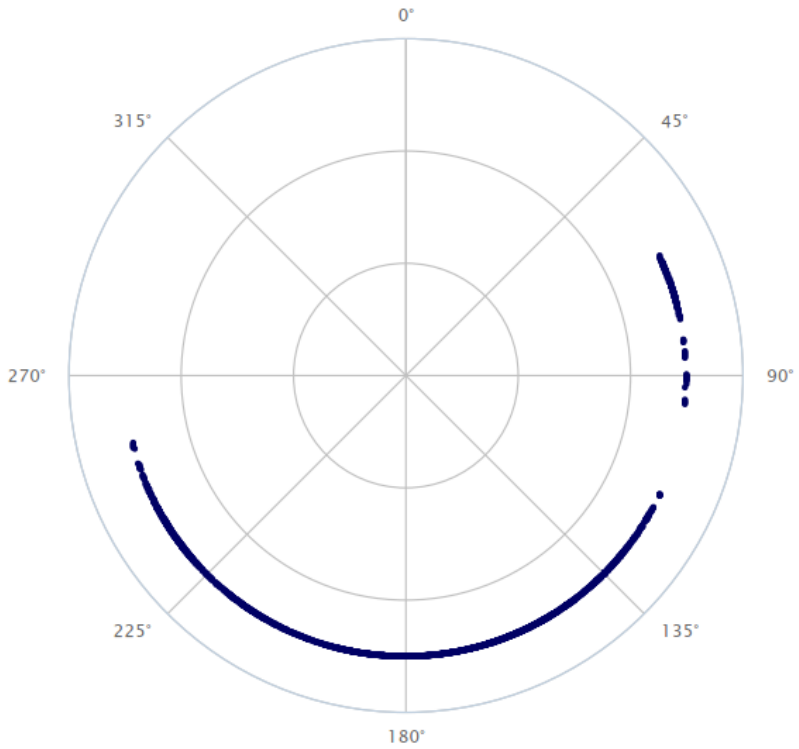
Typical distribution of measurements obtained by ISON for active GEO spacecraft by argument of latitude over OD arc:

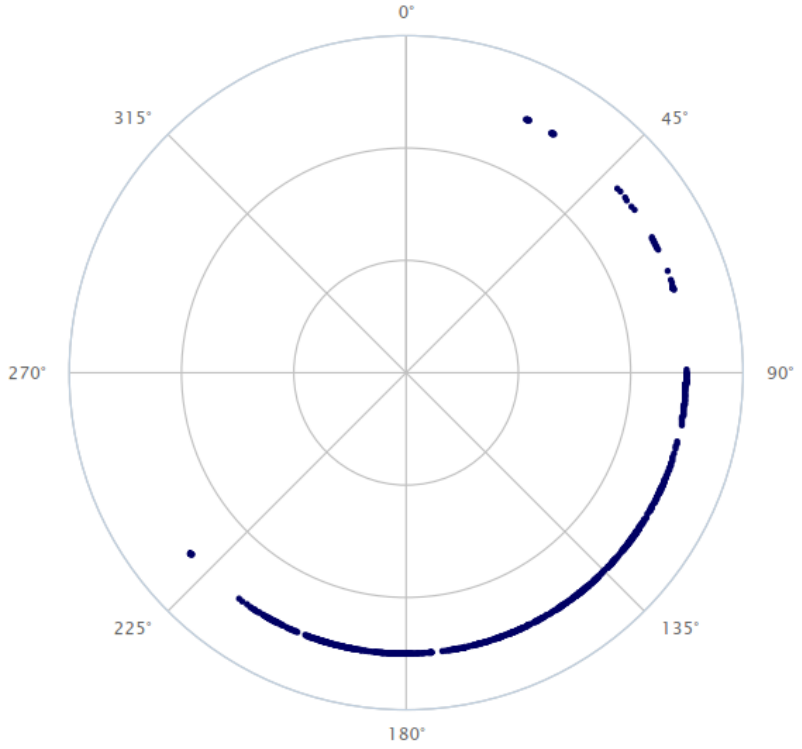
- performing only E-W stationkeeping manoeuvres (LUCH 5V at 94.6E, left, OD arc length – up to 23 days)
- performing both E-W and N-S stationkeeping manoeuvres (SESAT 2 at 53E, right, OD arc length 1.5-3 days)



41% of space debris objects in GEO region have orbital data derived only from ISON measurements

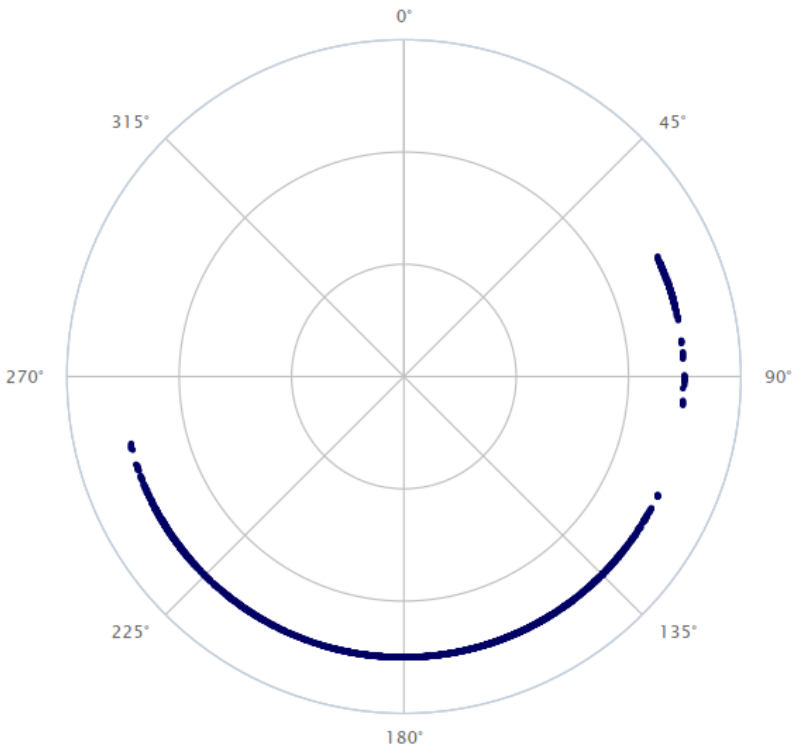

Number of nights
with ISON observations for non-active GEO objects in 2014
Number of objects per bin
300
250
200
150
100
50
0
Faint, HAMR, fast drifters
≤30
31-60
61-90
91-120
121-150
151-180
181-210
211-240
241-270
271-300
301-330
331-365
Number of observation nights

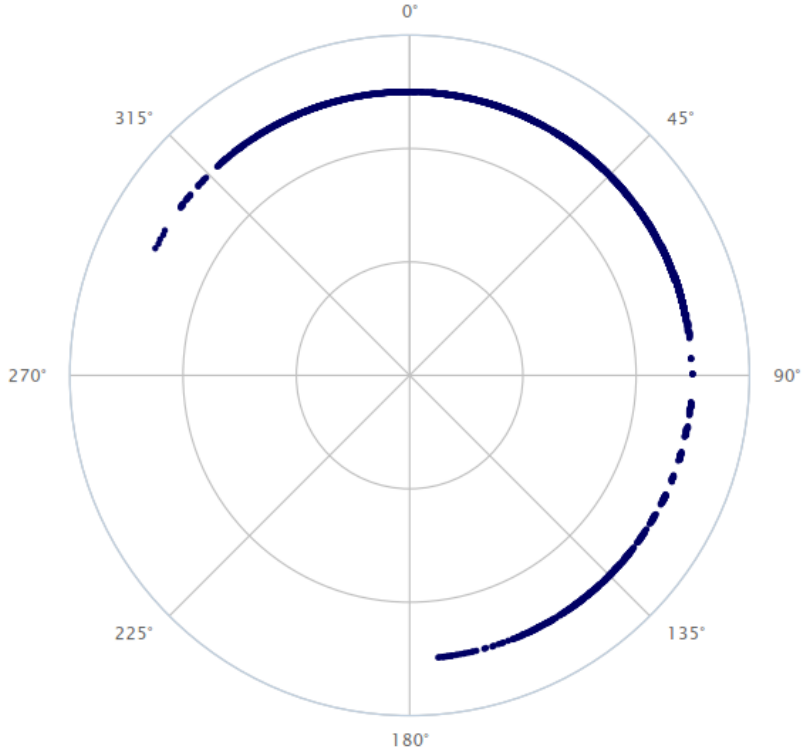




Typical distribution of measurements obtained by ISON for non-active GEO objects by argument of latitude over OD arc (normally the OD arc length is 50-90 days):

- slow drifter (CENTAUR R/B 1998-029B, left, OD arc length 59.9 days)
- fast drifter (BREEZE-M R/B 2014-023C, right, OD arc length 54.5 days)





Specific range of covered arguments of latitude is varying during a year.

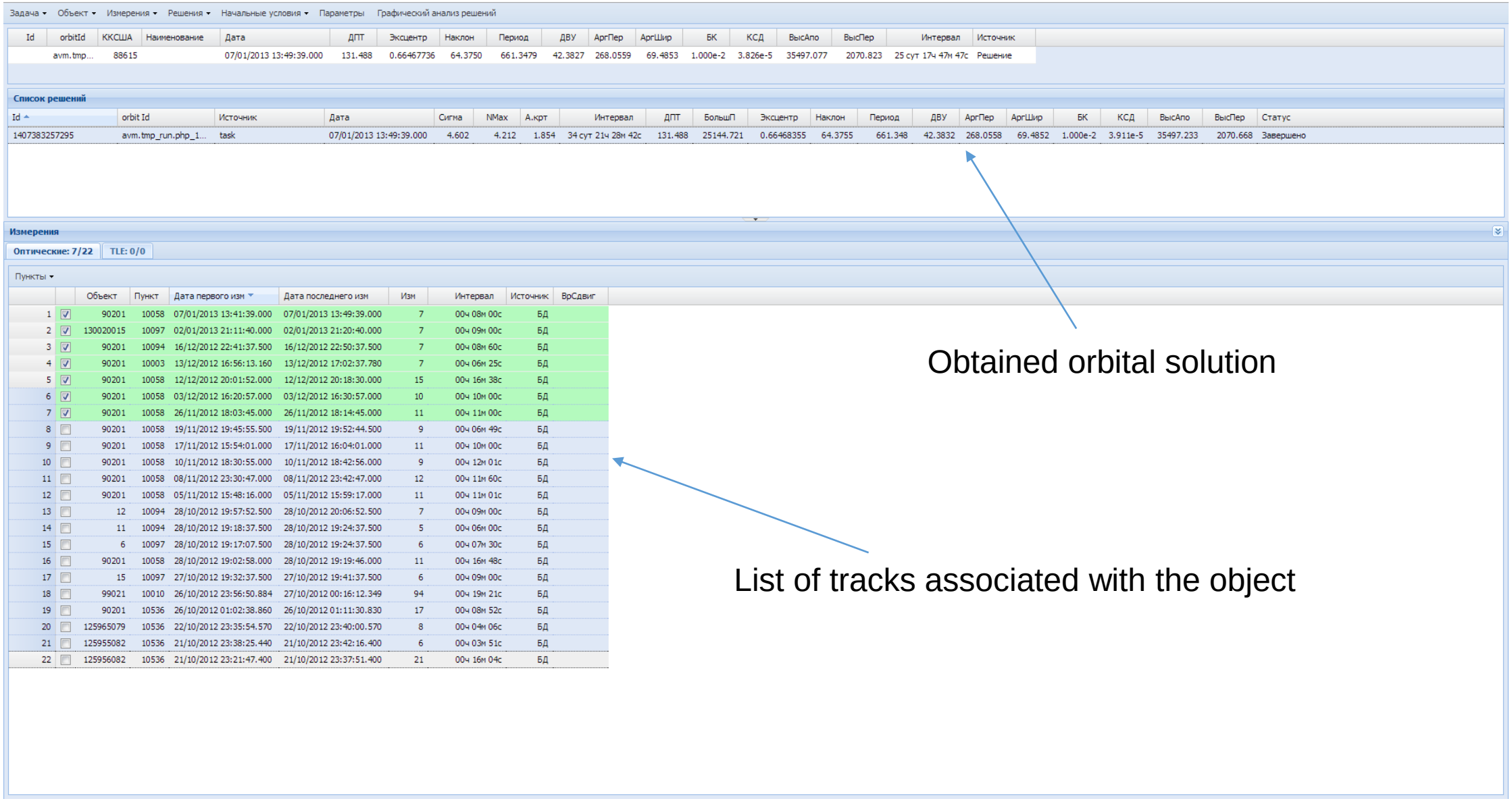
- CENTAUR R/B 1998-029B, OD at the end of Apr 2015, left
- CENTAUR R/B 1998-029B, OD at the end of Dec 2014, right

Orbit determination and accuracy control

Orbit Determination

- Numerical propagator taking into account following perturbations (tunable for specific orbit):
  - Earth gravity (selection of a gravity field model is possible)
  - 3rd bodies gravity (Sun, Moon - DE405)
  - atmosphere drag (selection of a density model is possible)
  - SRP (cylinder or conical Earth shadow)
- Estimation of 6, 7 or 8 parameters (state vector in combination with ballistic and/or SRP coefficient – decision is making automatically on what combination would be the most appropriate in particular OD) + covariance
- Possibility of setting a-priory values for certain orbital parameters
- Automatic setting of measurements arc length at which motion can be considered as ‘passive’
- Automatic filtering of anomalous measurements

Orbit determination and analysis



Id	orbitId	ККСША	Наименование	Дата	ДПТ	Эксцентр	Наклон	Период	ДВУ	АргПер	АргШир	БК	КСД	ВысАпо	ВысПер	Интервал	Источник
	avm.tmp...	88615		07/01/2013 13:49:39.000	131.488	0.66467736	64.3750	661.3479	42.3827	268.0559	69.4853	1.000e-2	3.826e-5	35497.077	2070.823	25 сут 17ч 47м 47с	Решение

Id	orbit Id	Источник	Дата	Сигма	NMax	А.крт	Интервал	ДПТ	БольшП	Эксцентр	Наклон	Период	ДВУ	АргПер	АргШир	БК	КСД	ВысАпо	ВысПер	Статус
1407383257295	avm.tmp_run.php_1...	task	07/01/2013 13:49:39.000	4.602	4.212	1.854	34 сут 21ч 28м 42с	131.488	25144.721	0.66468355	64.3755	661.348	42.3832	268.0558	69.4852	1.000e-2	3.911e-5	35497.233	2070.668	Завершено

		Объект	Пункт	Дата первого изм	Дата последнего изм	Изм	Интервал	Источник	ВрСдвиг
1	☑	90201	10058	07/01/2013 13:41:39.000	07/01/2013 13:49:39.000	7	00ч 08м 00с	БД	
2	☑	130020015	10097	02/01/2013 21:11:40.000	02/01/2013 21:20:40.000	7	00ч 09м 00с	БД	
3	☑	90201	10094	16/12/2012 22:41:37.500	16/12/2012 22:50:37.500	7	00ч 08м 60с	БД	
4	☑	90201	10003	13/12/2012 16:56:13.160	13/12/2012 17:02:37.780	7	00ч 06м 25с	БД	
5	☑	90201	10058	12/12/2012 20:01:52.000	12/12/2012 20:18:30.000	15	00ч 16м 38с	БД	
6	☑	90201	10058	03/12/2012 16:20:57.000	03/12/2012 16:30:57.000	10	00ч 10м 00с	БД	
7	☑	90201	10058	26/11/2012 18:03:45.000	26/11/2012 18:14:45.000	11	00ч 11м 00с	БД	
8	☐	90201	10058	19/11/2012 19:45:55.500	19/11/2012 19:52:44.500	9	00ч 06м 49с	БД	
9	☐	90201	10058	17/11/2012 15:54:01.000	17/11/2012 16:04:01.000	11	00ч 10м 00с	БД	
10	☐	90201	10058	10/11/2012 18:30:55.000	10/11/2012 18:42:56.000	9	00ч 12м 01с	БД	
11	☐	90201	10058	08/11/2012 23:30:47.000	08/11/2012 23:42:47.000	12	00ч 11м 60с	БД	
12	☐	90201	10058	05/11/2012 15:48:16.000	05/11/2012 15:59:17.000	11	00ч 11м 01с	БД	
13	☐	12	10094	28/10/2012 19:57:52.500	28/10/2012 20:06:52.500	7	00ч 09м 00с	БД	
14	☐	11	10094	28/10/2012 19:18:37.500	28/10/2012 19:24:37.500	5	00ч 06м 00с	БД	
15	☐	6	10097	28/10/2012 19:17:07.500	28/10/2012 19:24:37.500	6	00ч 07м 30с	БД	
16	☐	90201	10058	28/10/2012 19:02:58.000	28/10/2012 19:19:46.000	11	00ч 16м 48с	БД	
17	☐	15	10097	27/10/2012 19:32:37.500	27/10/2012 19:41:37.500	6	00ч 09м 00с	БД	
18	☐	99021	10010	26/10/2012 23:56:50.884	27/10/2012 00:16:12.349	94	00ч 19м 21с	БД	
19	☐	90201	10536	26/10/2012 01:02:38.860	26/10/2012 01:11:30.830	17	00ч 08м 52с	БД	
20	☐	125965079	10536	22/10/2012 23:35:54.570	22/10/2012 23:40:00.570	8	00ч 04м 06с	БД	
21	☐	125955082	10536	21/10/2012 23:38:25.440	21/10/2012 23:42:16.400	6	00ч 03м 51с	БД	
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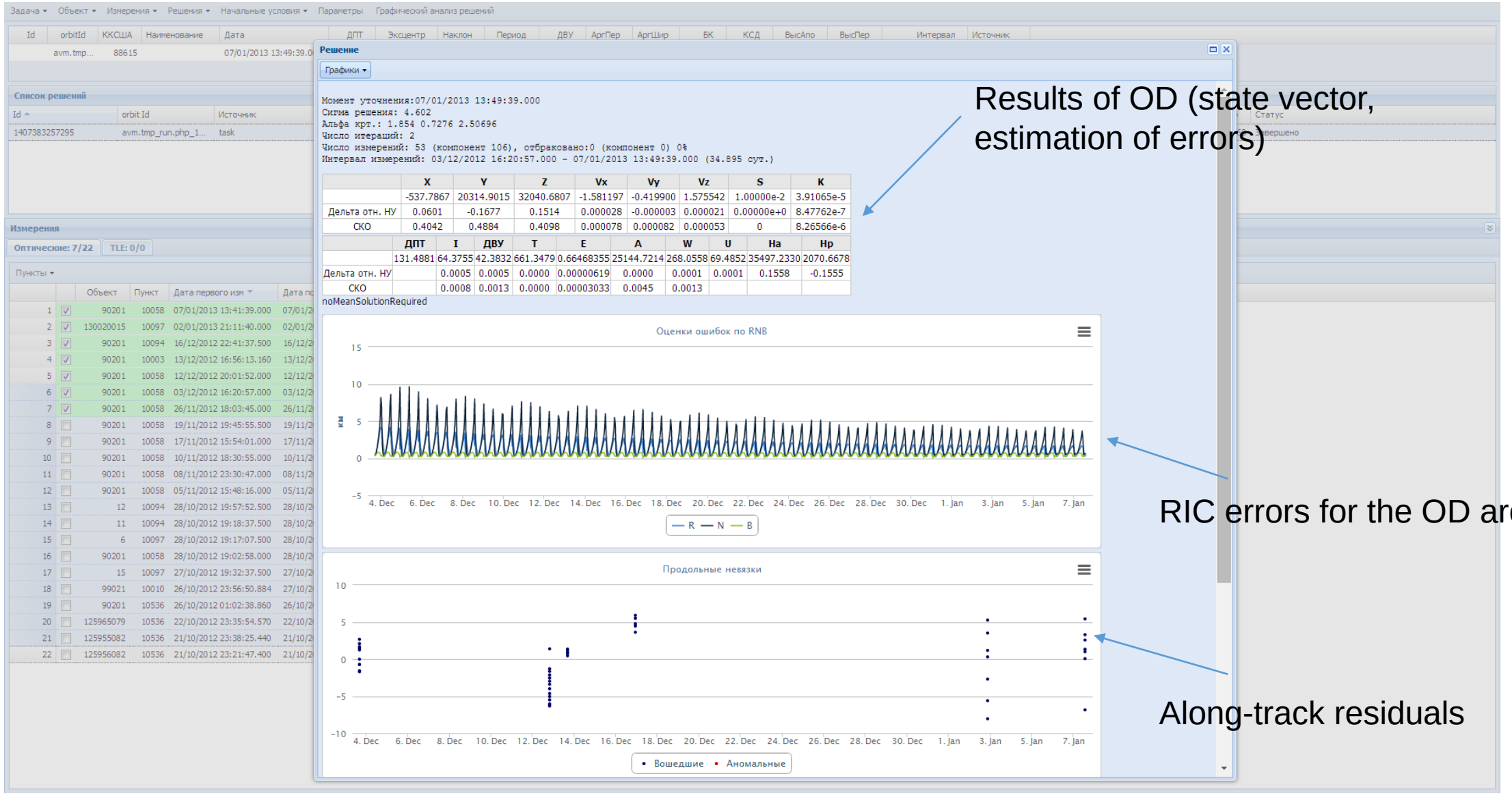
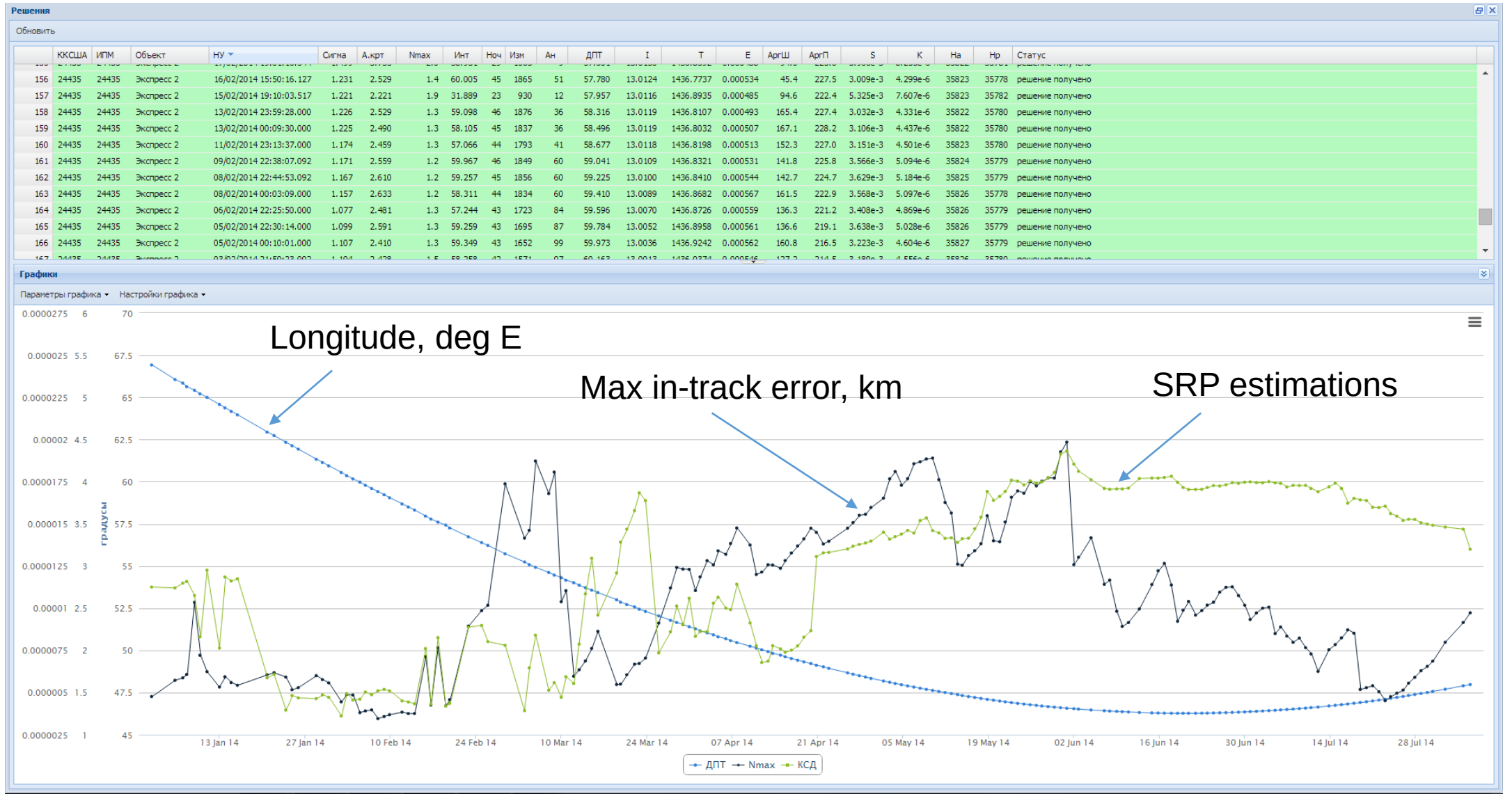
Orbit determination and analysis (2)



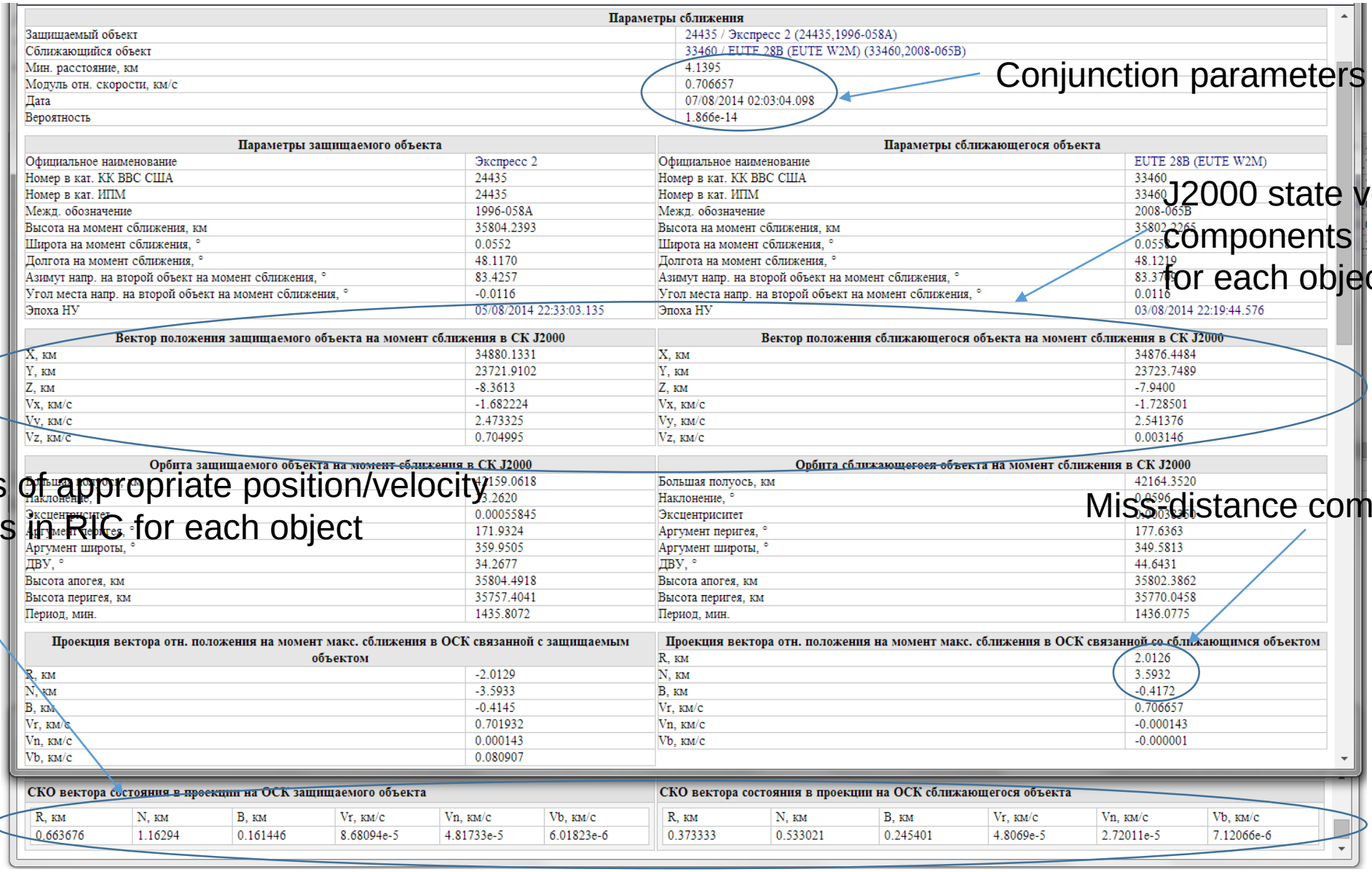
Orbit determination and analysis (3)



	ККСША	ИПМ	Объект	НУ	Сигма	A.крт	Nmax	Инт	Ноч	Изм	Ан	ДПТ	I	T	E	АргШ	АргП	S	K	Ha	Hp	Статус
156	24435	24435	Экспресс 2	16/02/2014 15:50:16.127	1.231	2.529	1.4	60.005	45	1865	51	57.780	13.0124	1436.7737	0.000534	45.4	227.5	3.009e-3	4.299e-6	35823	35778	решение получено
157	24435	24435	Экспресс 2	15/02/2014 19:10:03.517	1.221	2.221	1.9	31.889	23	930	12	57.957	13.0116	1436.8935	0.000485	94.6	222.4	5.325e-3	7.607e-6	35823	35782	решение получено
158	24435	24435	Экспресс 2	13/02/2014 23:59:28.000	1.226	2.529	1.3	59.098	46	1876	36	58.316	13.0119	1436.8107	0.000493	165.4	227.4	3.032e-3	4.331e-6	35822	35780	решение получено
159	24435	24435	Экспресс 2	13/02/2014 00:09:30.000	1.225	2.490	1.3	58.105	45	1837	36	58.496	13.0119	1436.8032	0.000507	167.1	228.2	3.106e-3	4.437e-6	35822	35780	решение получено
160	24435	24435	Экспресс 2	11/02/2014 23:13:37.000	1.174	2.459	1.3	57.066	44	1793	41	58.677	13.0118	1436.8198	0.000513	152.3	227.0	3.151e-3	4.501e-6	35823	35780	решение получено
161	24435	24435	Экспресс 2	09/02/2014 22:38:07.092	1.171	2.559	1.2	59.967	46	1849	60	59.041	13.0109	1436.8321	0.000531	141.8	225.8	3.566e-3	5.094e-6	35824	35779	решение получено
162	24435	24435	Экспресс 2	08/02/2014 22:44:53.092	1.167	2.610	1.2	59.257	45	1856	60	59.225	13.0100	1436.8410	0.000544	142.7	224.7	3.629e-3	5.184e-6	35825	35779	решение получено
163	24435	24435	Экспресс 2	08/02/2014 00:03:09.000	1.157	2.633	1.2	58.311	44	1834	60	59.410	13.0089	1436.8682	0.000567	161.5	222.9	3.568e-3	5.097e-6	35826	35778	решение получено
164	24435	24435	Экспресс 2	06/02/2014 22:25:50.000	1.077	2.481	1.3	57.244	43	1723	84	59.596	13.0070	1436.8726	0.000559	136.3	221.2	3.408e-3	4.869e-6	35826	35779	решение получено
165	24435	24435	Экспресс 2	05/02/2014 22:30:14.000	1.099	2.591	1.3	59.259	43	1695	87	59.784	13.0052	1436.8958	0.000561	136.6	219.1	3.638e-3	5.028e-6	35826	35779	решение получено
166	24435	24435	Экспресс 2	05/02/2014 00:10:01.000	1.107	2.410	1.3	59.349	43	1652	99	59.973	13.0036	1436.9242	0.000562	160.8	216.5	3.223e-3	4.604e-6	35827	35779	решение получено

Estimation of reliability of the conjunction assessment results

Conjunction assessment results analysis



Параметры сближения	
Защищаемый объект	24435 / Экспресс 2 (24435,1996-058A)
Сближающийся объект	33460 / EUTE 28B (EUTE W2M) (33460,2008-065B)
Мин. расстояние, км	4.1395
Модуль отн. скорости, км/с	0.706657
Дата	07/08/2014 02:03:04.098
Вероятность	1.866e-14

Параметры защищаемого объекта	
Официальное наименование	Экспресс 2
Номер в кат. КК ВВС США	24435
Номер в кат. ИПМ	24435
Межд. обозначение	1996-058A
Высота на момент сближения, км	35804.2393
Широта на момент сближения, °	0.0552
Долгота на момент сближения, °	48.1170
Азимут напр. на второй объект на момент сближения, °	83.4257
Угол места напр. на второй объект на момент сближения, °	-0.0116
Эпоха НУ	05/08/2014 22:33:03.135

Параметры сближающегося объекта	
Официальное наименование	EUTE 28B (EUTE W2M)
Номер в кат. КК ВВС США	33460
Номер в кат. ИПМ	33460
Межд. обозначение	2008-065B
Высота на момент сближения, км	35802.2265
Широта на момент сближения, °	0.0552
Долгота на момент сближения, °	48.1219
Азимут напр. на второй объект на момент сближения, °	83.3776
Угол места напр. на второй объект на момент сближения, °	0.0116
Эпоха НУ	03/08/2014 22:19:44.576

Вектор положения защищаемого объекта на момент сближения в СК J2000	
X, км	34880.1331
Y, км	23721.9102
Z, км	-8.3613
Vx, км/с	-1.682224
Vy, км/с	2.473325
Vz, км/с	0.704995

Вектор положения сближающегося объекта на момент сближения в СК J2000	
X, км	34876.4484
Y, км	23723.7489
Z, км	-7.9400
Vx, км/с	-1.728501
Vy, км/с	2.541376
Vz, км/с	0.003146

Орбита защищаемого объекта на момент сближения в СК J2000	
Большая полуось, км	42159.0618
Наклонение, °	3.2620
Эксцентриситет	0.00055845
Аргумент перигея, °	171.9324
Аргумент широты, °	359.9505
ДВУ, °	34.2677
Высота апогея, км	35804.4918
Высота перигея, км	35757.4041
Период, мин.	1435.8072

Орбита сближающегося объекта на момент сближения в СК J2000	
Большая полуось, км	42164.3520
Наклонение, °	0.0596
Эксцентриситет	0.0003580
Аргумент перигея, °	177.6363
Аргумент широты, °	349.5813
ДВУ, °	44.6431
Высота апогея, км	35802.3862
Высота перигея, км	35770.0458
Период, мин.	1436.0775

Проекция вектора отн. положения на момент макс. сближения в ОСК связанной с защищаемым объектом	
R, км	-2.0129
N, км	-3.5933
B, км	-0.4145
Vr, км/с	0.701932
Vn, км/с	0.000143
Vb, км/с	0.080907

Проекция вектора отн. положения на момент макс. сближения в ОСК связанной со сближающимся объектом	
R, км	2.0126
N, км	3.5932
B, км	-0.4172
Vr, км/с	0.706657
Vn, км/с	-0.000143
Vb, км/с	-0.000001

СКО вектора состояния в проекции на ОСК защищаемого объекта					
R, км	N, км	B, км	Vr, км/с	Vn, км/с	Vb, км/с
0.663676	1.16294	0.161446	8.68094e-5	4.81733e-5	6.01823e-6

СКО вектора состояния в проекции на ОСК сближающегося объекта					
R, км	N, км	B, км	Vr, км/с	Vn, км/с	Vb, км/с
0.373333	0.533021	0.245401	4.8069e-5	2.72011e-5	7.12066e-6

Conjunction parameters

J2000 state vector components for each object

Estimations of appropriate position/velocity components in RIC for each object

Miss-distance components, km

Estimation of reliability of conjunction assessment results

Following simple criteria are used to consider conjunction assessment results as reliable (applicable for GEO at near-circular orbits):

$$dR/(3\sigma_R) > 1.5…2$$

$$dI/(3\sigma_I) > 1.5…2$$

where

dR – miss distance in radial direction at the moment of the closest approach

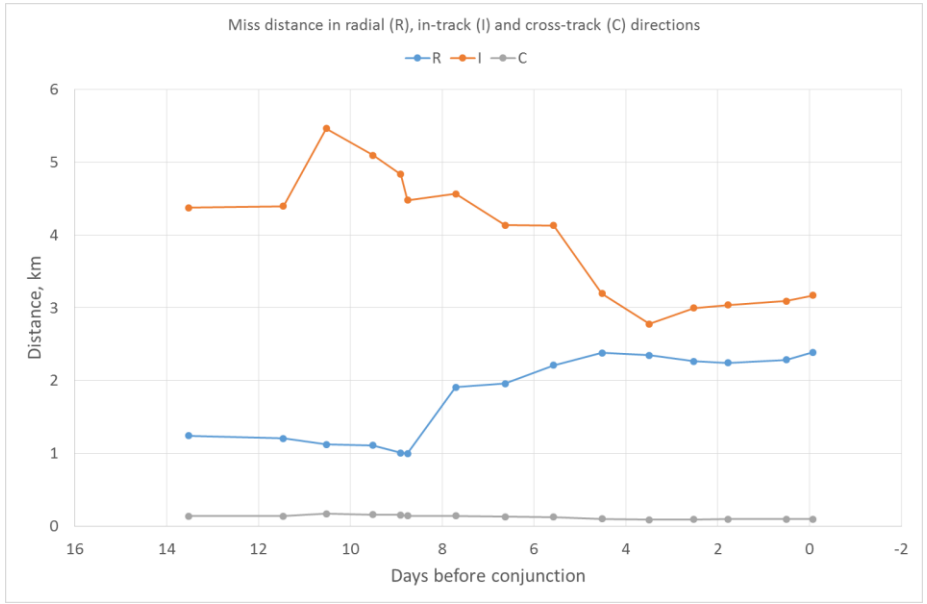
dI – miss distance in in-track direction at the moment of the closest approach

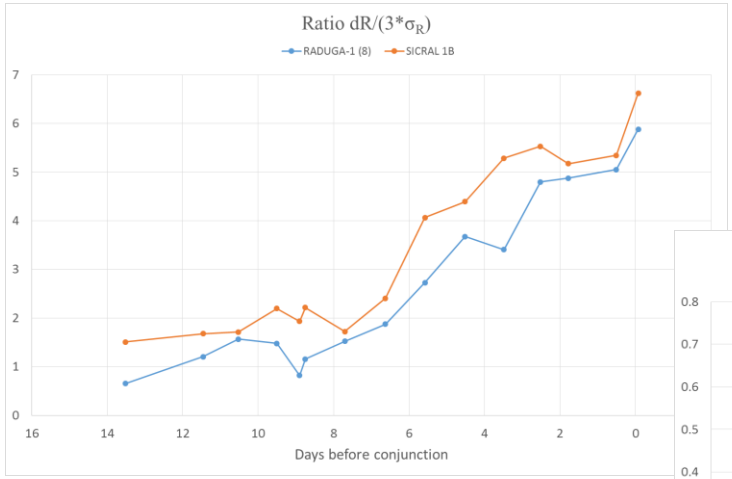
σ_R – estimated from covariance position error in radial direction

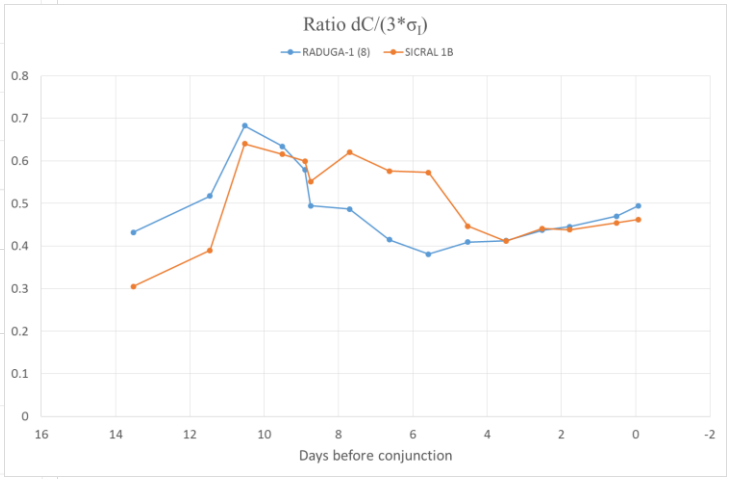
σ_I – estimated from covariance position error in in-track direction

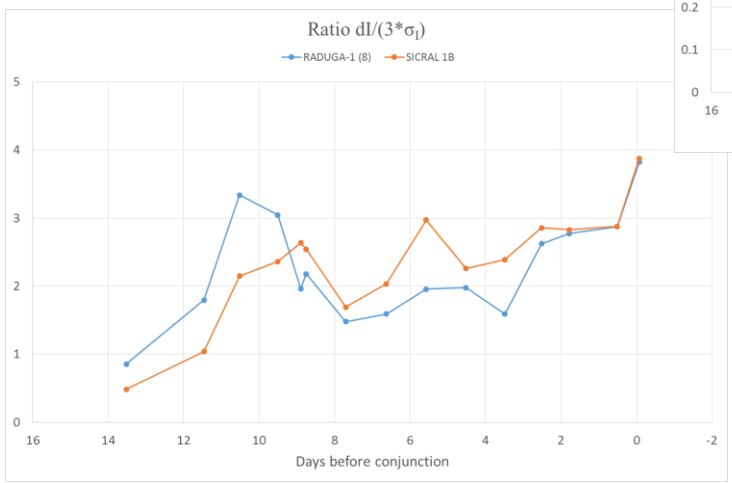
Data for each of two objects are checked against these criteria.

Conjunction Assessment.
Case of RADUGA-1 (8) & SICRAL 1B









- 16 Oct 2014 14:50:50 UTC, 12.6 km
- 17 Oct 2014 02:49:02 UTC, 11.3 km
- 17 Oct 2014 14:46:47 UTC, 3.9 km
- 18 Oct 2014 02:44:58 UTC, 7.9 km

Final accuracy:
σ_R = 120-135 m
σ_I = 275 m
σ_C = 65-70 m

Decision on acceptability of conjunction assessment results

Provided example tends to come to the following conclusions:

1. Conjunction assessment results that are considered reliable may not be deemed acceptable to produce a conjunction warning message if

$$dR > dR_{max}$$

$$dI > dI_{max}$$

dR_{max} and dI_{max} – some arbitrary values which are specific for different orbit classes

2. And vice versa, formally not reliable assessments may serve as a trigger to produce a conjunction warning message if

$$dR/(3\sigma_R) < 1…1.5$$

even in case $dI/(3\sigma_I) > 1.5…2$

Conjunction Assessment Based on ISON Data. Key Results

- Only orbits numerically derived from ISON optical measurements are using for analysis of conjunctions (including orbit determinations for even those functioning spacecraft for which orbital data are provided by operators)
- Screening for all conjunctions that satisfy given criteria in miss-distance (total, in-track and radial)
- Control of reliability of the result
- If required, additional measurements have being collected in order to improve orbit for both objects in conjunction. Observation sessions have scheduling so that to obtain the best possible accuracy of prediction for the conjunction moment
- Standard conjunction data message (in XML format) is sending to a customer

Conclusion

- ISON network is providing significant contribution into awareness on objects and events in the near-Earth space
- Nearly 1800 objects in GEO region and nearly 2300 objects at HEO and MEO orbits (orbital period more than 200 min) are observed by ISON in 2014
- At present ISON provides full GEO coverage with revisiting time less than 2 days for 61% of all active GEO spacecraft
- ISON is capable to provide near-real time observations as a part of launch support operations and in a case of expected conjunction between non-cooperative objects in GEO
- ISON project is open for cooperation
- Number of customers working with ISON/KIAM is increasing

Conclusion (2)

- KIAM Space Debris Data Center is a modern low-cost solution to maintain information awareness on space objects and events at high altitude orbit (MEO, HEO, GEO)
- Using ISON observations the Center's Master Database currently keeps records on more than 4100 high altitude objects, including 1300+ space debris objects in GEO that is 41% more than in any other available source
- The Center provides full support to the operation of ISON
- Orbit determination and conjunction analysis is performing on a routine daily basis
- The Center is capable to fulfill requests of different customers launching and operating spacecraft at high near-Earth orbits as well as of scientific users studying space debris problem