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CASCADE – A demonstrator for rule-based coordination of conjunctions

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Abstract

Historically, the largest share of conjunctions of satellite in space were against passive (debris) objects. In that case, and under the assumption that the conjunction event is evaluated as critical, the possibility for risk reduction is mostly limited to performing collision avoidance manoeuvres by the active satellites.

With the increasing number of operational spacecraft in orbit, this picture is changing: Conjunctions between two active satellites are becoming the norm. Additionally, new operational concepts, usually exploiting electric propulsion, rely on frequently performed manoeuvres. Those, however, lead to a reduced predictability of future state vectors of objects and increased uncertainties in the data. Particularly in altitudes between 500 km and 600 km, which are heavily populated by Starlink and other constellations, the complexity of safe operations increases with every additional launch.

To mitigate this new situation, two corner stones are required: a) Data sharing between all operators and b) Coordination. Both items contribute differently to the problem at hand, but also bring their specific challenges.

Data sharing can be considered the baseline requirement for an efficient space traffic management in an environment with continuously manoeuvring satellites. Challenges here range from used data formats and physical models employed to derive future states, the timeframe over which manoeuvre plans of a constellation remain valid, and the trustworthiness and accuracy of data from different sources.

Coordination builds on the availability of shared data, but focuses on finding a viable solution in case of a conjunction or, more simply, on the decision: Who evades? Recently, the term "rules of the road" is being used more frequently in the context of space traffic management. "Rules of the road" describe a set of very simple formulated rules, similar to priority rules in car traffic, that shall apply to spacecraft during a conjunction. Examples for these rules are a priority for the older, heavier etc. object. As of now though, these are a theoretical concept that are discussed for the evolution of space laws and debris mitigation standards and requirements.

CASCADE (Collision Avoidance, Satellite Coordination Assessment Demonstration Environment) is a demonstrator that is currently developed by OKAPI:Orbits and TU Darmstadt, building on the findings of TU Darmstadt results from the "Rules4CREAM" activity. The goal is to develop a demonstrator coordination system, with the first step to be optimzed for frequently interfering constellations in orbit. It will include a data sharing component, with a focus on the coordination part. The coordination is inspired by the rules of the road idea, but as currently no requirements are available, the demonstrator will foresee the negotiation of rules in a 1-on-1 approach, thus allowing operators of satellites to cooperate on data driven decisions in case of a conjunction. Part of the demonstrator is furthermore a software to assess the long-term impact of different rules agreed between constellations on their concept of operations and to freely distribute the effort between constellations.

This paper will outline the approach of the CASCADE demonstrator. It will provide insights in collected stakeholder requirements for a coordination system, provide an overview and the solution for attached legal challenges, and, using a set of demonstration cases, describe the workings and advantages of a rule-based coordination approach. As an intermediate result of an on-going research activity involving the authoring entities, a major goal of the presentation is to engage with satellite operators as major stakeholder to drive the results of the activity towards their actual needs for coordination.

Keywords: Space traffic management, collision avoidance, coordination

1. Introduction

Since the beginning of humankind's exploration of space, the number of artificial object in Earth's orbits has steadily been increasing [1; 2]. After a near hibernation of space activities in the early 2000s, commercialisation of space has driven the number of launches and active objects in orbit to unprecedented heights. Studies analysing different future scenarios of the debris environment around Earth have come to the conclusion that over-excessive traffic to frequently used orbits will render spaceflight to become close-to-impossible over the coming decades [3, 4]. It is additionally note-worthy that these studies assume traffic rates clearly below the number observed over the last years and announced by commercial satellite operators, such as Starlink, OneWeb, Kuiper, or GW, an announced Chinese constellation with up to 12,992 satellites [5].

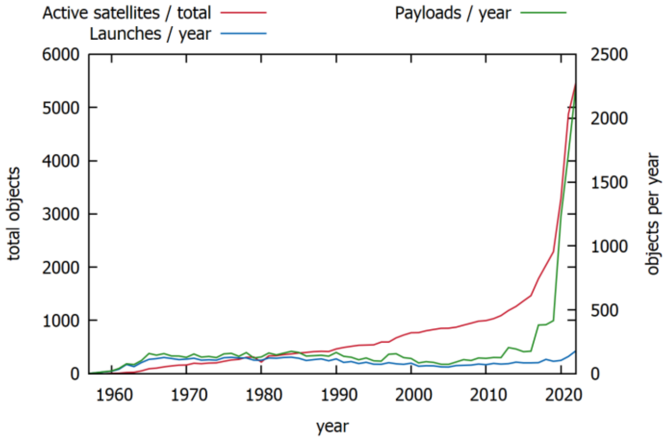


Figure 1. Overview of the evolution of active objects over time (red), as well as the number of launches and launched payloads per year. Data from [2].

To mitigate doomsday scenarios of the space environment, which especially would make manned spaceflight an almost non-acceptable risk, differently applicable space laws, i.e. [6], and industry standards, i.e. [7], exist that pose different requirements to operators of satellites under the jurisdiction of a law or applicable standard. Not discussing the content of these in detail, one requirement that is getting more relevant is to foresee the ability to perform collision avoidance. In the past, collision avoidance mostly had to be performed against derelict objects ("Space Debris"), for which, under consideration of more-or-less known uncertainties, the future trajectory could be propagated using physical models. In recent years though, the number of active objects in the environment has changed so drastically that by now, close approaches between active satellites are becoming the new norm. In contrast to debris objects, active satellites often have the ability to perform manoeuvres, and especially those from modern constellations are doing so quite frequently. Therefore, simply relying on observations and physically propagated orbits and conjunctions derived-from and handled-based-on this "passive" data becomes less trustworthy. To alleviate this, it is slowly becoming practice to share operational data more actively between operators of satellites, including manoeuvres as foreseen by the operations schedule. In geostationary orbits, this has been coordinated by the Space Data Association for almost 15 years, covering about 50% of the satellites operated there, with some reaching into LEO. In LEO itself, it is slowly getting more common to share the operator's own ephemeris via space-track or other public sources, but this is mostly done by operators of large constellations.

The next step beyond increasing the transparency in active operations is to enable satellite operators to act in a coordinated manner. In the context of this papers, coordination means specifically: If trajectories, as known by all involved partners, interfere at some point in the future, how can two operators coordinate, who must act in what ways to mitigate the risk of a potentially critical conjunction.

To the current date, no generally agreed-upon rules or guidelines for such a coordination exist, which is why there are basically two options:

- Case-by-case: If a close approach is detected, satellite operators reach out to each other and decide case-by-case, who must act and how. Some tools exist to support these activities, but generally, every combination of satellite operators might lead to a deviating result.
- Assumed responsibility: A special case is Starlink, who assumes general responsibility for themselves for all conjunctions that are detected for their satellites [8]. For most cases, this assumption is implicit; between

NASA and Starlink though, a specific agreement exists through which Starlink takes the responsibility to undertake all required collision risk mitigation measures for close approaches involving Starlink and NASA spacecraft [9].

In recent years, the concept of employing a rule-based collision avoidance in space traffic management has been discussed. A very short overview of the rule-based approach for space traffic management including its advantages is given by Frandsen in [10], which is openly accessible and therefore shall not be repeated here.

Generally applicable "rules of the road" come with one big disadvantage: there is no international body that is in the position to make these generally applicable, neither de-jure nor de-facto; even more so, there are no means available to go even further and enforce the adherence to such rule or even consider sanctions in the case of disregard.

Nevertheless, there is a high intrinsic motivation for operators of satellites to reduce their on-orbit collision risk while at the same time keeping the associated transaction cost minimal. The example of Starlink additionally shows that the cost to consider avoidance measures in modern satellite operations might be lower compared to the cost associated with an uncertain process to handle risks.

Therefore, OKAPI:Orbits and TU Darmstadt have initiated the CASCADE activity, funded by ESA through the GSTP programme office to demonstrate the applicability and acceptance of the "rules of the road" approach to coordinate satellites in space. Naturally, such activity is not able to impose rules and requirements on the global population of satellites.

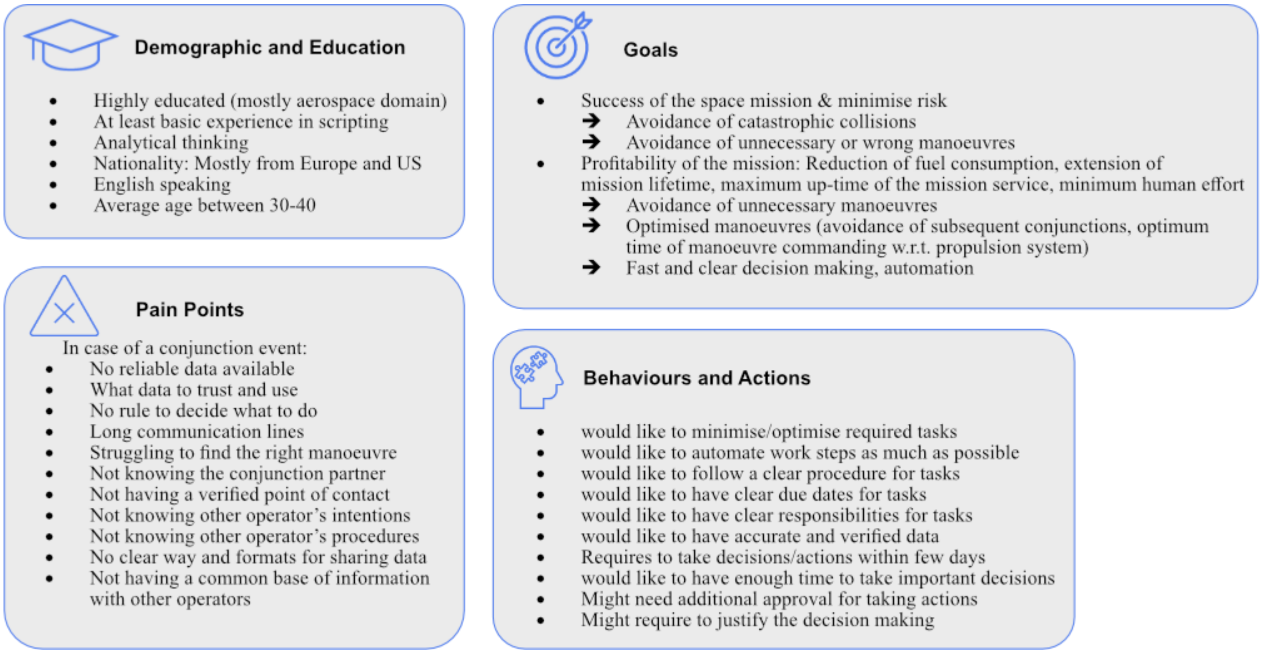
For this reason the chosen approach is to provide tools to satellite operators to transparently share data and handle close approaches between them rather than defining these rules globally. To additionally increase the automatability in the process, operators will have the ability to pre-define non-binding rules agreed between them which define how to handle future occurring conjunctions between them and distribute the effort related to them. This will reduce the effort of coordination and decision taking during operation. The actual definition of the content of these rules is supposed to be as open as possible, to be able to accommodate as many different requirements from different operators as possible. To facilitate the definition and better understand the impact of such rule, a simulation tool is being developed to up-front analyse potentially interfering satellites and operations and analyse the application of different rules. This tool will though not be in the centre of this paper, but earlier versions and its application have been described in [11, 12].

This paper gives an overview of the status of this activity in particular for the coordination application. As such, it provides initially collected requirements and derived use cases, whereas it is clearly noted that one goal of this paper is to reach out to further satellite operators for their views and insights on the requirements. Following, the currently foreseen concept of handling conjunctions is presented, alongside the tools being developed to assess the application of rules with satellite operators. Lastly, the application is demonstrated using three different use cases. The activity is still ongoing and expected to conclude end of 2024.

2. Personas, use cases and user requirements

To better understand the underlying assumptions and thoughts behind the suggested solution, this section gives an overview of the proto-persona, use cases, as well as central requirements that are driving the functionality and design of the software. For brevity, the focus in this section is on the satellite operator as primary user. Naturally, several other potential users with interest in the system and its result might exists. These include the providers of space traffic management related services and data, "regulators" interested in understanding the workings of the rules-based approach and interested in general user statistics, mission designers to understand the impact of rules on their concept of operations and others. A validation of them with the target user group is currently on-going, which might lead to minor changes in future versions.

Figure 2 gives a summary of the "typical" target user involved in satellite operations and collision avoidance measures as perceived by the authors of the paper. Based on the persona, two groups of users are derived: One user that is subscribed to the system, and a guest user, who gets access to a conjunction event but is not subscribed and thus has only limited access to its features.



Demographic and Education

- Highly educated (mostly aerospace domain)
- At least basic experience in scripting
- Analytical thinking
- Nationality: Mostly from Europe and US
- English speaking
- Average age between 30-40

Goals

- Success of the space mission & minimise risk
  - ➔ Avoidance of catastrophic collisions
  - ➔ Avoidance of unnecessary or wrong manoeuvres
- Profitability of the mission: Reduction of fuel consumption, extension of mission lifetime, maximum up-time of the mission service, minimum human effort
  - ➔ Avoidance of unnecessary manoeuvres
  - ➔ Optimised manoeuvres (avoidance of subsequent conjunctions, optimum time of manoeuvre commanding w.r.t. propulsion system)
  - ➔ Fast and clear decision making, automation

Pain Points

In case of a conjunction event:

- No reliable data available
- What data to trust and use
- No rule to decide what to do
- Long communication lines
- Struggling to find the right manoeuvre
- Not knowing the conjunction partner
- Not having a verified point of contact
- Not knowing other operator's intentions
- Not knowing other operator's procedures
- No clear way and formats for sharing data
- Not having a common base of information with other operators

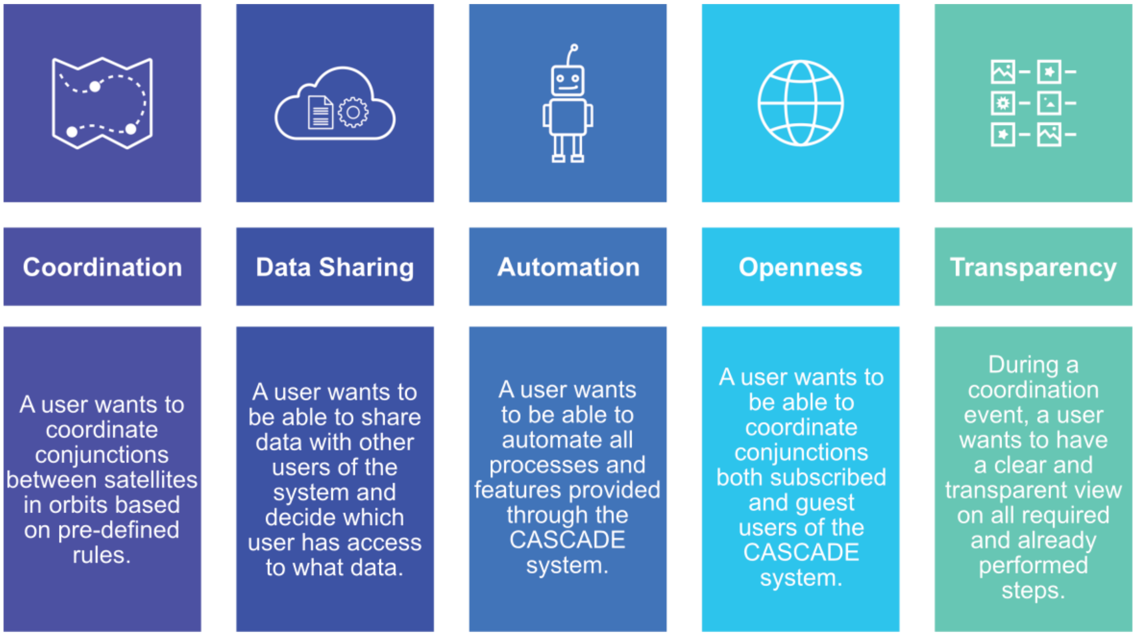
Behaviours and Actions

- would like to minimise/optimise required tasks
- would like to automate work steps as much as possible
- would like to follow a clear procedure for tasks
- would like to have clear due dates for tasks
- would like to have clear responsibilities for tasks
- would like to have accurate and verified data
- Requires to take decisions/actions within few days
- would like to have enough time to take important decisions
- Might need additional approval for taking actions
- Might require to justify the decision making

Figure 2. Summary of the main persona (satellite operator), for whom the CASCADE system is being designed.

Using the persona and the described problem, several use cases have been derived for the CASCADE system to fulfil. Naturally, here not the full description of all possible use cases inside the software are given, but rather a high-level view on the most relevant ones to transport the idea of the system to the reader. The representation of these use cases is given in Figure 3.

1. **Coordination:** Naturally, this is the main purpose of the system: The coordination of conjunctions between objects in space using pre-determined rules. Nevertheless, it is also important that CASCADE is able to support the coordination in those cases where no rules were defined prior.
2. **Data sharing:** Especially for satellites regularly manoeuvring, the capability of sharing data is important to ensure that all potential conjunctions are detected and additionally as well as that no unneeded avoidance manoeuvres are performed. Additionally, data sharing is of great use during the negotiation and iteration of avoidance manoeuvres.
3. **Automation:** Especially for constellations operating in adjacent orbital regions, the number of close approaches can be very high. Therefore, a very high degree of automatability is desirable.
4. **Openness:** For a system to coordinate between satellite operators, it is a fundamental need to be able to use it not only with other subscribed users, but also with all satellite operators that are not part of the system itself. Therefore, guest access will be offered to allow using the main features of CASCADE during the coordination.
5. **Transparency:** As the system is supposed to act as a guide through the handling of a complex process, a high degree of transparency is required. This covers being aware of all past, current, and future steps to be performed to come to a conclusion of the event, as well as a clear timeline, until when which steps need to be done.



Coordination
A user wants to coordinate conjunctions between satellites in orbits based on pre-defined rules.

Data Sharing
A user wants to be able to share data with other users of the system and decide which user has access to what data.

Automation
A user wants to be able to automate all processes and features provided through the CASCADE system.

Openness
A user wants to be able to coordinate conjunctions both subscribed and guest users of the CASCADE system.

Transparency
During a coordination event, a user wants to have a clear and transparent view on all required and already performed steps.

Figure 3. Overview of the main use cases of the CASCADE system for satellite operators.

To ensure a successfully usable system, aside from the stated use-cases, the coordination process needs to cover several additional requirements :

1. The CASCADE system itself shall provide access to relevant flight dynamic and risk computation features. Examples are the screening of ephemeris against high precision space object catalogues, the re-computation of conjunction data messages when data was updated, orbit determination from provided measurements (i.e. GNSS positions) and others. Initially, these features will be made available through OKAPI:Orbits’ space traffic management platform, whereas it shall be possible to also use other service providers for these tasks.
2. To enable the use of other services and to facilitate easy and simple data exchange, the system shall utilise widely used and accepted standards for data formats and contents. Where possible and available, these shall be based on CCSDS.
3. The system shall be usable both via API and GUI. Either of the components shall allow access to all features of the platform, whereas the API shall mostly be available to enable automation.
4. After the conclusion of a conjunction, the system shall provide a report, summarizing the result of the coordination.
5. The use of the system and the participation in a coordination case shall be voluntary. As such the system will be designed in a way that it considers the fact that participating operators would act in-line with the stated use cases.

Following the definition of the purpose of the system, the next step is to define an operational process how to coordinate conjunctions.

3. Coordination process

Based on the requirements and use cases defined before, a process has been created to handle close approaches in the CASCADE environment. In the centre of the process are two items:

1. **Coordination cases** are the collection of all information available to describe a close approach between two active satellites and are always created when such is detected in the near future (~4 days). As a bare minimum, a coordination case contains a single Conjunction Data Message (CDM) describing an event. Coordination cases have different states:
   - Assignment: A coordination case is always either assigned or unassigned. Assigned means that one of the two operators has agreed to take action in case if is it needed.
   - Criticality: Describes whether a mitigation action (avoidance manoeuvre) is recommended.

- Actionable: Critical cases are marked as "action needed", which means that the operators have to actively participate in the coordination. All other are tracked in the system for the purpose of sharing information and being prepared in case the criticality increases suddenly.

2. A **timeline**, which pre-determines what decision has to be made at what point-in-time before Time of Closest Approach (TCA). The following deadlines are defined in the process:
   - Event detection: Time at which the close approach between two objects is detected. In LEO, this is usually 3 – 4 days before TCA, but shorter time frames are possible.
   - Assignment acceptance deadline: a time before TCA, at which one satellite operator should have accepted to take an action for a coordination case.
   - Manoeuvre decision deadline: a time before TCA, at which the decision on whether to perform the avoidance manoeuvre is made.
   - Manoeuvre execution deadline: a time before TCA, at which the manoeuvre, if decided so on the previous point, has to be performed.
   - TCA: The time of closest approach in a conjunction; it also marks the end of the coordination case.

It needs to be kept in mind that the CASCADE system has no governing capabilities over the participating satellites and no means to sanction any non-compliance with them exist. Thus, all defined deadlines exist as a guideline to simplify the coordination process and to increase transparency. They are computed from the latest time a satellite with given capabilities can perform an avoidance manoeuvre reducing the collision probability to an acceptable level. This can be as late as half an orbit before the event for satellites with chemical propulsion systems, or even up to a day before TCA for satellites with small electric propulsion.

The starting point for the CASCADE system is the detection of a close approach between two active satellites. Independent from the content of the message, a *coordination case* is created in the system. From the very beginning, the *coordination case* would be unassigned. At the same time, the *coordination case* would be rated on its criticality, where three criticality levels are foreseen. For the sake of this paper, the computed collision probability **PoC** shall serve as the only metric for the classification. Description and exemplary metrics are given in Table 1.

Table 1. Overview of the used classes for coordination cases.

Class	Description	PoC
Non-critical	All data available at the current time indicates that it is not required to perform any mitigation measures	< 1.e-5
Observed	All data available at the current time indicates that it is not required to perform any mitigation measures, but the analyses also show that the used metrics are close to the threshold of becoming more critical. Observed cases have a higher visibility in the system than non-critical cases	1.e-5 ≤ 1.e-4
Critical	The data available at the current time indicates that the event surpasses defined thresholds for a critical conjunction which, when following the thresholds, would require a mitigation action to be taken	≥ 1.e-4

Irrespective of the criticality, upon creation of a *coordination case*, it is always unassigned which means, it is not set who has to take an action. There are two ways of how an assignment can take place:

1. The two satellite operators have agreed on a rule acting between them: The case is assigned following the agreed upon rule.
2. The two satellite operators have not agreed on a rule[*] acting between them: Assignment is requested from both involved operators, meaning they can accept/reject to take an action in this case.

Combined, a coordination case can be in the states as shown in Figure 4. The main goal of the CASCADE system is to avoid uncoordinated critical cases (top right corner of the figure).

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[*] Over time and development of CASCADE, it is foreseen to establish a general or basic rule to act between all satellite operators who are part of the CASCADE system but not having negotiated a bilateral agreement (yet). To pursue this though, better understanding of acceptable rules and requirements throughout satellite operators need to be gathered.

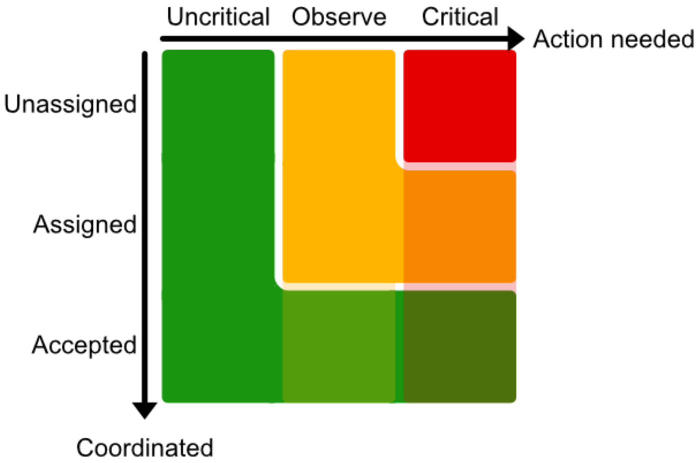

Figure 4. Overview of the different statuses for a coordination case. Main goal is to avoid uncoordinated critical cases.

In the next step, the assignment needs to be acknowledged (or accepted) by the assigned satellite operator (which is omitted in the case of voluntary self-assignment). In case the assignment is not made within the set deadline or rejected, the case is re-opened again and suggested to both operators to take on the actions.

Upon acceptance, the remaining timeline is computed based on the current data available and the capabilities of the satellite. Relevant steps in the timeline have been explained in Section 3.2.

From there, an iteration and validation phase begins, during which the operators involved in the coordination case share their own ephemeris data (which, if based on very recent GNSS positions is often of higher accuracy than the data included in the CDM messages themselves), manoeuvre plans (which might lead to solving the case, for example if another manoeuvre is already planned to be performed before TCA that automatically leads to a sufficient risk reduction), and iterate on mitigation manoeuvres. The CASCADE system on the other hand re-computes the risk based on the additionally available data, updating the classification of the case, and provides the expected outcomes for suggested mitigation manoeuvres; also, basic Space Traffic Management (STM) features such as screening manoeuvre plans against high precision orbital catalogues are provided through the system. Furthermore, in this phase, the operators can decide to change the acceptance status of the conjunction: This can happen because the assigned operator drops the assignment (where a reason can, but does not have be given) or the other operator asks to be assigned (which might make sense in cases where the operational plan of the initially unassigned operator foresees manoeuvring for other reasons anyways).

After the decision is made, the manoeuvre is commanded and flown by the satellite. At this stage, the acting satellite operator has the option to confirm a successful manoeuvre execution; in case something went wrong, and sufficient time remains, the case can be re-opened again to find an alternative solution. Once independent data is available and stable, which is usually the case ca. 24 hours after a manoeuvre, the CASCADE system will independently try to verify its execution and provide a summary of the overall coordination case.

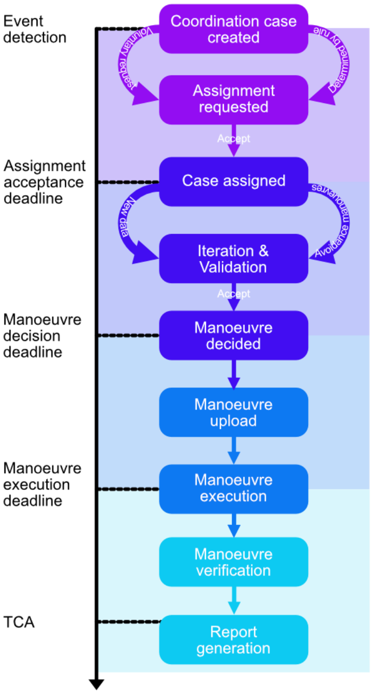

Figure 5. High-level view of the coordination process followed in CASCADE. At all times, an already committed user can reject the assignment (for example due to operational constraints, issues with the satellite etc.), which leads to a resetting of the case and request for commitment from either operator.

4. Operational System

CASCADE comprises two software components:

- A *mission analysis software* (MAS) to define rules and simulate their consequences in different orbit population scenarios.
- An *operational coordination platform* (OCP) to coordinate conjunction events based on rules that can be imported directly from MAS.

They share their user management, so that subscribed users can use both tools from one account.

The operational coordination platform follows an API-first approach, i.e. all functionality is available through the exposed web API. The platform also employs an event-based architecture, where events comprise updates regarding conjunctions or manoeuvres, actions taken by the user, requests for information or actions, and notifications. It implements the logic of coordinating operator actions with respect to a conjunction, deciding on responsibilities according to an agreed upon rule set, keeping track of the status of a case and determining the next steps.

Furthermore, CASCADE interfaces to external software systems, such as the OKAPI:Orbits platform, for computations (conjunction assessment, manoeuvre generation and validation, etc.), and to communication channels like email and messengers, in order to notify users of important events and updates. For the beginning, only CDMs provided via Space-Track will be considered; it is aimed though to open the system to CDMs from other providers as well to act as a general interfaces between different service providers. The main architecture and interfaces are shown in Figure 6.

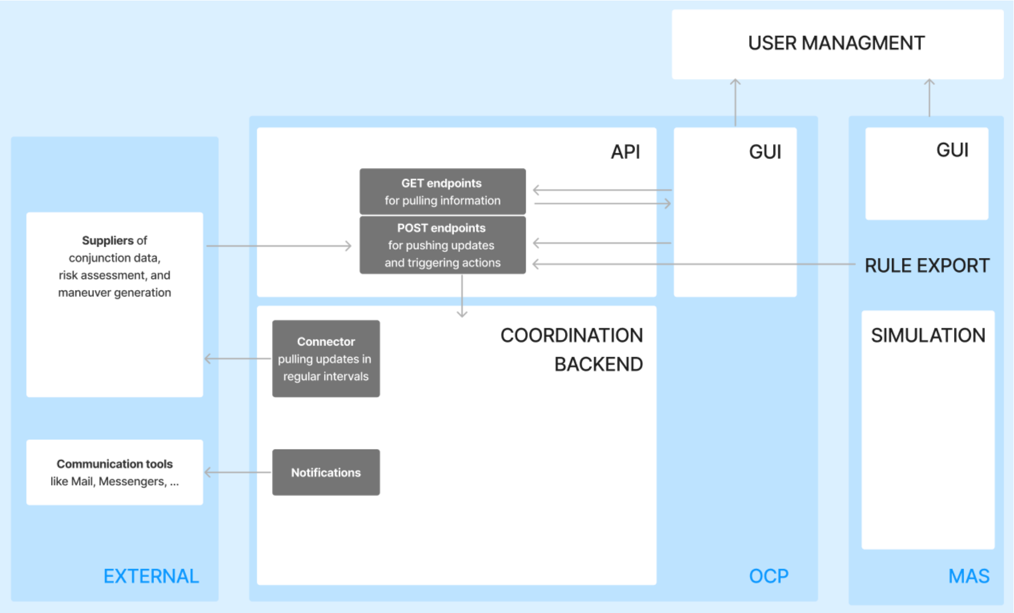

Figure 6. The two software components and their interfaces.

5. Demonstration Cases

To this point, CASCADE exists as a concept that is in the stage of being tested and validated with stakeholders, specifically satellite and constellation operators. For these, three demonstration cases have been designed to guide potential users through the CASCADE system, explain its benefits, and collect feedback and reactions.

1. Scenario 1: Manoeuvre case

Operator A and Operator B are both CASCADE users. The story is told from the view of Operator A. Critical case where operator A needs to execute a CAM before the TCA.

Days to TCA	Update
3	Operator A receives critical CDM. Critical means: The PoC is clearly above 1.e-4. A coordination case is created. An assignment protocol exists between Operators A and B. Event is assigned to A by protocol. Operator A logs in to CASCADE, to check the conjunction partner. Sees that they are already part of CASCADE, thus this case is handled completely internally.
2.5	Operator A accepts the assignment of the event after checking viability.
2.2	Operator B acknowledges the assignment to A
daily	Operators A and B upload ephemeris. The event remains critical.
2	Operator A proposes a CAM. Screening is successful. SW Waits for CAM uplink confirmation
1	SW confirms CAM is still valid and good to go. Operator A confirms the CAM to be executed 3 h before TCA.
0.2	Operator A reports that CAM is executed as expected according to telemetry.
+0.5	Both satellites are ok. Event concludes. Report is generated.

2. Scenario 2: Nominal case

Operator A and Operator B are both CASCADE users. The story is told from the view of Operator A. Nominal case where operator A does not do much and no CAM is executed

Days to TCA	Update
4	Operator A receives critical CDM. Critical means: The PoC is clearly above 1.e-4. A coordination case is created. An assignment protocol does not exist between Operator A and B. Assignment is asked openly to both users. Operator A logs in to CASCADE, to check the conjunction partner. Sees that they are already part of CASCADE, thus this case is handled completely internally.
3.5	Operator B accepts the assignment of the event
daily	Operators A and B upload ephemeris. The event remains critical. Operator B prepares manoeuvre
2	A new ephemeris update from Operator A shows that the event is no longer critical. CAM is not needed. Operator B cancels CAM execution
0	All new updates remain non-critical. The event is concluded with non-critical risk
+0.5	Operator B proposes an assignment rule for all events with Operator A. In this protocol Operator B always manoeuvres.
+0.9	Operator A accepts the assignment protocol and thanks Operator B

3. Scenario 3: Guest case with negotiation

Operator A is a CASCADE user, but operator B is not. The story is told from the view of Operator B. Event is mitigated after agreeing on some common thresholds and updating ephemeris 3 days before TCA.

Days to TCA	Update
5	Operator A receives critical CDM. PoC=1.3e-5. A coordination case is created. An assignment protocol does not exist between Operator A and B. Assignment is asked openly by both users. An invitation link is sent to Operator B. Operator B logs into CASCADE following the invitation link. Sees that they are not part of the platform but registering information is available. Operator A information is also available, as well as help and documentation. Operator B registers.
4.5	Operator B account gets accepted. They are now CASCADE users! Operator B accepts the assignment of the event after checking viability. Operator B requests a change to the risk threshold for critical from 1.0e-5 to 2.0e-5. Operator B also updates the HBR and the ephemeris of the satellite.
4	Operator A reviews Operator B requests. Accepts them and uploads new ephemeris. PoC is reduced to 1.1e-5. The event is no longer critical. No further action is required, but the system recommends to keep uploading new data (ephemeris)
daily	Operators A and B upload ephemeris. The event risk is reduced to non-critical.
0	All new updates remain non-critical. The event is concluded with non-critical risk

6. Summary and outlook

The idea to use the concept of rule-based coordination in STM has been around for some time now, but until now mostly discussed in theory. The importance of being able to simply coordinate conjunctions (and trajectories) in general is currently in the rise already, which is why the CASCADE initiative was started, to communicate to and test this approach directly with satellite operators.

For this, a concept has been derived, how rule-based coordination could work during actual operations, where the clear focus is on providing the satellite operators with tools to enable this task as simple and transparent as possible, without imposing or enforcing any pre-determined behaviour. This concept is currently being tested with satellite operators and will be further iterated and refined based on their feedback. From there, a Minimum Viable Product (MVP) version of an actual software to support collision avoidance operations will be developed and made available to interested satellite operators.

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The opinions expressed in this publication are those of the authors. They do not purport to reflect the opinions or views of ESA or its members.

References

[1] ESA Space Debris Office, ESA's Annual Space Environment Report, GEN-DB-LOG-00288-OPS-SD, 22. April 2022

[2] www.space-track.org, data retrieved from Space-Track Tempo on 27.01.2023

[3] B. Bastida Virgili, J.C. Dolado, H.G. Lewis, J. Radtke, H. Krag, B. Revelin, C. Cazaux, C. Colombo, R. Crowther, M. Metz, Risk to space sustainability from large constellations of satellites, Acta Astronautica, Volume 126, 2016, Pages 154-162, ISSN 0094-5765, https://doi.org/10.1016/j.actaastro.2016.03.034.

[4] D'Ambrosio, Andrea & Servadio, Simone & Siew, Peng Mun & Jang, Daniel & Lifson, Miles & Linares, Richard. (2022). ANALYSIS OF THE LEO ORBITAL CAPACITY VIA PROBABILISTIC EVOLUTIONARY MODEL.

[5] A New Chinese Broadband Satellite Constellation (circleid.com), last accessed 27.01.2023.

[6] French Space Operations Act n°2008-518 of 3rd June 2008 and Decree on Technical Regulation issued pursuant to Act n°2008-518 of 3rd June 2008, 31

[7] ISO 24113:2019

[8] SpaceX Orbital Debris Meeting Ex Parte (8-10-21).pdf, last accessed 27.01.2023.

[9] Nonreimbursable Space Act Agreement Between The National Aeronautics and Space Administration And Space Exploration Technologies Corp For Flight Safety Coordination With Nasa Assets. January 2021. Accessible via: nasa-spacex_starlink_agreement_final.pdf, last accessed 27.01.2023.

[10] Hjalte Osborn Frandsen, Looking for the Rules-of-the-Road of Outer Space: A search for basic traffic rules in treaties, guidelines and standards, Journal of Space Safety Engineering, Volume 9, Issue 2, 2022, Pages 231-238, ISSN 2468-8967, https://doi.org/10.1016/j.jsse.2022.02.002.

[11] Michel, Martin; Bertrand, Reinhold; Merz, Klaus; Flohrer, Tim (2021): Assessment of rule-based operations of manoeuvers avoiding collisions between active spacecraft. In: IAC 2021 congress proceedings: 72nd International Astronautical Congress (IAC), Dubai, United Arab Emirates, 25-29 October 2021, Paris, International Astronautical Federation (IAF)

[12] Michel, Martin; Bertrand, Reinhold (2021): Assessment of Inter-Operator Rule-Based Collision Avoidance Operations. Darmstadt, ESA Space Debris Office, 8th European Conference on Space Debris, Virtual, 20–23 April 2021.