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DATA FUSION OF MULTIPLE ORBITAL DATA SOURCES FOR OPTIMUM COLLISION AVOIDANCE SERVICES AT EUSST

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Abstract

Over the last few years, the space debris population in orbit has dramatically increased. The risk of collision for satellite missions is a problem more and more targeted thoroughly by all agents involved in SSA. The European Space Surveillance and Tracking (EUSST) provides Collision Avoidance (CA) service to European users on a hot redundancy scheme involving the French and Spanish Operation Centres (FR-SSAC and S3TOC, respectively). One of the main objectives of the EUSST is to provide the best CA service based on all the available information and attending to the specific user requirements. The available data might come from the well-known external sources (CDMs published by the 18th SDS, orbital information from the Special Perturbations catalogue, and public operator orbits, among others) as well as from internal sources to the EUSST: registered operator orbits and the data provided by the European Space Surveillance and Tracking Sensor Network (EUSST-SN), a continuously growing network of sensors providing thousands of measurements that are shared through the EUSST DB in a daily basis. Based on this data, FR-SSAC and S3TOC can generate enhanced CA products (CDMs based on refined 18th SDS CDMs), EUSST autonomous CDMs, and even mixed types through Data Fusion of the different orbital data sources. In addition, the CA service provided by EUSST is adapted to the particular needs by orbital regime, type of secondary object (debris or active) and primary spacecraft characteristics (GNC, propulsion system). Thus, the challenge is to manage all these sources of information in the most optimum manner, tailored to each user. An adequate assignment and evaluation of the priority of each type of CDM results in the most reliable source of data. Presenting only the relevant information to the s/c operators, prevents an overload of information at times when decisions need to be made within a few hours. A summary of the most interesting cases found in operations by the FR-SSAC and S3TOC operation centres will be presented illustrating the added value of the EUSST CA services fusing multiple orbital data sources.
Keywords: SSA, collision avoidance, EUSST, sensor network, space debris

Acronyms/Abbreviations

Collision Avoidance or Conjunction Assessment (CA), Conjunction Data Message (CDM), European SST Support Framework (EUSST), European Space Surveillance and Tracking Sensor Network (EUSST-SN), 18th SDS High Accuracy Catalogue (HAC), High Interest Event (HIE), Operation Centre (OC), Orbit Determination (OD), Orbital Ephemeris Message (OEM), Satellite Owner and/or Operators (O/O), Probability of Collision (PoC), Special Perturbations (SP), Scaled Probability of Collision (SPoC), Space Situational Awareness (SSA), Space Surveillance and Tracking (SST), Station Keeping (SK), Spanish Space Surveillance and Tracking Operations Centre (S3TOC), Spanish Optical Sensor Network (S3TSN), Hard Body Radius (HBR).

1. EUSST CA Service

EUSST CA Service is a public Conjunction Assessment service, operational 24/7, provided to more than 280 s/c (as of July 1st 2022) belonging to Commercial companies, European Governments & Institutions and Universities. It was set in place after the Decision No 541/2014/EU of the European Parliament and of the Council of 16 April 2014 Establishing a Framework for Space Surveillance and Tracking Support [1].

The main purpose of CA Service is to generate and analyse CDMs, either generated from several sources of information such as ephemerides provided by Owner/Operators, measurements from national & EUSST sensors and orbital information from the 18th SDS, or received from external entities such as the 18th

SDS and NASA CARA team, as depicted in the EUSST Service Portfolio [3].

A severity level (INFO, WARNING, ALERT) will be associated to each CDM depending on thresholds on scaled PoC and/or the geometry (radial separation & miss distance) which are agreed with each user in a Service Configuration Document (SCD).

By default, WARNING and ALERT products are all uploaded on the EUSST Service Provision Portal and manoeuvre recommendation can be provided to the user for ALERT products.

If the severity of an event is confirmed to ALERT, a tasking request will be issued by the nominal OC to all EUSST OCs through the EUSST Database. The other OCs will then evaluate the ability of each sensor to contribute and inform the OC in charge through the database. They will then upload on the EUSST Database the data collected until the end date of the Tasking Request.

If a collision avoidance manoeuvre is required to mitigate a risk, the OC in charge will propose one or several manoeuvre scenario optimized from Flight Dynamics point of view. The best scenario will then be determined based on the constraints expressed by the user, which may require a few iterations.

When a risky conjunction is detected with an active spacecraft, OCs providing EUSST CA service can also take in charge the coordination with other operators or CA providers (with the agreement of the user), will ensure that all parties share the assessment of the situation and will propose mitigation actions.

Furthermore, in case of exceptional operations (LEOP, End of Life, s/c relocations), EUSST CA service provides dedicated support such as a fast screening feature.

To sum up this introduction, EUSST CA service tries to match as much as possible the needs of the registered users and adaptations can be studied and set up if new needs are expressed. Furthermore, EUSST CA service ease the coordination between its registered users and the other operators & CA providers.

2. Available data sources

To provide CA service to the different EUSST users, FR-SSAC and S3TOC have access to objects' orbital data from multiple sources, either internal to the EUSST or published by external entities (i.e., trough space-track.org).

The available data sources are briefly described here below.

2.1 18th SDS CDM

This information comes directly from the 18th SDS and CARA routine screenings and is published in space-track.org. The orbital data for the primary/secondary objects may come from either O/O ephemeris provided by the owner/operator or the 18th SDS High Accuracy Catalogue (HAC), which is built based on sensor data from the U.S. Space Surveillance Network (SSN).

Conjunction events are detected within their screening volumes and CDMs are provided according to their reporting criteria: advanced or basic.

2.2 18th SDS SPCAT

The Special Perturbations Catalogue (SP Cat) is also used as an external source of information. It is generated and maintained by the 18th SDS and it is based on the observations from the U.S. Space Surveillance Network. Currently, it contains ephemerides for +20,000 public objects.

2.3 Operator Orbits published at space-track.org

Some organizations including mega constellations such as Starlink and OneWeb share their ephemerides through space-track.org. These ephemerides represent a valuable source of information, as they contain the planned manoeuvres and the most up-to-date spacecraft states. Operators can also keep up to date on space-track.org the active and manoeuvrability statuses of their spacecraft.

2.4 EUSST Operator Orbits

Nominally, O/O registered to EUSST CA service share their operational ephemerides through the EUSST Service Provision Portal (SST Portal) routinely. Additional information such as planned manoeuvres is typically provided.

In the same manner, special files containing tentative manoeuvres can be uploaded by the O/Os for planning or testing purposes.

2.5 EUSST Sensor Network measurements and products

Sensors from Member States are continuously contributing with data that is shared through a joint database (EUSST DB). These data constitute the basis for a future EU SST Catalogue that will be used for the SST services

Currently, FR-SSAC and S3TOC process thousands of daily measurements to build and maintain a catalogue at national level. The orbital data that is generated is used downstream in the nominal CA screenings to either detect new potential conjunctions or provide EUSST users with updated information for on-going events.

This information is autonomous with the added value to the user to confirm the information provided by any other external source.

2.5.1 EUSST Sensor Network System

The Sensor function consists of a network of sensors to survey and track space objects in all orbital regimes (LEO, MEO, HEO and GEO). The network currently comprises 44 sensors of the Member States of the SST Consortium, including radars, telescopes and laser ranging stations (see Fig. 1). The network includes tracking sensors and surveillance sensors.

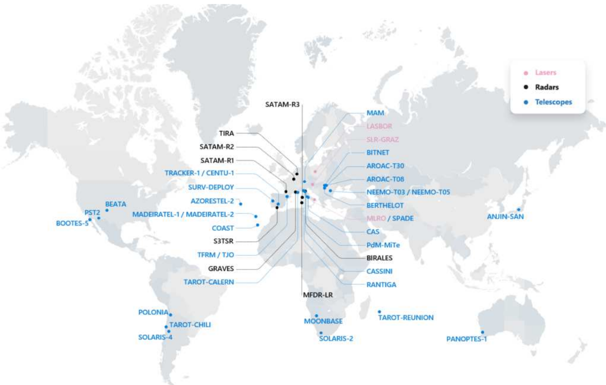

Fig. 1. EUSST Sensor Network (EUSST Service Portfolio, March 2022)

2.5.2 EUSST Sensor Network Planning and Tasking Requests

The architecture of the EUSST SN Tasking Requests and Sensor Planning processes is shown in Fig. 2. Currently, the sensor network planning is done at national level. In case of a CA High Interest Event (HIE) or any other event such as fragmentation or re-entry, the nominal OC will open a Tasking Request (TR) through the EUSST DB to communicate the need to obtain measurements for a specific object(s). The other OCs will then evaluate the TR and reply based on their ability or not to contribute.

This cooperation allows to improve the orbital information of the objects involved in the potential conjunctions and to provide new CDMs to the satellite O/O.

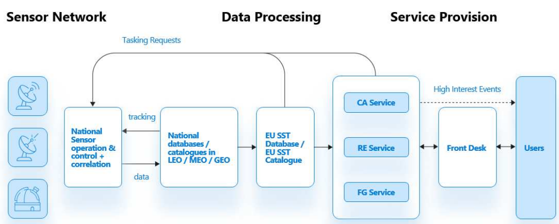

Fig. 2. EUSST Sensor Network Planning and Tasking Requests (EUSST Service Portfolio)

To optimize the available resources, the EUSST is integrating a new Coordinated Planner (COPLA), aiming at coordinating the planning of the EUSST network of sensors by the software evaluation and optimization of its operations in a routine basis.

2.6 Statistical methods for covariance computation of non-EUSST orbital sources (abacus)

Sometimes, the covariance information provided in the Orbital Ephemeris Message (OEM) of the primary object is not provided or is not realistic, although it is a key variable for the computation of the probability of collision. In these cases, the OCs are capable of computing a covariance abacus, also referred to as "observed covariance", from the differences between successive, uncoupled orbital determinations.

Fig. 3. Determined and predicted orbits

To calculate the covariance abacus, the predicted orbits available at a given time period are compared with subsequently reference (determined) orbits and their differences as a function of time are calculated (see

Fig. **3** and Fig. 4).

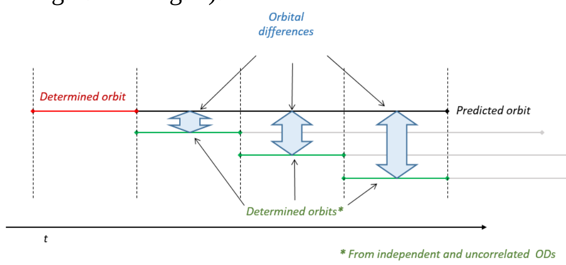

Fig. 4. Orbital differences between reference (determined) and predicted orbits

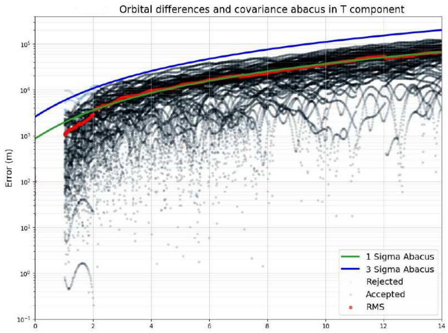

Fig. 5. Example of the along-track orbital differences for a GEO communication s/c with electric propulsion

When the number of orbits compared is sufficiently large, this process leads to obtaining a statistical dispersion of the orbital differences as a function of time in each of the spatial directions (see Fig. 5 for an example of orbital differences obtained in the T-component).

2.7 O/O quality estimation thanks to EUSST sensors data

Ephemerides provided by O/O are a crucial input of EUSST CA service, especially for manoeuvrable spacecraft, and any bias in them may lead to an inaccurate assessment of a conjunction.

The quality of ephemerides over time of a spacecraft performing station keeping manoeuvres every few months (or for a non-manoeuvrable spacecraft) can be assessed rather easily by comparing them to successive orbit determinations of the US SP catalogue or of EUSST OC national catalogue. However, it's much more difficult for spacecraft performing station keeping manoeuvres every few days (for instance, GEO s/c with chemical propulsion) or even nearly every days (for instance GEO s/c with electrical propulsion) as orbit determination are not so accurate.

Therefore, a methodology has been set up to assess the quality of ephemerides of a given s/c by using directly the measurement gathered by the EUSST-SN without the need to perform successive OD. This methodology will be depicted in the two examples below firstly for chemical propulsion spacecraft, on which it was validated, and then for electrical propulsion spacecraft

2.7.1 Chemical propulsionGEO spacecraft

Firstly, EUSST measurements were compared to the SP catalogue successive orbits of a GEO chemical spacecraft by computing the residuals. Globally, the residuals in Right Ascension and Declination are centered around 0°, with some outliers due to the maneuvers which are not reflected in real time in the SP catalog. This confirms the consistency between measurements provided by EUSST-SN and the 18th SDS SP catalog.

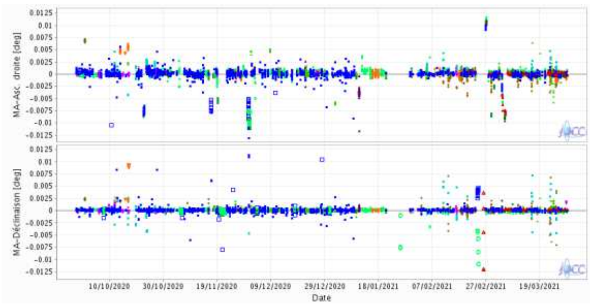

Fig. 6. Residuals of EUSST measurements compared to SP catalog successive orbits from October 2020 to March 2021

On the other hand, residuals of EUSST measurements computed against the O/O successives orbits during the same period shows at first a bias of around 6.8E-3° in right ascension which corresponds to a 5km bias in in-track.

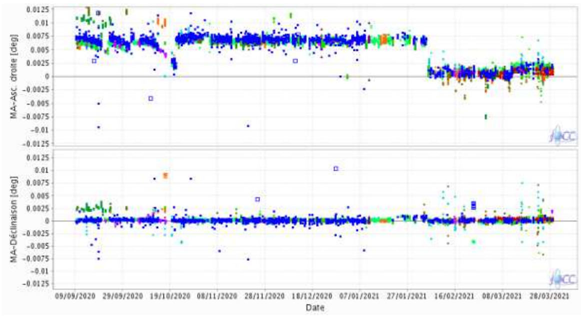

Fig. 7. Residuals of EUSST measurements compared to OO successive ephemerides (chemical spacecraft) from October 2020 to March 2021

This method was used on several GEO chemical s/c and confirmed that measurements could be used directly to evaluate biases in OO ephemerides. It can also be concluded that OO ephemerides should be trust blindly in case of close approach as a few kilometre bias on in-track is not negligible at all when compared to the screening volumes (typically 10km) as well as the miss distance threshold (a few km, depending on each s/c). Such biases should be removed as much as possible to ensure that the risk level of a given conjunction is correctly assessed.

2.7.2 *Electrical propulsion GEO spacecraft*

Since the methodology was validated for chemical propulsion GEO s/c, it was applied to electrical propulsion GEO s/c.

For these spacecraft, the 18th SDS SP catalog is unfortunately not accurate enough due to the frequency of maneuvers. However, in-track biases can be quickly identified by plotting the residuals of measurements of EUSST-SN against the O/O ephemerides. On the plot below, a bias of 6.3E-3° was detected on right ascension, which corresponds to an in-track bias of around 4.6km.

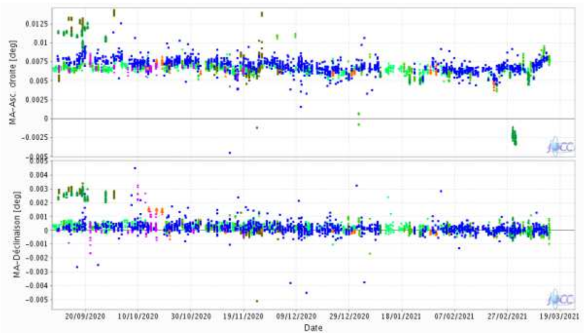

Fig. 8. Residuals of EUSST measurements compared to OO successive ephemerides (electrical propulsion spacecraft) from October 2020 to March 2021

3. Optimum use of data sources in conjunction data messages

FR-SSAC and S3TOC Operation Centres have developed algorithms that fuse the available orbital data sources to generate different types of Conjunction Data Messages, as it will be presented in the following section.

3.1 CDM generation at EUSST

The OCs are continuously developing and improving algorithms to automate, as much as possible, the provision of CA services. Nevertheless, analyst services are provided in case of specific events (e.g. HIE), ad-hoc O/O requests, etc.

3.1.1 CA screenings

There are basically two types of automatic screenings to identify the close approaches: those between the primaries against the full catalogue and the re-evaluation of the CDMs published at space-track.org.

Screenings against the entire catalogue use the different ephemerides available at that time to detect conjunctions inside the screening volumes (mainly dependent on the orbital regime and/or the risk level thresholds defined in the SCD, among others). The frequency of these screenings also depends on the orbital regime of the primary objects. Nevertheless, once a potential conjunction event is detected and lies below certain thresholds, the system will automatically compute a new update in a 1 vs 1 analysis as soon as the orbital information of the primary and/or secondary object is updated. In this manner, throughout the day different CDM types are computed internally with the most recent orbital information.

On the other side, OCs are also re-evaluating the CDMs published by the 18th SDS or CARA CDMs. In this process a scaled Probability of Collision (SPoC) is computed and the orbital information of the secondary object is screened against the latest O/O orbit available for the primary.

3.1.2 CDM types provided by the EUSST

As a result of the screenings, different CDM types are available at the OCs to evaluate each conjunction event.

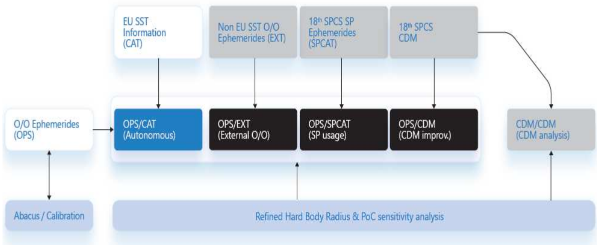

Fig. 9. EUSST CA CDM types (EUSST Service Portfolio)

Fig. 9 shows how the input orbital sources are fused, giving rise to the consequent CA EUSST CDM types defined in the Service Portfolio. Note that many other combinations can be generated but are not nominally provided to the users. However, they can be used internally by the OCs as complementary data, but are sometimes quite specific. In any case, their added value is being analysed and might be incorporated in future versions of the Service Portfolio.

EUSST autonomous CDMs: these products are based on the ephemerides maintained in the national catalogues (and in the future the EUSST catalogue) for the secondary object, while the O/O orbit is used for the primary; they are labelled as OPSvsCAT. These products rely on the measurements gathered by the EUSST Sensor Network, and as such constitute a consolidated source of information for EUSST CA services.

Enhanced CDMs: these products are based on CDMs published by external SSA providers (18th SDS and CARA). They are a re-evaluation of the input CDM firstly to use the hard body radius (HBR) considered by EUSST OCs and secondly to output the results of the scaled PoC analysis. Typically, two enhanced CDMs are computed internally for each update that differ on the source of the primary orbital data: O/O ephemeris and HAC; they are labelled as OPSvsCDM and CDMvsCDM, respectively. When the O/O ephemeris is used, the covariance data is obtained from the covariance abacus (see Section 2.6) and will be taken into account in the computation of the PoC and the SPoC.

Nevertheless, there can also be additional combinations in case the secondary object is active and its ephemeris are available to the EUSST:

CDMs based on operational orbits: additional types are obtained when the secondary object is active. In case the secondary is a EUSST registered asset, the OCs will generate an OPSvsOPS CDM type. Otherwise, if the operational orbit is available by other external means (direct contact with the secondary O/O, or shared through space-track.org) an OPSvsEXT CDM type will be generated. These products usually provide the most reliable information regarding the satellites' future states, as they include manoeuvre plan information, and it is particularly valuable to perform risk assessment of conjunctions between active-manoeuvrable objects.

CDMs based on SP Catalogue: in a similar manner as for autonomous orbits, the screening process will generate a CDM (labelled OPSvsSPCAT) in which the source for secondary orbital information is the SP Cat. Screenings against the SP Catalogue allow the OCs to detect potential events in advance and task the EUSST Sensor Network before the first 18th SDS detection/notification arrives (i.e., 18th SDS provides CDM for MEO/GEO spacecraft up to 10 days before TCA). In addition, screenings based on SP ephemeris allow confirming when an event decreased its risk level or lies outside screening volumes, and thus explains why no updated CDMs are provided by the 18th SDS. They also serve as secondary product confirming the conjunction assessment based on EUSST autonomous CDMs, when no Enhanced CDMs are available.

It is important to mention that the full SP Catalogue is updated only once per day, and that the processing of the raw SP Cat to produce the SP ephemeris is a time consuming process. This means that, although it should be in line with the HAC catalogue at the time of generation, it might not always represent the most updated source of information.

3.2 CDM type priorization

It is at this point that it becomes crucial to understand and be able to prioritize amongst the different products to present only the relevant information to the s/c operators. As such, this priorization presents a challenge, as it not only depends on the needs by orbital regime, but also on many other factors such as the type of secondary object (debris or active) and primary spacecraft characteristics (GNC, propulsion system).

3.2.1 CA service events typology

The service to be provided facing a HIE is tailored to each O/O, based on the characteristics of the registered assets, the user needs and the particular characteristics of a given conjunction. A great variety of factors have a weight on this process:

- Orbital regime:
  - LEO
  - MEO
  - GEO
  - HEO
- Object status:
  - Debris
  - Unknown
  - Active
- Object manoeuvrability status:
  - manoeuvrable
  - not manoeuvrable
- O/O status:
  - EUSST
  - non-EUSST
- Confidentiality status/military assets
- Object orbital information:
  - O/O orbit (EUSST or public)
  - other sources (from autonomous observations, SPCAT, 18th SDS CDMs)
- Primary-Secondary pair:
  - collocated
  - common user
  - none
- Objects suitability for tracking:
  - trackable
  - not trackable

3.2.2 CA service priority

The main driver of the logic is whether the secondary object is manoeuvrable or not. For this reason, it is important to know the manoeuvring capabilities of each object, and a historic of the manoeuvring cycles. This status is sometimes publicly available but is as well determined by the OCs based on manoeuvre detection algorithms.

When the object is manoeuvrable, the orbital information from autonomous predictions, SP Catalogue or HAC products may not represent the actual course of the s/c. Instead O/O orbits either internal or external to the EUSST are the preferred orbital data sources. Indeed, it is likely to find such discrepancies in operations when managing HIEs with this type of secondary objects.

For not manoeuvrable objects, the discrepancies that may arise are more related to the freshness of the data and its quality, and it is the OC role to identify which is the most reliable source of information at a given time.

In cases where it is not possible to acquire enough autonomous measurements to compute an orbit accurate enough (i.e. SMALL objects in LEO), then the CA service will be based on 18th SDS information: CDMs and SP Catalogue data. Note that, due to the latency in the SP information update, the former is considered as the most reliable information.

3.2.3 Risk level evaluation

All the products generated and described in previous sections are not directly published, as they could overload the user with many discrepant information. Instead, the OCs will evaluate the risk level in two different stages:

1. The risk level of the CDMs is computed based on geometry and probability thresholds.
2. The risk level of the conjunction is assigned based on the risk level of the most reliable CDM type. The most reliable CDM type may change during the follow-up of an event, for instance, if for a given event the first EUSST autonomous CDMs is computed after the first Enhanced CDM.

In this manner, it is possible to present only relevant information to the s/c operators.

3.2.4 Publication and communication to the user

Based on the computed risk level of the conjunction, is then possible to determine which events represent a dangerous situation and have to be reported to the O/O, and those that might even require a mitigation action (i.e., CAM).

The information is clearly presented to the user, as the published products for the same pair of primary-secondary with close TCAs (typically within one fourth of the s/c orbital period) are organized under a single event ID. This ID is constructed with the objects IDs together with the TCA. The product with higher priority at each time is then uploaded and the user can readily see the evolution of the event in terms of geometry, B plane changes and probability values (including scaling factors sensitivity analysis).

When a HIE event is declared, the analyst will notify the situation to the O/O. Usually, the notifications are done via email, although some operators demand a phone call at first detection or if there is little margin until TCA. Daily updates until TCA are always provided in case of HIE events which are monitored by the analysts.

The OCs are also capable of providing CAM support to the operators. In this case, the user will set their target post-cam thresholds (in terms of geometry and/or probability), and the OC will provide with different CAM strategies and recommendations.

4. EUSST Operational cases

The present section list a brief summary of the most interesting cases found in operations.

4.1 Real event A - CA event between a GEO communication satellite against a debris

This is an example of the added value of the autonomous product OPSvsCAT in GEO to detect a potential conjunction (prior to the first CDM issued by the 18th SDS) and of the importance of managing different sources to cross-check and monitor, by the OCs, the evolution of the conjunction and the discrepancies amongst them (if any), to provide a clear input to the O/O through the event updates.

The conjunction took place in June 2022. The primary object is a communications satellite in a geosynchronous orbit for which the O/O daily provides ephemeris, including Station Keeping (SK) plan. On the contrary, the secondary object is a large, non-active payload that crosses the GEO belt in an orbit with almost 15 º inclination.

The geometry evolution of this event is shown in Fig. 10 and Fig. 11, for each of the most relevant CDM types computed by the OC.

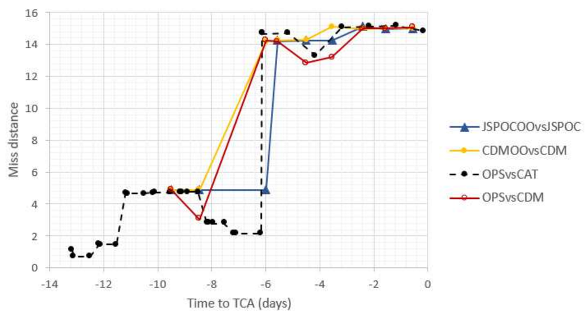

Fig. 10. Miss distance evolution

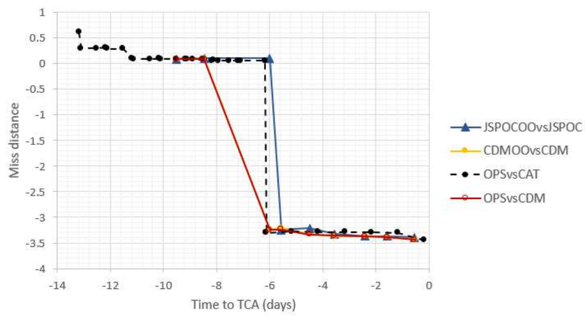

Fig. 11. Radial distance evolution

The first product was published more than 13 days before TCA. It was an EUSST autonomous CDM (or OPSvsCAT). The ephemeris of the primary object was provided by the O/O while the orbit of the secondary object came from the OC national catalogue (i.e., it was determined from the available measurements in the EUSST DB from the European Space Surveillance and Tracking Sensor Network (EUSST-SN)).

At this moment, considering that the event was classified as a HIE, a Tasking Request was created to confirm the orbital information of the secondary object and to which sensors from 5 different countries contributed. The availability of new measurements and, consequently, the updated ephemeris for the secondary object confirmed the risk and new updates of OPSvsCAT CDMs were generated.

Nearly 10 days before TCA, the conjunction was confirmed by the 18th SDS. The miss-distance and radial distance were both aligned with the EUSST autonomous predictions. Given this coherence among the different sources of CA information, the event continued to be managed autonomously (The S3TOC provided service for this High Interest Event based on 100% autonomous EUSST products. Nevertheless, used 18th SDS information for double confirmation all along the event.). A visualization of the conjunction at TCA at this point is shown in Fig. 12.

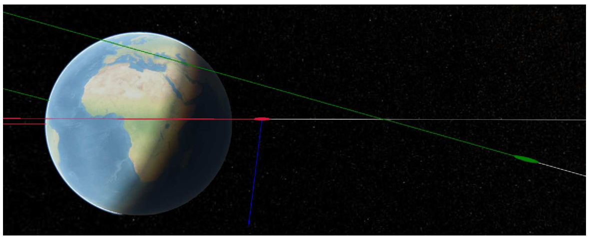

Fig. 12. Visual representation of the conjunction event at TCA, before the SK plan update. It includes the ellipsoids of the primary (red) and secondary (green) objects.

Almost 6 days before TCA, the O/O sent a new ephemeris containing an update in the SK cycle in order to mitigate this conjunction while ensuring the spacecraft's main mission. S3TOC screening against the national catalogue using the O/O orbit with the modified manoeuvre plan confirms the decrease of risk, informing the user of the s/c. A few hours later this decrease of risk is also confirmed by the 18th SDS.

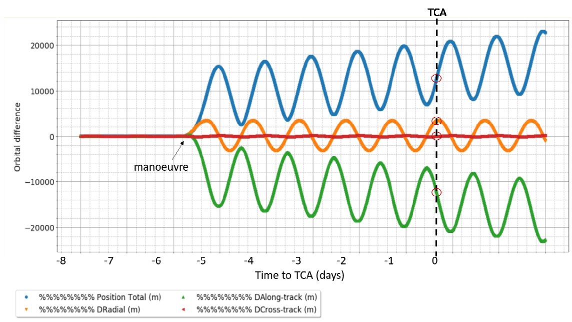

Fig. 13. Orbital differences between the pre- and post-manoeuvre

The orbital differences between the pre and post station keeping manoeuvre updates are shown in Fig. 13. It shows the effect of the modified SK plan on the s/c orbit.

Even though no CAM service has been requested by this user, the EUSST computed updated CA screenings perfectly in-time, confirming the risk mitigation of the proposed CAM, providing the user useful information for the CAM design and the GO/NOGO decision. The OC in charge also sustained continuous, effective and clear communications with the O/O until TCA.

Even after the event risk level decreased and the conjunction was considered as mitigated, EUSST autonomous CDM updates continued to be published until TCA confirming no further change in geometry.

4.2 Real event B - LEO event between two EUSST users

This case illustrates a particular scenario in which both objects, registered in the EUSST CA service, are operated by two different O/O and are each serviced by one of the two EUSST OCs in charge of the CA service (FR-SSAC and S3TOC).

The primary object is a manoeuvrable s/c in sun-synchronous orbit for which the O/O daily provides ephemeris. On the contrary, the secondary object is a medium, active not manoeuvrable payload in sun-synchronous orbit. Both sun-synchronous orbits were opposed in RAAN at a very similar altitude, which led to a quasi-frontal close encounter on first half of 2020.

Fig. 14 and Fig. 15 show the evolution in miss-distance and radial distance for the EUSST computed series of CDMs (in particular, those combining O/O orbits and 18th SDS data).

The first product was published by the 18th SDS almost 7 days before TCA and it was a CDM based on catalogue orbital information (HAC) for both objects.

Indeed, several updates of this type were generated until 5 days to TCA, when products with operator ephemeris were computed (this corresponds with nominal screening criteria in LEO for both EUSST and 18th SDS).

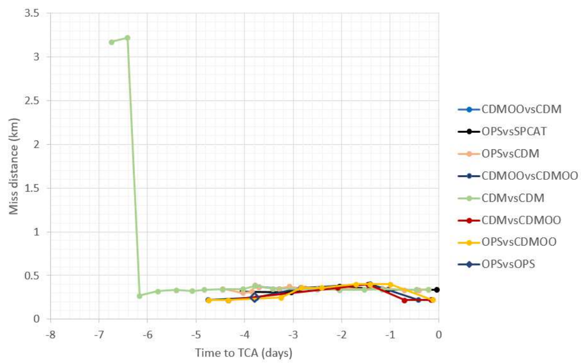

Fig. 14. Miss distance evolution for EUSST computed CDMs

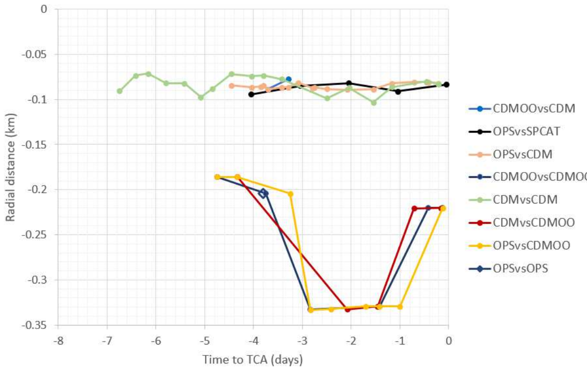

Fig. 15. Radial distance evolution for EUSST computed CDMs

The discrepancies between the different products lies on the orbital information of the secondary object, as the CDMvs. and CDMOOvs. CDMs are consistent. The geometry showed by the CDMs computed with catalogue information for the secondary object was indicating a radial distance below 100m while the series using the operator orbit indicated a MD > 200m. It is worth mentioning that the HIE threshold agreed with the users was a radial distance below 100m.

This effect was also observed when analysing 18th SDS CDMs (see Fig. 16).

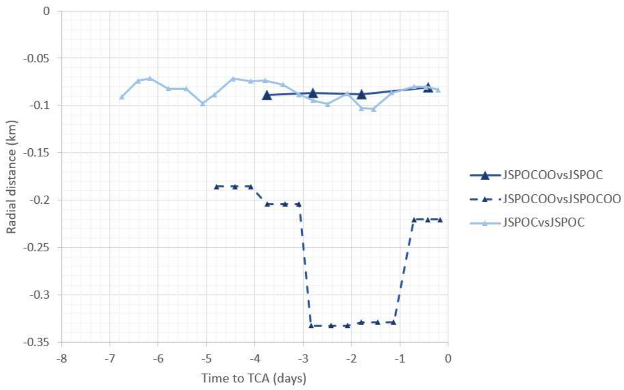

Fig. 16. Radial distance evolution for 18th SDS CDMs

The event was closely followed and both FR-SSAC and S3TOC OCs cross-checked the consistency between the updates computed independently. Additionally, O/O ephemerides were shared between the EUSST OCs -under agreement of the owner operators involved-. With this information, an OPSvsOPS CDM was computed (see blue-diamond in Fig. 14, Fig. 15 and Fig. 17). This product allowed to confirm the geometry as well as scaled PoC value.

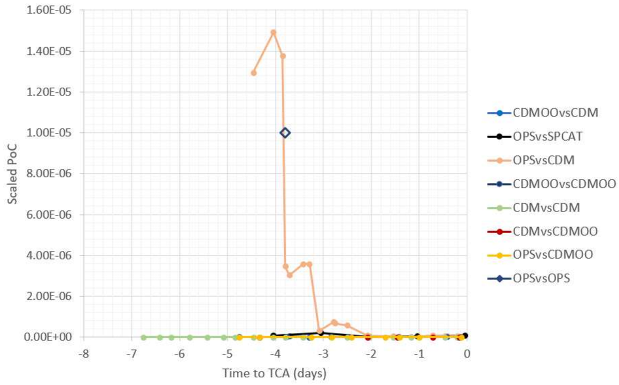

Fig. 18. Scaled PoC evolution for EUSST computed CDMs

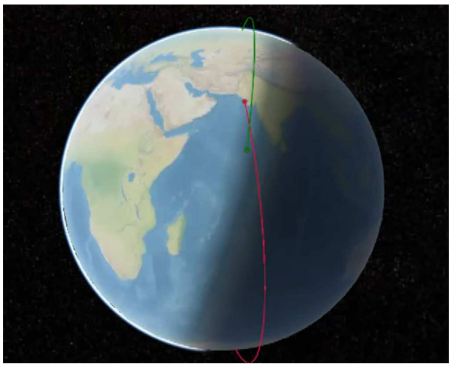

Fig. 19. Visual representation of the conjunction event after TCA

Given that the situation was stable outside the HIE limits (considering types with secondary operational orbit as the most reliable sources of information) EUSST recommended not to perform mitigation action and no CAM manoeuvre was performed. Therefore, the EUSST cooperation throughout the event and its outcome did provide the O/O with reliable information and prevented the extra cost and risks derived from unnecessary CA manoeuvres.

4.3 Real event C – First Galileo CAM

For MEO and GEO s/c, a screening is performed daily against the SP catalogue by the OCs to identify the conjunction that may become risky in the future and for which a tasking request should be sent to increase the tracking of the secondary by the sensors contributing to EUSST.

On February 25th, 2021, this screening against SP catalogue raised a conjunction between GALILEO 23 (2018-060C) & an ARIANE 44LP R/B (1989-062C), with a TCA on March 07th 2021. Consequently, FR-SSAC issued a tasking request on the secondary object. Later that day, the first 18th SDS CDM was received and the first OPSvsCDM product was generated with a

Scaled PoC one order of magnitude above the ALERT threshold for Galileo fleet.

The first optical measurements were received from EUSST-SN on February 25th around 23h, proving a good reactivity of OCs.

Consequently, on February 26th, the Galileo team sent a first test ephemeris including a CAM. During the following days, as the risk level remained high, OC and the users refined the sequence of events of a potential CAM and tested several CAM scenarios.

In parallel, FR-SSAC continued to generate OPSvsCDM products based on 18th CDM and to perform OD of the secondary object to generate OPSvsCAT products.

Discrepancies between these two kinds of products were observed as expected due to the high eccentricity (~370km / 33300 km orbit) and drag at perigee but the risk remained above ALERT threshold for nearly all products.

A Scaled PoC of 1E-3 was reached for the last CDMs (both OPSvsCDM and OPSvsCAT) provided by FR-SSAC before Galileo team had to decide on the execution of a Collision Avoidance Maneuver, this threshold is several orders of magnitude over the maneuver threshold for Galileo spacecraft. A final manoeuvre support was provided, and the user set the CAM around 1.5 orbits before TCA. FR-SSAC confirmed that no risk was detected on the ephemeris including the CAM and generated the products based on this ephemeris.

Support to the user continued after the CAM execution as the user had to maneuver the spacecraft to return on its nominal orbit. Thus, the follow-up of this event ended with the screening of the last return maneuver several days later.

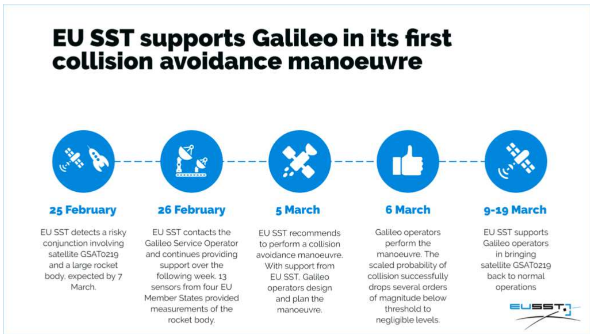

Fig. 20. Timeline of the event

Fig. 21: Map of sensors contributing to the event

4.4 *Real event D – LEO spacecraft event against Mega constellation*

Several LEO spacecraft registered to EUSST CA service regularly cross the orbits of Mega constellation spacecraft, either during their orbit raising phases or during nominal operations.

In numerous cases, alert based on CDMs using the HAC orbit of the 18th SDS as source for the secondary spacecraft were spurious, as this orbit does not take into account the scheduled manoeuvres. The difference between such a predicted orbit and the actual one may amount to hundreds of kilometres a few days before TCA. For a specific s/c registered to EUSST, such false alarms occurred several times per week.

On the other hand, conjunctions are regularly confirmed by using ephemerides of mega constellation available on space-track.org.

For such conjunction, experience showed that only OPSvsEXT are a reliable data source, but that coordination is nevertheless required between EUSST OC and the other spacecraft operator to ensure that the both teams shares the same assessment of the situation. Experience also showed that, when a manoeuvre is needed and when one spacecraft has an automated CA, letting the automated CA process to perform the maneuver minimizes the effort on both side. Of course, the other spacecraft shall not maneuver.

However, management of such conjunctions showed that spacecraft operators should keep up to date their spacecraft statuses (active or not, maneuverable or not) and share publicly their ephemerides on space-track.org to ease coordination between operators.

It is to be noted that conjunctions with non-public s/c cannot be managed by mega constellation operators (as well as other operators) as they do not receive 18th SDS CDMs for these s/c (typically MoD ones). For these cases, it is the OC responsibility to screen its ephemerides against all available ephemerides and warn the operators when needed.

To conclude this section, EUSST OCs deeply thanks mega constellation operators for their willingness to share up to date data as well as to answer quickly when a coordination is needed.

4.5 Support to exceptional operations - Fast screening

Following a request of Galileo operational team to support the relocation of spacecraft within the constellation, the need arose to implement a new feature allowing a user to automatically receive the results of a screening of an ephemerides against the whole catalog as fast as possible and at any time (i.e. out of classic working hours, when the on call teams are not in their operational centers).

As a result, dedicated chains were set up on OC side in order to limit as much as possible all the latencies and to allocate hardware and software resources so that the results are provided as fast as possible.

From the user perspective, the procedure is simple as he is only required to add an agreed tag (for instance SPECIAL) in the name of the ephemeris uploaded on the portal. Ephemerides which does not include that tag in their name will be process normally which allow to receive in parallel CDMs on the free drift orbit for instance. The user will then receive a mail informing him when the ephemeris was ingested by the OCs, followed by a second when the screening is done, with the number of generated CDMs. This allows the user to check that everything is running as expected during critical operations, in particular out of EUSST OC working hours. The user also have access to these statuses and related CDM on the EUSST portal, either manually or per API.

These fast screening processed were used on multiple times by EUSST OC: 5 Electric Orbit raising Phase, 7 chemical s/c LEOP, 4 relocations and 7 End of Life (As of August 2022). Results were usually provided in a few minutes.

4.6 Events between objects from the same launch

As the number of spacecraft registered to EUSST CA service grows with time, the number of unusual cases managed by the OC also increase.

For instance, while low velocity conjunctions (relative velocity of a few tens m/s) often occur in GEO, these events seldom appeared in LEO. However, such cases occurred four times with different spacecraft of a user in around 4 months. These conjunctions occurred with spacecraft that belonged to the same launch batch. A secondary was even involved in two of these 4 conjunctions, and performed a collision avoidance maneuver in both cases.

The low relative velocity implies that a small orbit determination change for these objects can lead to a change in TCA of several seconds (and even 25min in one case) which can lead to significant changes in geometry and scaled PoC. The other point is that 2D PoC cannot be trusted in those cases and that all PoC had to be computed with an adequate method, here based on Monte-Carlo. As a result, exchanges of ephemerides allows to have a better assessment of the conjunction

These points were made clear to both operators to ensure that each entity involved shared the same assessment on the situation.

	Event 1	Event 2	Event 3	Event 4
Prim. s/c	LEO1	LEO2	LEO3	LEO4
Sec. s/c	SEC1	SEC1	SEC2	SEC3
Lauch Date	2021-06	2021-06	2021-01	2021-01
TCA	2021-08	2021-09	2021-09	2022-01
Scaled PoC	>1E-2	>5E-2	5E-4	1 E-3
Relative Velocity	4.4 m/s	6.0 m/s	1.0 m/s	24 m/s
Delta TCA	15s	15s	25 min.	5s
Comment	CAM by SEC1	CAM by SEC1	Risk level decreased	Risk level decreased

5. Conclusions

This paper describes how multiple orbital data sources are used and fused by EUSST CA OCs and gathers a summary of the most interesting cases found in operations by the FR-SSAC and S3TOC OCs. This illustrates the added value of the EUSST CA services fusing multiple orbital data sources as well as the importance of coordination and data sharing to manage conjunctions between active and maneuverable spacecrafts.

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