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RESEARCH

International ISON project & databases on space debris and asteroids

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Abstract

The exploration and investigation of near-Earth outer space (NES) have highlighted attention to potential threats, namely the dangers posed by asteroids and the emergence of techno-genic pollution known as space debris (SD). To address these challenges, an international initiative known as the ISON Optical Observatories Global Network was established. The International Scientific Optical Network (ISON) volunteer project commenced in 2004 intending to serve as an open repository of scientific data related to NES objects. At its zenith, the project collaborated with 33 observatories across 17 countries, operating 100 telescopes. Currently, ISON conducts its research using approximately 50 optical telescopes situated in 23 observatories across Europe, Asia, the Far East, Africa, and North & South America. The network is coordinated in conjunction with the dedicated company Research and Development Institution ISON Orbital Dynamics (RD ISON-OD), which owns 32 telescopes, observation scheduling centers, and databases focusing on SD and asteroids. ISON actively monitors the entire Geostationary Earth Orbit (GEO) region, tracking objects at GEO, Geostationary transfer orbit (GTO), High Earth Orbit (HEO), and Low Earth Orbit (LEO), while also maintaining the orbits of around 10,000 space objects. The data collected by ISON on space debris contribute to validating space debris population models and conducting conjunction assessment analyses for satellites in high orbits. Additionally, ISON is developing technology for asteroid surveys using small telescopes, providing follow-up observations, and conducting regular photometry observations of near-Earth asteroids. The project has resulted in the discovery of approximately 1600 new asteroids, obtaining 1.25 million astrometry measurements, and acquiring around 700 light curves for 300 asteroids. Space debris represents a unique subject of study, as it intersects the interests of various industries, scientific institutions, and governmental agencies.

Keywords Space debris · Near-Earth asteroids · Optical telescopes · Astrometry measurements · Photometry light curves

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1 Introduction

The term “space debris” encompasses a broad category of artificial space objects in near-Earth orbits, including non-operational satellites, rocket components, and fragments generated during launches or destruction events. The proliferation of these objects has reached a critical point, posing substantial risks not only to manned orbital stations and operational spacecraft but also to Earth’s ecology and the broader near-Earth space environment. In September 2023, the European Space Agency cataloged 35,430 SD objects, and incidents of collisions with operational satellites are documented. The sustainable development of NES is hindered without a thorough understanding of the current state and an analysis of the sources and evolutionary laws governing space debris.

Despite its technogenic origin, the study of the laws and trends governing the development of the space debris population and the creation of a space debris population model is of significant interest in the natural sciences. Within the vast array of small celestial bodies in the Solar System, there exists a distinct population of asteroids that consistently approach Earth, known as near-Earth asteroids (NEA). According to the Minor Planet Centre (MPC), as of November 24, 2023, approximately 33,660 NEAs have been identified. Instances of smaller asteroids impacting Earth are documented, while larger ones possess the potential for catastrophic, planet-wide damage. Conversely, these NEAs represent valuable reservoirs of resources within near-Earth space.

Many NEAs share the same age as the Solar System itself, and unlike planets and planetoids that undergo evolution and transformation, asteroids often preserve their original state since the inception of the Solar System. Consequently, understanding the composition of asteroids provides insights into the formation of the entire Solar System, including its planets and planetary satellites. The distinctive characteristic of NEAs lies in their periodic close encounters with Earth, facilitating ground observations. Ongoing research on NEAs encompasses the detection and cataloging of these celestial bodies, exploring the evolution of their orbits, and investigating their physical and mineralogical properties. This comprehensive study significantly contributes to our understanding of the Solar System’s history and the potential utility of these asteroids in space exploration and resource utilization.

Due to the acute relevance of both issues, they are routinely addressed at the annual meetings of the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS). What further unites these challenges is the shared reliance on similar research tools, with optical telescopes being instrumental in obtaining vast amounts of essential data. Consequently, numerous global projects involving optical telescope networks are dedicated to the exploration of space debris and near-Earth asteroids (NEAs). One notable initiative in this domain is the International Scientific Optical Network project (Molotov et al. 2008 & Molotov et al. 2021b).

2 International Scientific Optical Network project

The International Scientific Optical Network volunteer project started in 2004 to be an open source of scientific data on SD objects and asteroids.

2.1 Network composition

ISON works in 2005-2007 allowed the firstly in nation history to cover the Geostationary orbit in the whole (Molotov et al. 2008). Still, after the start of regular research, it became obvious that outdated non-automated telescopes with small fields of view (FOV) and insufficient sensitivity are not suitable. Since arranged telescope network modernization (automation of their mounts and purchasing the modern CCD-cameras) did not cause the expected effect on measurement obtaining rate, a decision was made to apply dedicated small survey telescopes. At this time no industry produced such telescopes, therefore the second stage of the ISON project in 2008-2011 had the elaboration of a few series of small survey telescopes with large FOV, that are still operating to date. Financing the development and production of new telescopes was carried out at the expense of Russian and international grants and through R&D with the involvement of observations of the ISON network.

The observations of space debris were primarily conducted using small telescopes with apertures ranging from 18 cm to 25 cm and a FOV spanning 5.5 to 50 square degrees. Additionally, middle-class telescopes with apertures between 35 cm and 50 cm and a FOV of 0.5 to 6 square degrees, all of which were produced in-house, were employed for these observations (Molotov et al. 2021a). Further details can be found in Table 1.

All participating telescopes are equipped with GPS-based time reference systems to accurately timestamp measurements. Additionally, these telescopes predominantly feature a standard set of software for equipment control and image processing (Kouprianov and Molotov 2017 & Elenin and Molotov 2020).

The ISON project is actively engaged in operations, utilizing approximately 50 optical telescopes distributed across 23 observatories located in Europe, Asia, the Far East, Africa, and North and South America, as illustrated in Fig. 1. It displays geographical locations and names of the ISON observatories up to 2023, using different colors to denote various statuses. Green represents working own telescopes,

Table 1 Parameters of telescopes developed for the ISON project

No.	Name	Optical scheme/producer	Aperture/focal length (mm)	FOV Degree	CCD chip mm
1	VT-78a	Schenker-Terebizh/Borisov	192/296	7 × 7	36
2	SRT-220	Slefogt-Richter- Terebizh/Borisov	220/507	4 × 4	36
3	ORI-22	Hamilton-Terebizh/Borisov	220/510	4 × 4	36
4	ORI-25	Hamilton-Terebizh/Borisov	250/625	3.3 × 3.3	36
5	Santel-400A	Hamilton-Yudin/ Sankovich	400/1200	1.75 × 1.75	36
6	ORI-40	Hamilton-Terebizh Borisov	400/920	2.25 × 2.25	36
7	ORI-50	Hamilton-Terebizh/Borisov	500/1160	2.5 × 2.5	50

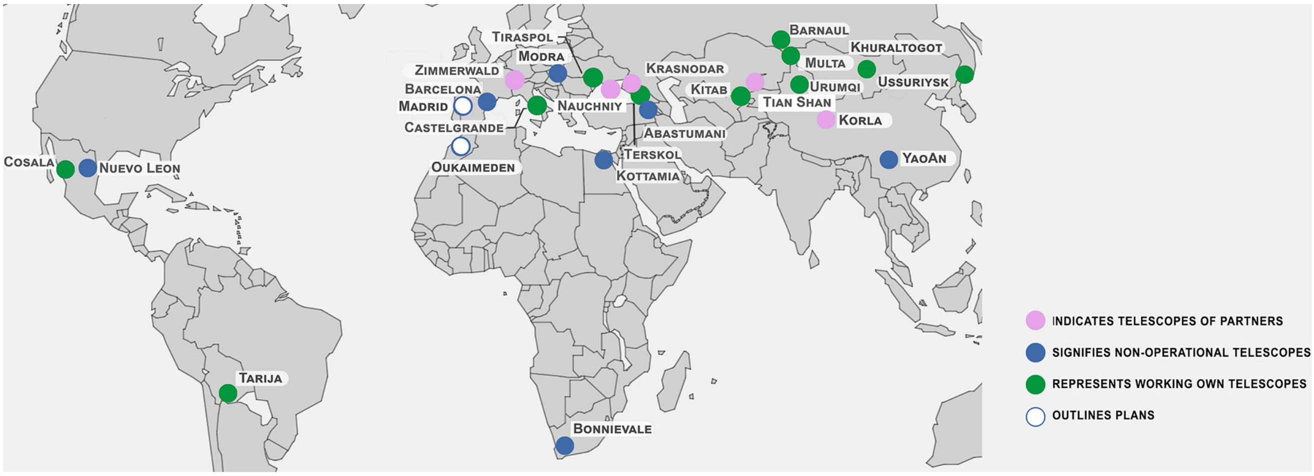

Fig. 1 Geographical locations and names of the ISON observatories at the end of 2023

violet indicates telescopes of partners, blue signifies non-operational telescopes, and white outlines planned installation.

In terms of space debris observations, ISON conducts a comprehensive global survey of the entire GEO, HEO, and Medium Earth Orbit (MEO) objects. This includes the search and follow-up of faint debris objects. The primary objectives of these activities are to maintain a comprehensive SD database, generate a daily updated list of SD orbits to support conjunction assessment analyses (Shilin et al. 2013). verify the SD population model at high orbits (Usovik et al. 2017), and accurately determine the orbits of requested objects (Escobar et al. 2017).

To enhance the quantity of measurements stored in the ISON database, a novel concept was introduced, the creation of an international center for the exchange of measurement and orbital information on space debris. Spearheaded by the Research and development institution ISON orbital dynamics (RD ISON-OD), which boasts 32 proprietary telescopes, this initiative aimed to facilitate international collaboration. RD ISON-OD effectively initiated data exchanges with numerous observatories, universities, and scientific institutes, leading to a significant increase in the volume of measurements within the ISON database (Molotov et al. 2019 & Molotov et al. 2023).

2.2 Space debris database

The software system for space debris data collection and analysis relies on the open-source object-relational database management system PostgreSQL (an object-relational database management system (ORDBMS) which is based on POSTGRES, Version 4.2), operating under the Ubuntu Linux 20.04 LTS operating system. The fundamental structure of the database is illustrated in Fig. 2.

Two types of data, namely optical position measurements and orbit lists, are acquired on the server through FTP or SFTP protocols, after which a validation process takes place. The system supports multiple encodings to facilitate collaboration with international partners. Additionally, source files can be uploaded in archive formats such as tar.

Upon successful validation and identification of the data type, the information is directed to one of two processing pipelines, specifically tailored for measurements and orbits. In these pipelines, the data undergo parsing and are subsequently written to the database. The system operates with two distinct tables, "measurements" and "orbits." In

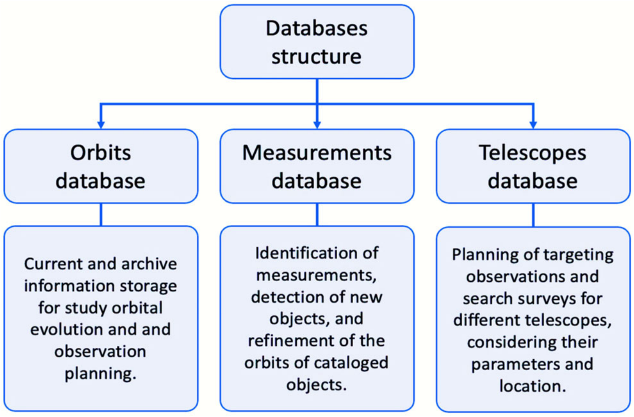

Fig. 2 The main structure of the ISON database on SD

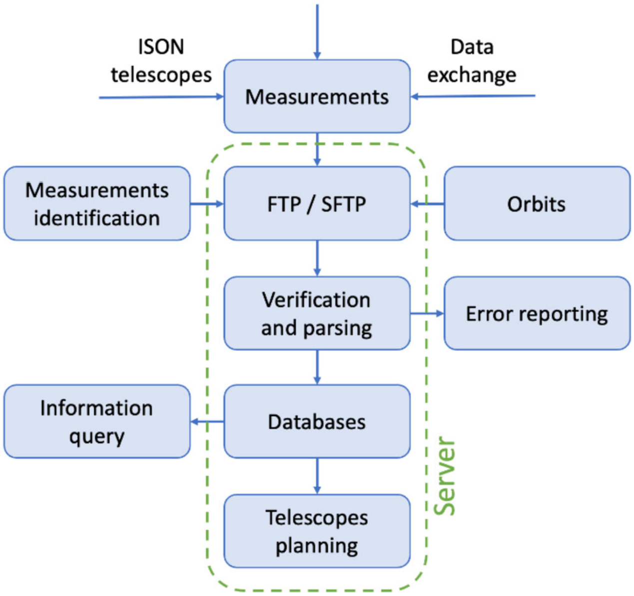

Fig. 3 The overall scheme of the system

the event of errors detected during input validation, an automated system notifies the source, prompting them to rectify potential formatting issues or other errors. Comprehensive data on telescopes, including coordinates and technical parameters, are stored, encompassing all essential information for the automated observation planning subsystem. The structure of this subsystem is depicted in Fig. 3.

The data processing software package has been created using the free cross-platform framework .NET Core 6, enabling deployment on various x86 operating systems such as Linux, Windows, and Mac OS. The server's hardware infrastructure is built around an Intel Xeon E2697 v2 processor, with 12 cores and 24 threads, accompanied by 64 GB of RAM. The storage capacity of the server totals 12 TB, organized in a RAID 1 array, with the flexibility to expand if needed.

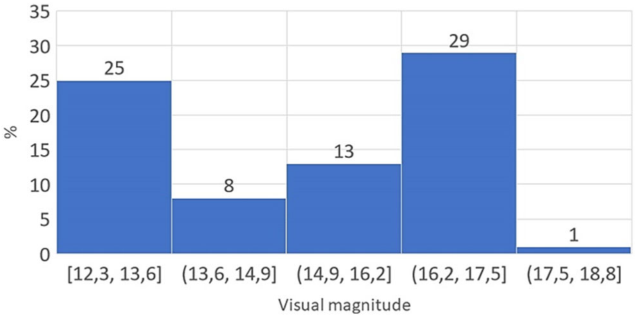

Fig. 4 Visual magnitude distribution of measurements

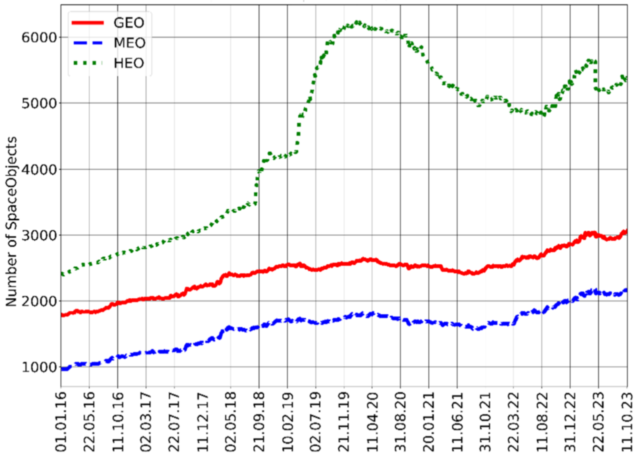

Fig. 5 Changing the number of objects at high orbits by year

As of September 1, 2023, the cumulative database comprises over 127 million entries, occupying more than 45 GB of disk space. This extensive dataset includes 96,333,409 measurements and 9,750,341 tracklets. The distribution of these measurements, categorized by magnitudes, is illustrated in Fig. 4.

3 Characteristics of SD population at high orbits

As of September 1, 2023, the ISON database manages the orbits of 10,086 space objects at high orbits. Within this dataset, 3122 objects are situated in Geostationary orbits, 5267 objects occupy highly-elliptical orbits, and 1697 objects are positioned in Medium Earth orbits. The distribution of objects by year and type of orbits from 2016 to 2023 is illustrated in Fig. 5, depicting the curves representing the number of GEO, HEO, and MEO objects over each year.

From Fig. 5, it is evident that the composition of high-orbit objects has undergone significant changes. By the end of 2019, the quantity of highly-elliptical orbit (HEO) objects increased by 2.5 times, surpassing the number of Geostationary orbit (GEO) objects by 2.2 times. This notable

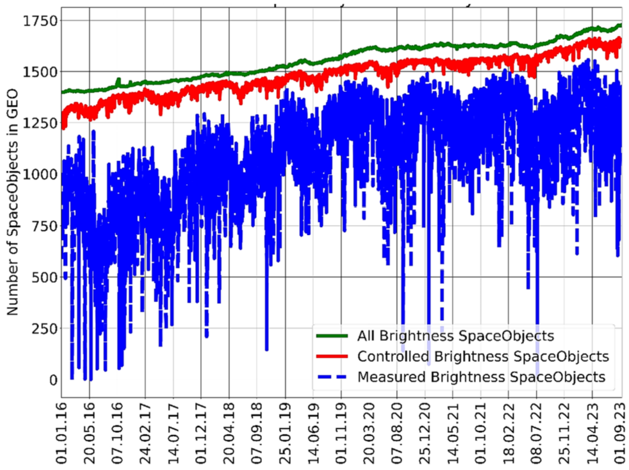

Fig. 6 Parameters of the database of bright GEO objects

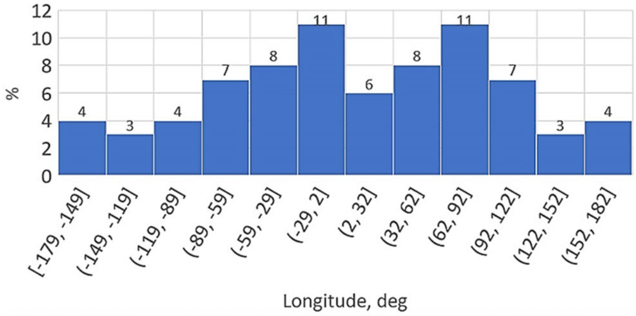

Fig. 7 Distribution of 1165 GEO-objects with accurate orbits in % by longitude

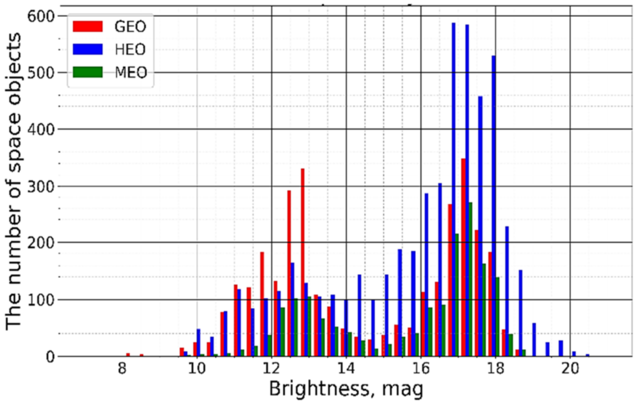

Fig. 8 Distribution of space objects at high orbits by brightness

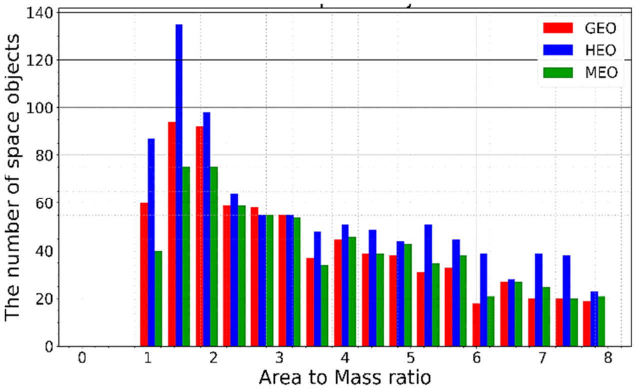

Fig. 9 Distribution of 3226 space objects at high orbits by AMR

shift was attributed to the occurrence of three destruction events involving the Atlas 5 Centaur rocket stages (2014-055B, 2009-047B, and 2018-079B) situated at HEO. These events generated more than 2000 new fragments (Molotov et al. 2021a), as indicated by the spikes in the green graph around 07.09.18 and after 25.01.19. The abrupt increase in the number of cataloged objects posed challenges for existing telescopes, resulting in the inability to confidently track more than 1200 objects, not only in HEO but also in GEO and MEO. The subsequent surge in the number of objects in the database after 25.11.22 is attributed to the commissioning of additional telescopes to address these tracking challenges.

The parameters of the database for bright Geostationary Earth Orbit objects are depicted in Fig. 6. The curves of different colors represent various metrics, including the total number of bright objects with a magnitude of 15.5 mag (green), the number of objects measured during the current night (blue), and the number of objects with accurate orbits (red). For orbit accuracy, a criterion of 0.1-minute error along the object's orbit was chosen.

The data in Fig. 6 illustrates that measurements for 90% of the bright Geostationary Earth Orbit objects are consistently obtained, ensuring the update of accurate orbits for 98% of the population. This level of data acquisition is a crucial prerequisite for conducting effective conjunction assessment analysis (Streltsov et al. 2019). Furthermore, Fig. 7 displays the distribution in the percentage of 1165 GEO-objects with accurate orbits by longitude.

Figure 8 illustrates the distribution of objects in the database based on brightness. The gap observed between 13 and 15.5 mag is attributed to the state of the space object population, while the decline beyond 18.5 m is a result of the insufficient sensitivity of the telescopes employed. Consequently, there exists an area of insufficient control on the right side of the graph, and it remains uncertain how many space debris objects can be expected in this region.

Among these space objects, there are 3226 objects with high are-to-mass ratio (HAMR) > 1 m^2/kg (901 GEO, 1461 HEO, and 884 MEO) which makes up 34.5% of the known debris population. This is 2 times more than it was in 2021 (Molotov et al. 2021b). The distribution of HAMR-objects in the database by average value of ARM is shown in Fig. 9.

4 Asteroid observations

The observation of asteroids within the ISON project is organized using middle-class telescopes with apertures ranging from 40 cm to 50 cm, and large-class telescopes with apertures from 60 cm to 2 m. The selection of telescopes is based on a peer-review process of scientific proposals (Krugly et al. 2010).

Asteroid research within the ISON project is conducted through three primary avenues, as outlined in reference (Molotov et al. 2021b). These directions include the search for new asteroids and comets, the follow-up of newly discovered asteroids (which involves obtaining astrometry to refine their orbits), and the photometry of asteroids to delve into the study of their physical properties.

4.1 Asteroid database

The primary objective of the database is to gather, archive, and analyze measurements of small bodies within the Solar System. These measurements are acquired in the formats of the Minor Planet Center and standard measurements obtained from ISON network observatories. In the event of centralized submission of measurements from observatories to the MPC, a thorough check for formatting errors will be conducted. If no errors are identified, the measurements will be converted into the MPC format, uploaded into the specified database, and transmitted to the MPC. The observer will then receive a confirmation letter indicating that their measurements have been successfully received, verified, recorded, and forwarded. In cases where errors are detected, the measurements will be declined, and the observer will be provided with a detailed report. This approach aims to mitigate issues arising from measurement submissions by observation sites lacking experience in measurement processing.

Users of the database will be able to receive archival data and statistical information on their requests in an unlimited mode using the web interface. The structural complex for collecting and analyzing optical measurements of small bodies of the Solar System can be divided into the following modules:

1. Information collection system
- processing data from the incoming mail server;
- processing data from local or network storage;
- collection of measurements published by MPC (MPEC circulars, MPS).

2. PostgreSQL Database Management System module:
- data uploading and extraction;
- performing search queries;

3. Independent measurement identification system (MPCORB, internal catalog);

4. A system for evaluating the accuracy of measurements and calculating residuals;

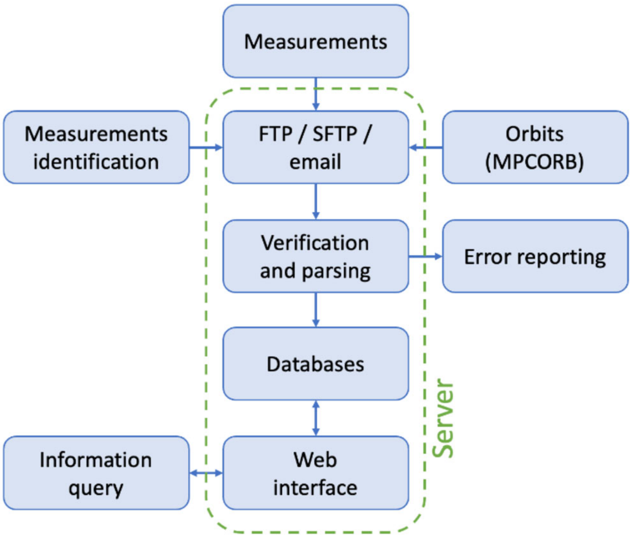

Fig. 10 Structure of the program system of ISON database on asteroids

5. Web interface for working with the database.

The general block diagram of the program package is shown in Fig. 10.

Free object-relational database management system PostgreSQL, cross-platform software platform .NET 6.0, and open-source web framework Blazor were used for the project implementation. The database is undergoing a testing process, after which it will be populated with archived measurements from the ISON project. Table 2. lists the required fields for the measurement acquisition database.

The software package incorporates an internal task scheduler enabling the periodic execution of routine operations, such as the verification of incoming measurements. Upon receipt, a subsequent pipeline for processing and analyzing the acquired data is initiated. A distinct software module is dedicated to collecting measurements of Near-Earth Asteroids (NEAs) published in MPC electronic circulars (MPEC). Each received measurement is assigned a unique identification number, and the original forms of these measurements (emails, files) are preserved in their original state within the file storage. The primary directory for identification is MPCORB, with daily updates.

Identification is carried out based on the spatial position of the object, considering the positional angle and speed of movement. The calculation of measurement residuals is conducted numerically using the Adams method, a finite difference multistep method of numerical integration of the first order. The DE431 motion model from the Jet Propulsion Laboratory is employed for calculations. Both the measurement accuracy assessment subsystem and the identification subsystem ensure the daily updating of the MPCORB orbit catalog, ensuring its ongoing relevance.

Table 2 List of fields of the measurements database on asteroid

Field	Type	Description
id	string	The unique identifier of the measurement.
designation	string	A temporary designation or object number.
code	string	Additional measurement code describing the specifics of the measurement (image defects, poor visibility, observing mode, etc.).
Date Obs	timestamp	Epoch of the measurement in the format: yy mm dd.d (d).
Date Obs Decimal	float	Epoch of the measurement in decimal format: yy. Y
Date Obs JD	float	Julian's date of the measurement.
Date Obs Year	int	Year of the measurement.
Date Obs Month	int	The month of the measurement.
dateObsDay	float	Day of the measurement in decimal format: dd.d(d).
Ra String	string	Coordinate of Right Ascension in source format: hh mm ss.ss
Ra Decimal	float	Coordinate of Right Ascension in decimal format.
Dec String	string	Coordinate of Declination in source format: dd mm ss.s
Dec Decimal	float	Coordinate of Declination in decimal format.
mag	float	Magnitude.
band	char	Photometric filter.
observatory	string	IAU code of the observatory (line COD).
observer	string	Observer last name (line OBS).
measurer	string	Measurer last name (line MEA).
telescope	string	Telescope specification (line TEL).
date	timestamp	The date the measurement was received in the database.
time	timestamp	The time when the measurements are received in the database.
source	string	Measurement source: e-mail address, user login, or circular number.
Path To Source	string	Path to the saved data source (email, attached text file, circular).
comment	string	Comments, notes.

4.2 ISON asteroid survey

The ISON asteroid test survey, initiated in 2010, aimed to pioneer the technology for a "second wave" survey, characterized by large sky coverage and low sensitivity. The primary objective was to detect asteroids and comets that may have been missed by "deep" asteroid surveys conducted with larger telescopes. Between 2015 and 2017, the survey utilized two 40-cm telescopes—one located at Mayhill (H15, USA) with a field of view (FOV) of 1.75° and another at Siding Spring (Q60, Australia) with a FOV of 2.2°. Observations were conducted using single frames, employing a triplet of time-spaced frames to identify moving objects, and the limiting magnitude for detection was set at 20.5.

These observations were remotely conducted via the Internet, and the combined efforts of both telescopes covered up to 900 square degrees per night. The survey successfully addressed three key tasks: developing an effective search strategy for Near-Earth Asteroids, selecting an optimal set of equipment, and creating a comprehensive suite of dedicated software (Elenin 2017). Throughout this initiative, more than 1,230,500 astrometric measurements of asteroids were obtained, leading to the discovery of 1605 main belt asteroids, 17 NEAs, 8 comets, 20 Trojans of Jupiter, 4 objects from the family of Hilda, and 4 Centaurs. Figure 11 depicts the distribution of the ISON-discovered asteroids by semi-major axis and eccentricity.

The data obtained from this survey were utilized to develop a model for the probability of NEA detection in various parts of the sky (Ipatov and Elenin 2018). This model is expected to significantly enhance the efficiency of future asteroid surveys.

The continuation of the ISON asteroid survey involved the use of 40-cm telescopes in Huraltogoot (O75, Mongolia) with a field of view of 2.2°. In this phase, a novel approach was adopted, employing a joint analysis and processing of dozens and even hundreds of short consecutive exposures. Summarizing the obtained frames (stack processing) based on random motion vectors of potential Near-Earth Asteroids allowed for an increase in the working sensitivity of the survey tool. This technique proved effective in efficiently detecting fast-moving NEAs with angular speeds reaching tens of angular seconds per minute.

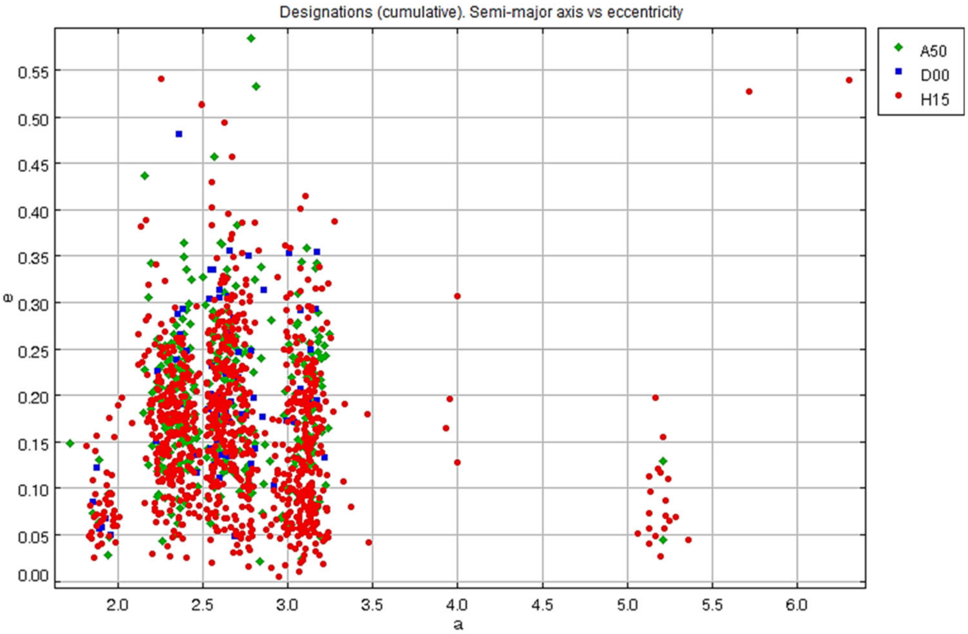

Fig. 11 Distribution of asteroids discovered with ISON by orbital elements (semi-major axis/eccentricity)

Throughout the survey at Huraltogoot, more than 100,000 measurements were obtained, leading to the discovery of 81 main belt asteroids and four NEAs—2022 VG2,2023 QM5, 2024 EB3, and 2024 GF. Additionally, another NEA (2021 UL17) was detected on CCD frames of a 70-cm telescope in Abastumani (119, Georgia), utilizing the same method of stack processing. These discoveries were made as a by-product of observations of a scientific satellite at the Lagrange point.

4.3 ISON follow-up asteroid observations

The Follow-Up ISON subsystem was developed to support the ISON asteroid survey by promptly tracking newly discovered objects. Swift confirmation is crucial for cataloging and maintaining priority in the discovery process. In the initial phase, focused efforts were dedicated to acquiring MPC codes for telescopes at 14 observatories. The ISON network observatories consistently conducted astrometric observations of small bodies within the Solar System, specifically Near-Earth Asteroids from the NEO Confirmation Page. In total, 1490 NEAs were observed, resulting in 14,334 measurements. These measurements were subsequently included in 2084 Minor Planet Electronic Circulars issued by the Minor Planet Center.

Following the suspension of its own ISON surveys, the Follow-Up ISON subsystem transitioned to operating upon requests from interested institutions. From 2018 to 2020, the subsystem contributed to the European Space Agency's network of follow-up telescopes. Starting in 2021, urgent follow-up observations were facilitated based on requests from the Chinese Near-Earth Object Survey Telescope (CNEOS) project. Table 3 provides comprehensive statistics on astrometric observations of Near-Earth Asteroids conducted by observatories within the network, including estimates of the accuracy of the measurements obtained. Since end of 2023 the 1.88 m telescope of the Kottamia observatory (088, Egypt) of National Research Institute of Astronomy and Geophysics is regularly involved which provide the follow ups of objects to 22 mag.

4.4 ISON photometry ad-hoc campaigns

For 11 years, international photometric observation ad-hoc campaigns were organized to investigate Near-Earth Asteroids, particularly those deemed potentially dangerous asteroids. The primary objectives of these campaigns were to determine the size, rotation parameters, shape of bodies, and the optical properties of surfaces. The research programs were tailored for NEAs whose orbits and properties suggested the possibility of detecting the Yarkovsky-O'Keefe-Radzievskii-Paddack (YORP) effect (Rubincam 2000)—a phenomenon involving non-gravitational forces influencing the rotation speeds and tilts of the axes of rotation of asteroids. The campaigns also aimed to identify binary asteroids and determine the parameters of these systems, with a focus on detecting the Bi-YORP effect (YORP effect for binary systems).

Additionally, the observation program encompassed small NEAs with a diameter of less than 300 meters, known to exhibit very fast rotation. The ISON extended network proved to be well-suited for studying asteroids that could be observed quasi-continuously, covering multiple possible rotation periods during the short time when NEAs pass near Earth and are accessible for ground observa-

Table 3 Common statistics on the observation of NEAs with observatories of the ISON network

Observatory	Code MPC	Quantity of objects	Quantity of measurements	Quantity of MPC circulars	Accuracy of measurements, ″
Simeiz	094	74	1246	90	−0.11/+0.15
Abastumani	119	11	75	14	+0.14/+0.22
Chuguev	121	29	462	39	+0.04/+0.18
Ktab	186	57	672	93	−0.03/−0.13
Andrushivka	A50	414	3528	421	+0.01/+0.08
Mayhill	H15	518	4106	899	+0.00/+0.02
Uzhgorod	K99	3	118	3	+0.03/−0.11
Tien-Shan	N42	23	1935	38	−0.10/+0.08
Multa	N82	61	215	62	−0.01/+0.01
Huraltogoot	O75	113	424	121	+0.10/−0.03
Siding Spring	Q60	187	1553	304	+0.03/+0.00
Total	$\sum$	**1490**	**14,334**	**2084**	—

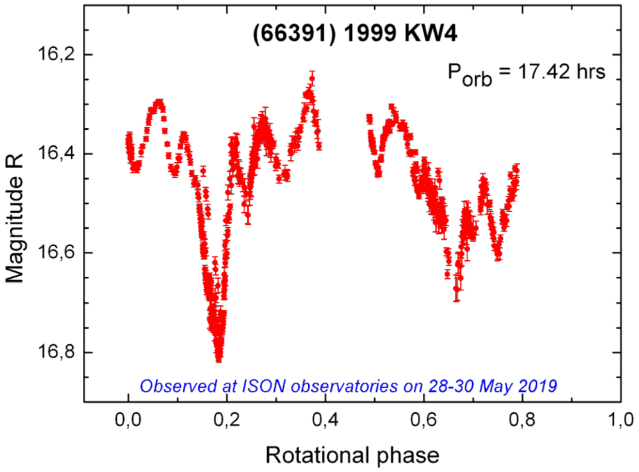

Fig. 12 Composite light curve on 1999KW4 for May 28-30

tions. Figure 12 provides a typical example of such observations.

In May-July 2019, the ISON network actively took part in an international monitoring campaign organized by the International Asteroid Warning Network (IAWN) of the United Nations. The focus of this campaign was the study of the binary Near-Earth Asteroid (66391) 1999 KW4, now named Moshup. For 55 nights, the asteroid was observed using 10 telescopes ranging in diameter from 36 cm to 1 m. The 36 light curves obtained covered an orbital period of 1999 KW4 (17.4 hours) three times. The composite light curve shown in Fig. 12 reveals two minima, characteristics of events in binary systems.ISON's participation in this IAWN campaign was in response to a request from the European Space Agency, contributing valuable insights into the characteristics and behavior of the binary asteroid Moshup.

Each observation campaign incorporated new Near-Earth Asteroids, pre-selected asteroids identified as candidates for systems with signs of the YORP effect and binarity, and already-known binary asteroids with an attempt to identify the Bi-YORP effect. On average, approximately 50 asteroids were observed during 250 nights per year, resulting in around 700 light curves for 300 NEAs. The observations and their reduction were conducted using an original technique designed for fast-moving NEAs, developed by the Institute of Astronomy of V.N. Karazin Kharkiv National University (Krugly et al. 2002 & Krugly 2004).

Out of the 190 observed NEAs, 18 were confirmed as binaries, and 30 NEAs were suspected to be binary (with the signs of binarity confirmed for 7 of them). Overall, the rotation periods of 67 NEAs were determined or clarified as a result of these observations (Molotov et al. 2021c). The campaign significantly contributed to the understanding of the rotational characteristics and potential binary nature of these asteroids.

The extensive acquisition of light curves for Near-Earth Asteroids over multiple oppositions has facilitated engagement in numerous pioneering theoretical and observational works (Becker et al. 2015; Pravec et al. 2016 & Pravec et al. 2019). The incorporation of ISON data into these studies resulted in the discovery of the YORP effect for (1620) Geographos, (3103) Eger, and (1685) Toro (Durech et al. 2021). Additionally, the Bi-YORP effect was first detected for the binary NEA (88710) 2001 SL9 (Scheirich et al. 2021 & Agapov et al. 2020). These breakthroughs highlight the significant contributions of the ISON project to advancing our understanding of asteroid dynamics and their effects.

5 Conclusion

The ISON project, spanning nearly two decades, has made substantial contributions to scientific understanding, particularly in the investigation of space debris populations at high orbits. Over the last 15 years, ISON has been at the forefront, providing scientific leadership to its team and elevating knowledge about the space debris population in Geostationary Earth Orbit and Highly Elliptical Orbit to unprecedented levels. As of September 1, 2023, the ISON database maintains the orbits of 10,086 space objects in high orbits, including 3122 at GEO, 5267 at HEO, and 1697 at Medium Earth Orbit. Notably, 3226 of these are categorized as High Area-to-Mass Ratio objects, representing 34.5% of the known debris population at high orbits. The doubling of HAMR-object quantities in the database over the past two years, now constituting at least half of the high-orbit debris population, raises concerns for the safety of operational satellites. The orbits of HAMR objects pose challenges for accurate prediction, leading to decreased forecast precision for potentially hazardous encounters. Over 11 years, ISON has conducted numerous photometric observation campaigns for asteroids, observing over 50 asteroids annually for more than 250 nights. This extensive effort has resulted in around 700 light curves for 300 Near-Earth Asteroids, enabling the project to actively participate in pioneering theoretical and observational studies. These studies have led to the detection of binary asteroids and asteroids exhibiting the YORP effect and BYORP effect, showcasing ISON's significant contributions to asteroid research. Currently, ISON operates on approximately 50 optical telescopes at 23 observatories across Europe, Asia, the Far East, Africa, and North and South America. The project is in the process of developing an international exchange of space debris data with interested institutions, resulting in a substantial increase in the volume of measurements within the ISON database, now reaching 40 million. These ongoing efforts underscore ISON's commitment to advancing our understanding of near-Earth space and providing critical data for the safety and sustainability of space activities.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

References

Agapov, V.M., Molotov, I.E., Borovin, G.K., Streltsov, A.I.: Study of a population of space debris objects with a high area-to-mass ratio in high Earth orbits. Eng. J. Sci. Innov. **2**, 26 (2020)

Becker, T.M., Howell, E.S., Nolan, M.C., Magri, C., Pravec, P., Taylor, P.A., Oey, J., Higgins, D., Világi, J., Kornoš, L., Galád, A.: Physical modeling of triple near-Earth Asteroid (153591) 2001 SN263 from radar and optical light curve observations. Icarus **248**, 499–515 (2015)

Durech, J., Vokrouhlicky, D., Pravec, P., Krugly, Y.N., Kim, M.J., Polishook, D., Ayvazian, V.V., Bonev, T., Choi, Y.J., Datashvili, D.G., Donchev, Z.: (2021). Rotation acceleration of asteroids (10115) 1992 SK,(1685) Toro, and (1620) Geographos due to the YORP effect. ArXiv preprint arXiv:2110.06548

Elenin, L.V.: Robotic asteroid survey of the ISON network, search of asteroids and comets from both hemispheres of the Earth. Ecol. Bull. Res. Cent. Black Sea Econ Coop. **4**(3), 32–38 (2017)

Elenin, L.V., Molotov, I.E.: Software for the automated control of robotic optical observatories. J. Comput. Syst. Sci. Int. **59**, 894–904 (2020)

Escobar, D., Ayuga, F., Antón, A., Agueda, A., Molotov, I.: GMV/ISON combined optical campaigns. In: Proceedings of the 7th European Conference on Space Debris, ESA, vol. 7, p. 7 (2017)

Ipatov, S.I., Elenin, L.V.: Suggested models for calculation of the probabilities of detection of near-Earth objects in different sky regions. In: 81st Annual Meeting of the Meteoritical Society, vol. 81, p. 6249 (2018). 2067

Kouprianov, V., Molotov, I.: FORTE: ISON robotic telescope control software. In: Proc. 7th European Conference on Space Debris, vol. 7, p. 9 (2017)

Krugly, Y.N.: Problems of CCD photometry of fast-moving asteroids. Sol. Syst. Res. **38**, 241–248 (2004)

Krugly, Y.N., Belskaya, I.N., Shevchenko, V.G., Chiorny, V.G., Velichko, F.P., Mottola, S., Erikson, A., Hahn, G., Nathues, A., Neukum, G., Gaftonyuk, N.M.: The near-Earth objects follow-up program: IV. CCD photometry in 1996–1999. Icarus **158**(2), 294–304 (2002)

Krugly, Y., Molotov, I., Agapov, V., Elenin, L., Gaftonyuk, N., Kouprianov, V., Minikulov, N., Gulyamov, M., Abdulloev, S., Donchev, Z., Ivanova, V.: Observations of asteroids in international scientific optical network. In: Proc Workshop Gaia Fun-SSO: Follow-up Network for the Solar System Objects, pp. 101–104 (2010)

Molotov, I., Agapov, V., Titenko, V., Khutorovsky, Z., Burtsev, Y., Guseva, I., Rumyantsev, V., Ibrahimov, M., Kornienko, G., Erofeeva, A., Biryukov, V.: International scientific optical network for space debris research. Adv. Space Res. **41**(7), 1022–1028 (2008)

Molotov, I.E., Ruy, S.Y., Zhang, C., Barres de Almedia, U., Zakhvatkin, M.V., Titenko, V.V., Streltsov, A.I., Mokhnatkin, A.V., Kokina, T.N., Elenin, L.V.: Russian-Chinese observations of fragments of the destruction of the Centaur rocket stage are the first step to the network of BRICS observatories. In: Proc Space Debris: Fundamental and Practical Aspects of the Threat, pp. 95–102 (2019)

Molotov, I., Elenin, L., Krugly, Y.: Asteroid survey and follow-up observations with small telescopes in the framework of ISON network. In: 7th IAA Planetary Defense Conference, p. 23 (2021a)

Molotov, I.E., Krugly, Y.N., Elenin, L.V., Schildknecht, T., Rumyantsev, V.V., Inasaridze, R.Y., Aivazyan, V.R., Kapanadze, G.V., Canals, L.R., Graziani, F., Teofilatto, P.: Search and study of the space debris and asteroids within ISON project. Anais da Academia Brasileira de Ciências **93** (2021C)

Molotov, I., Sibichenkova, M.A., Zhang, C., Zhu, T., Yu, S., Elenin, L.V., Streltsov, A.I., Zakhvatkin, M.V., Stepanyants, V.A., Yudin, A.N., Schildknecht, T.: Development of survey telescopes in the

ISON project. In: Proceedings of the International Astronautical Congress, IAC (2021b)

Molotov, I.E., Zhang, C., Elenin, L.V., et al.: The new status of ISON - an open international project and database for space debris information exchange. In: Proceedings of the 74th International Astronautical Congress (IAC), Baku, Azerbaijan, 2-6 October 2023, IAC-23-A6.1.9, x76215, p. 1–6 (2023)

Pravec, P., Scheirich, P., Kušnirák, P., Hornoch, K., Galád, A., Naidu, S.P., Pray, D.P., Világi, J., Gajdoš, Š., Kornoš, L., Krugly, Y.N.: Binary asteroid population. 3. Secondary rotations and elongations. Icarus **267**, 267–295 (2016)

Pravec, P., Fatka, P., Vokrouhlický, D., Scheirich, P., Ďurech, J., Scheeres, D.J., Kušnirák, P., Hornoch, K., Galad, A., Pray, D.P., Krugly, Y.N.: Asteroid pairs: a complex picture. Icarus **333**, 429–463 (2019)

Rubincam, D.P.: Radiative spin-up and spin-down of small asteroids. Icarus **148**(1), 2–11 (2000)

Scheirich, P., Pravec, P., Kušnirák, P., Hornoch, K., McMahon, J., Scheeres, D.J., Čapek, D., Pray, D.P., Kučáková, H., Galád, A., Vraštil, J.: A satellite orbit drift in binary near-Earth asteroids (66391) 1999 KW4 and (88710) 2001 SL9—indication of the BYORP effect. Icarus **360**, 114321 (2021)

Shilin, V.D., Lukyanov, A.P., Molotov, I.E., Agapov, V.M., Kolessa, A.E.: Problems of prevention of dangerous situations in near-Earth space, plans, and opportunities, role of optical observations. Ecol. Bull. Sci. Cent. Black Sea Econ Coop. **4**(2), 171–175 (2013)

Streltsov, A.I., Zakhvatkin, M.V., Voropaev, V.A.E., Molotov, I.E., Pavlova, E.A., Stepaniants, V.A.E., Usovik, I.V.: Identification of potentially dangerous space objects and conjunctions. Keldysh Inst. Prepr. **3**, 1–30 (2019)

Usovik, I., Stepanov, D., Stepanyants, V., Zakhvatkin, M., Molotov, I., Nazarenko, A.: Improvement of the space debris model in MEO and GEO regions according to the catalog of the Keldysh Institute of Applied Mathematics (Russian Academy of Sciences). In: Proceedings 7th European Conference on Space Debris (2017)