STATE OF THE ART AND FUTURE NEEDS IN CONJUNCTION ANALYSIS METHODS, PROCESSES AND SOFTWARE

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ABSTRACT

In order to accurately characterise the state of the art in Conjunction Analysis (CA) methods, processes and software Deimos UK conducted first a literature review and then a survey of stakeholders in the community within the Collision Assessment Processes and Software (CAPROS) project for UK Space Agency, in first quarter of 2020. These stakeholders fell into 3 categories; Satellite Operators, SSA/SST Providers and Developers of Methods and Tools. The survey addressed questions on current processes, methodologies, communication protocols and best practices, and also the expected future needs for CA activities. The survey was carried out via an online questionnaire and follow up interviews. The results of both the literature review and the survey will be discussed in detail herein.

1 INTRODUCTION

An ever-increasing demand for satellite services has led to an increase in the number of objects being launched into Earth orbit. This increase, along with events such as on-orbit collisions and break-ups has led to a large number of objects in orbit. It is estimated that there are more than 24,000 trackable objects greater than 10cm in size in orbit, along with many hundreds of thousands, perhaps millions, of untrackable debris pieces. This large population of space objects poses a real danger to the active satellites in orbit. In order to keep the active satellites safe, it is necessary to model the population and predict any potential collisions such that active satellites can be moved to avoid the danger.

Conjunction analysis, collision avoidance, collision assessment, all amount to essentially the same thing: figuring out when and where collisions might occur in space and analyse the probability and outcome of such a collision. In this study the broad range of activities carried out are studied to complete this analysis. The results of a series of surveys carried out to learn the extent to which these practices are already in place and how they might evolve are also presented.

Collision avoidance procedures typically have four stages:

1. Initial automated screening for potential collisions
2. Manual or automated risk assessment of identified collisions
3. Refinement of the risk assessment with updated orbital data
4. Collision avoidance action

In some cases, it will be discovered in step 2 or 3 that the later steps are not required as the initial screening produced a false positive alert, i.e., a potential collision was identified in the screening, however, once the risk assessment was refined it was deemed a non-event and therefore not requiring an avoidance action.

2 CONJUNCTION ANALYSIS METHODS

Conjunction Analysis (CA) methods include several steps from object filtering to identifying eventual conjunctions (on the basis of Owner/Operator (O/O) ephemeris, or SST catalogues), positions and covariances to be propagated to the time of closest approach (TCA), computation of collision probability, identification of high interest events (HIE) whose risk exceeds user-defined thresholds, computing optimum collision avoidance manoeuvres, and evaluating the impact of the satellite manoeuvres. All of these aspects will be analysed in the following sections.

2.1 Identification of Conjunction

Conjunction identification is normally based on a catalogue of the current population of space objects, the object of interest's future ephemerides are compared to those of objects in the catalogue. When every object is compared to every other object in the catalogue, it is typically called an all-on-all analysis. This type of analysis is computationally expensive and mostly unnecessary, but has been demonstrated in [1, 2, 3]. In order to reduce the computational load an all-on-all analysis is not usually completed, instead the catalogue is filtered to discard objects that cannot lead to collisions. For example, if the object of interest is in a low Earth orbit (LEO) then objects that never enter the LEO region (i.e., Geosynchronous Earth Orbit (GEO) objects) are discarded. The most common filtering techniques include those proposed by Klinkrad [4] and Sánchez-Ortiz [5]. Three common filters are depicted in Figure 1. They are as follows (from left to right in Figure 1):

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- The apogee-perigee filter: filters based on orbit altitudes; the orbits never intersect because the apogee of the lower orbit is not high enough to reach the perigee of the higher orbit.
- The radial distance filter: filters based on the radius of the objects orbit on the line of intersection between the two orbits.
- The phase filter: filters for when orbits may overlap but objects are not at risk because they do not pass through the orbit crossing point at the same time.

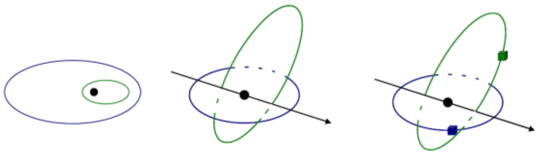

Figure 1. Typical filters in the conjunction event search (perigee-apogee, radial distance and phase filter)

This step is typically done autonomously. These filtering steps shall account for the uncertainties associated to the orbital information.

In order to filter, a catalogue of objects is first required. The only publicly available catalogue of orbit ephemerides is the two-line element (TLE) catalogue (available at space-track.org), based on mean orbital elements, according to Simplified Perturbation model (SGP4/SDP4) theory. The TLE catalogue is produced by the United States Space Command. It currently includes objects larger than ~10cm in LEO, and ~1m in GEO, approximately 20000 objects; though it’s estimated that there are thousands, possibly millions, of objects that are not currently trackable. The name TLE comes from the format of the data; two lines of data are given for each object, each with 60 characters, including the object ID, epoch, and orbit information. The orbit information is updated daily, but the TLE does not provide accuracy of the orbit. The TLE also does not include some vital information on the object for example mass, dimensions or materials. However, it does contain a term, B*, that includes this information and some propagators do not require them as separate inputs.

If required, mass and dimension information can be obtained in a number of ways; directly from the O/O, from interested third parties, from other catalogues such as ESA’s DISCOS (Database and Information System Characterising Objects in Space) [6]. DISCOS is the most complete database in Europe, containing information such as object mass, dimensions, cross-sectional areas, launching state and more. It is not made publicly available but access can be requested from ESA (at: discosweb.esoc.esa.int).

Once all of the required information has been obtained for an object the next step is to propagate its current position from the TLE catalogue forward to calculate its future ephemerides and those of the other catalogue objects and find if any possible conjunctions.

A Special Perturbations (SP) catalogue is also available to particular users from the Space-Track website under dedicated agreements. This catalogue contains the most accurate orbital information of space objects maintained by the 18th Space Control Squadron (18SCS). Unlike the TLE catalogue, it is a set of ephemerides (typically valid for a 3-day interval), which can be interpolated to get the actual position and velocity at any time within the interval. The reference frame of the data is the same as that of the TLE (True Equator Mean Equinox, TEME). One file per object is provided.

In spite of the improved accuracy of SP data with respect to TLE information, several limitations are found with this source of data. First, the lack of orbital uncertainty information (as is also the case with TLE). SP data does not contain covariance information associated to the orbital data. The second limitation is the duration over which the ephemerides are valid. As the search for eventual conjunctions is normally done for longer intervals than the 3-day validity of SP data, the SP, when available, may not be completely suitable for improving the conjunction avoidance processes. As the SP are intended for interpolation, the data does not include relevant parameters for propagation to extend the time interval where orbital states can be obtained.

In order to solve this situation, some users and providers of Conjunction Avoidance systems generate extended state vector information of each object, by fitting the ephemerides data set of each object (as provided by the Space-Track website) to obtain the state vector (position and velocity) together with perturbations parameters (Ballistic coefficient for example), that allow the propagation of the object state at longer intervals. This fitting process also provides the covariance associated to the orbital state vectors.

2.2 Propagation of Ephemeris

In order to identify conjunctions, the state vectors of objects with the potential to collide are propagated into the future to determine if the orbits of the objects ever intersect. This step is typically done autonomously.

There are many methods available to propagate the orbit of a space object. They are general grouped into three categories; numerical, analytical and semi-analytical. Typically, numerical propagators produce the most reliable results, however they are also the most computationally expensive.

Numerical propagators are the simplest in design, all numerical propagators work on the principal of adding perturbing forces to an unperturbed model. Each perturbing force creates an acceleration, which are summed and integrated to find the velocity and position of an object at the future time. The advantage of a numerical solution is its simplicity; allowing a user to capture all conceivable forces, thus producing an accurate result. However, this approach is also computationally expensive by nature.

Until modern computers became available numerical solutions were impractical and so many analytical theories were developed. Analytical propagators come in many shapes and sizes, there is no single equation we use for every solution. The results depend entirely on the formulation of the solution, but all involve some form of averaging or simplifying of the problem to provide a simple version of the equations of motion. Most analytical solutions rely on series expansions, introducing a practical difficulty; an infinite series cannot be solved for, and series truncation introducing an additional error source. While analytical solutions offer an advantage over numerical, their speed, it has widely been accepted that they are unable to produce accurate results.

Semi-Analytical solutions aim to capture the benefit of both numerical and analytical solutions, offering a trade-off between speed and accuracy. They can capture time-dependant perturbations that analytical solutions cannot but retain some of the computational efficiency of a purely analytical solution.

If TLE information is used, a dedicated method (such as SGP4, SDP4, SGP8, or SDP8) which is appropriate for propagating mean orbit elements must be selected; two options are the methods proposed by Hoots [7] and Vallado [8]. SGP referring to the Simplified General Perturbations Propagator, and SDP referring to the Simplified Deep Space Perturbations Propagator. SGP is used for orbits with periods of up to 225 minutes (approximately 5878km altitude), beyond that SDP is used. The development of the SGP series began in the 60s, but because it is still useful for TLE propagation today, it is still occasionally updated.

All propagators face a range of issues, the largest among them are typically input errors. Input errors arise from many issues, from atmospheric modelling to SRP modelling, and errors in area and mass information. Much of the data fed into propagators is estimated rather than measured directly and therefore is subject to potentially large errors. Take for example a piece of space debris in low Earth orbit. The mass and dimensions are estimated from radar measurements, then the atmospheric conditions are estimated from index of solar and geomagnetic activity. The estimation of some of these parameters can sometimes be very accurate leading to a good propagation result but can also be very poor leading to a wildly inaccurate result. There is still a significant amount of fundamental research to be done in this field to address these issues.

Another source of error that propagators face is from improper use; the timestep and setup must be carefully considered for the problem faced. If timesteps are too large or if too few perturbations are captured then the propagation will return poor results. In most cases this can be avoided by validating the propagator prior to use using historical data for well-known objects with well-known orbits.

It is also worth noting that not all ephemeris used in the CA processes require propagation at the user level. SP catalogue data, shared by 18SCS, or CCSDS OEM format do require interpolation methods, instead of propagation modules. These ephemeris types are providing orbital information along a period of time (typically 3 days for the SP case) which allows the computation of the full state vector at any time within the interval without the need of propagating (and thus, without additional information on the perturbation forces coefficients). These types of ephemeris require in any case a propagation model to be used for its generation, but not the final user or the CA analyst. These ephemerides (for interpolation) may be accompanied by Covariance data (which will be also used through interpolation technique), while not all of them incorporate this uncertainty information (for example SP data). There is no significant limitation on interpolation methods nowadays.

2.3 Computing and Propagating Covariance

Covariance provides the mathematical representation of uncertainty of the objects estimated state vector. It is normally provided by the ephemeris provider (as it comes from the orbit determination process). Sometimes this information is not exchanged (with TLE for example). In those cases, it can be assessed by fitting techniques of historical ephemeris, comparison to ground-truth data or using look-up tables for different orbit types published in literature. The covariance matrix for a satellite position takes the form of a 3x3 matrix,

$$Covariance = \begin{bmatrix} C(R,R) & C(T,R) & C(N,R) \\ C(T,R) & C(T,T) & C(N,T) \\ C(N,R) & C(N,T) & C(N,N) \end{bmatrix}$$

where the diagonal elements represent the variance in each component [R,T,N] and the off-diagonal gives covariance between each pair of components, the product of the two components' standard deviations and their coefficient. The reference frame for an object's covariance matrix is the object's RTN frame. The RTN components being, radial (R), tangential (T) and normal (N). This matrix is calculated using the formula,

$$Covariance = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{n-1}$$

where x and y denote one of the RTN components each. The diagonal variance components of the covariance matrix can be used to define an uncertainty ellipsoid around an object (i.e., the object may be anywhere within the ellipsoid).

As the accuracy of a propagated orbit state degrades over time (the further into the future a state is propagated the worse the accuracy), the covariance matrix itself must be propagated to keep track of the uncertainties. The covariance can be propagated by means of a Monte-Carlo analysis or more directly using numerical or analytical methods much as the position of the object is propagated.

Covariance can be propagated using the state transition matrix (STM),

$$Covariance(t) = STM \cdot Covariance(t_0) \cdot STM^T.$$

The state transition matrix is formed of the partial derivatives of the state vector (position and velocity vectors combined in a 6x1 matrix) with respect to the initial state vector. Typically, these partial derivatives are computed numerically. Note that if the state vector is used the 6x6 state vector covariance matrix must also be used not just the position covariance as shown above.

Covariance can also be propagated analytically by linearizing the problem. The Clohessy-Wiltshire equations [9] can be used to linearize the equation of motion and hence provide a transition matrix. This transition matrix can then be used to propagate the covariance. As with any analytical solution, this method has its limitations. Assumptions are made in the linearization of the problem which introduce error. However, over small step sizes can be used to limit the error.

2.4 Computing Collision Risk

Once a conjunction is identified, operators have two options for evaluating the event; exclusion volume or Probability of Collision (PoC).

The exclusion volume approach involves defining a region in space around the object of interest, and if another object enters this region then an avoidance manoeuvre is recommended. This method does not allow for risk evaluation and can end up having conservatively large exclusions regions defined to deal with orbital uncertainties of both objects; ultimately leading to unnecessarily large numbers of manoeuvres. Exclusion volumes are generally used more in the screening step, before the conjunction event is studied in more detail.

The probability of collision approach involves defining an Accepted Collision Probability Level (ACPL) for a mission then only manoeuvring when this threshold is exceeded. There are a multitude of options for computing PoC, most focus on high relative velocity collisions and simple orbit geometries. Many CA service providers consider the Alfriend & Akella (A&A) algorithm [10, 11] which is based on several assumptions that allow determining collision potential by means of a double integral computation in the so-called b-plane (2D evaluation), as seen in Figure 2. The uncertainties of the two orbits are translated into the uncertainty of the miss distance. The probability associated to the miss-distance is integrated over the area projected by the collision volume (A_c) of the two objects to compute the risk of collision. In the case of a well understood orbit (blue line), the integration of the function over the area is almost null leading to a null risk. However, the density function for a worse-known orbit (red line) will produce a much larger risk.

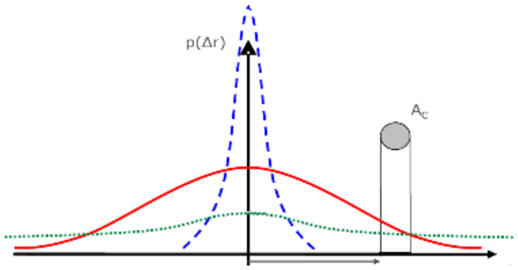

Figure 2. Representation of the Probability function of the miss -distance and integration area. Credits. H. Krag

Other authors also consider similar assumptions [12-20] for other numerical and analytical solutions. Low relative velocity encounters cannot make use of those assumptions, for which methods proposed by Sánchez-Ortiz, Chan and Patera can be used. For cases where the uncertainties of the orbits are very good and/or the geometry of the objects is very elongated, the assumptions of spherical objects is also not applicable. Several authors provide formulations for this case including DEIMOS' Sánchez-Ortiz's algorithms (published in PhD thesis [21]) as implemented in the ESA operational CA software. Other references on this topic include [22-28].

All these methods require the knowledge of covariance matrix, which is not always possible, thus some authors compute the eventual maximum PoC for an event (independent of the covariance). Typically, this is done by scaling estimated covariances but it is also possible using an analytical formula.

Another way to calculate the PoC is known as scaled covariance PoC, varying the covariance by means of a sensitive analysis. This method is able to take into account the variation of the uncertainty as the event is approaching. This technique was developed by CNES, and it is gaining popularity as it tends to alleviate the problem of lack of realism of the covariances. It lacks, however a standardised way to compute the scaling factors. The scaling factors are selected according to the observed variability of the covariances in historical data of past events. This empirical approach allows evaluation of a maximum risk over a reasonable range of covariance sizes.

In addition to the analytical or semi-analytical methods already mentioned, the conjunction can be simulated by a Monte Carlo approach which is valid for both low and high relative velocity encounters, spherical and complex geometries, but it is much slower than other methods. The lower the collision risk, the larger the number of Monte Carlo runs required for confidence in the solution. This method is usually used for validation purposes or for avoiding the propagation of the covariance matrix.

Finally, there is also a trend to apply Artificial Intelligence and Machine Learning techniques to the PoC computation task in view of the future evolution of population in space.

In some cases, the user or O/O may choose to set thresholds for both PoC and exclusion volume to assure they have no false negatives, ruling out event they shouldn't.

2.5 Identification of High Interest Events

High Interest Events are defined based on the requirements of each user or O/O, but are based on the time to closest approach, the PoC and distances in the local reference frame (along-track, cross-track and radial miss distances). Typical values for these parameters are: Time to TCA ≈ 3 days, PoC € [1^{-4}, 1^{-6}], RAC ≈ [0.5; 10; 10] km. The identification of proper values for those parameters can be done through standardised processes such as proposed in ESA's Debris Risk Assessment and Mitigation Analysis (DRAMA) Assessment of Risk Event Statistics (ARES) tool developed by Deimos. However, some entities set standard values for these. ESA set a threshold of PoC>10^{-4} for HIEs., as does DLR and CSA, while JAXA uses a threshold of 10^{-3} for PoC and a minimum miss distance of 1km [29]. NASA and CNES take a tiered approach, classing events into several different categories using multiple threshold values. For example, NASA classes events using red, yellow and green; any event with a PoC of greater than $4.4 \cdot 10^{-4}$ are red events, those with PoC of less than 10^{-7} are green events and those between these thresholds are yellow events. Green events are only investigated further if both objects are active spacecraft, to check that any planned manoeuvres do not affect to conjunction evolution. Yellow events are monitored and red events are actively investigated by a team of analysts.

High interest events identified are then typically analysed more closely, new data might be commissioned (via sensor tasking etc.), and if the thresholds are still exceeded then manoeuvres are recommended. This is typically the first step in conjunction analysis that required manual input. With the potential increase in catalogue populations due to more objects being launched and improvement in tracking technologies it is possible that this step will need to become autonomous in the future.

2.6 Improving Orbits (Measurements)

When a HIE is identified, the O/O or the SST system may trigger more observations of the involved objects in order to refine the state vector estimation and improve covariance so the event geometry, and its PoC is better assessed. Additionally, some work has been done on refining the published data, to improve its quality [5].

There are limitations to obtaining new observations. Sensor limitations or outages, along with visibility problems and higher priority observations, all mean that sometimes it is not possible to reacquire an object when necessary for refining CA. Errors in sensor calibration or pointing can mean that even if new observations are acquired, they are too poor quality and cannot be used in the refinement process.

Orbit Determination (OD) processes are intended to estimate an orbit, dynamic parameters, observation biases and manoeuvres out of a set of observations of the objects. Typical orbit determination methods are based on Batch least square or sequential filters like the Square Root Information Filter (SRIF), this latter one can be used in batch mode, or in a track-per-track basis.

The mathematical approach of the OD problem is based on an initial state vector estimation and, generally, the corresponding knowledge covariance matrix are required.

The first estimation of the state vector is the result of the Initial Orbit Determination (IOD) computation (not described here as they are not directly applicable for the conjunction analysis orbital updates), or by an initial orbit obtained by third party data. By using the same IOD algorithms, and by means of numerical derivatives, a first approximation of the knowledge covariance matrix can be also computed.

There are two more requirements for starting the estimation process. On one hand, the real model of motion is not completely known, mainly in regards to the Atmospheric contribution (Drag) and the Solar Radiation Pressure perturbations. There is an unknown noise in both contributions that must be estimated together with the orbital state information (so called extended state vector). Therefore, these unknowns are included as a dynamical variable of the numerical filter. Additionally, other parameters if observable through the object dynamics (for example manoeuvres) or through the sensor data (observation biases), can also be estimated.

The orbit determination process typically provides not only the estimated parameters, but also the mean and deviation of residuals of the processed measurements, the number of accepted and rejected observations.

2.7 Computing Avoidance Manoeuvres

When PoC or exclusion volume criteria exceeds user-defined threshold, several actions can be taken by the primary satellite O/O. The decision to manoeuvre may consider the operational constraints for the satellite together with the event risk. These actions can include change in orbital state, modification of attitude (to minimise cross-section in the encounter), etc. In all cases, post manoeuvre CA analysis should be done. A manoeuvre is only helpful if the spacecraft is moved on to a safer trajectory with a lower PoC.

The planning of the manoeuvre involves:

- Determining the time and Delta-V of the manoeuvre.
- Selecting the previous values so that they comply with operational or functional constraints imposed by the satellite hardware, ground segment and operational procedures.
- Minimization of the fuel expenditure while achieving the objective of the manoeuvre (reduce the risk of the encounter).
- Verifying that the planned manoeuvre does not result in a new close approach event with a different object.

The simplest case is a collision avoidance manoeuvre that is planned independently from any other considerations. In this case, optimisation is carried out by selecting a manoeuvre that achieves a pre-selected risk reduction with minimum fuel expenditure.

Even though the number of potential collision avoidance manoeuvres that could be performed is extremely large, the manoeuvres can be chosen from typical approaches (along-track, cross-track). These approaches make optimisation easier to implement and faster to execute, as they effectively reduce the space of possible solutions. However, it is often the case that the computation of the manoeuvre is coupled with different considerations.

- If the satellite has tight requirements regarding its orbit, new factors need to be taken into consideration, such as the time outside the nominal orbit (which can involve an interruption of a service, and should be minimised).
- If there is a planned station-keeping manoeuvre around the date of the conjunction, it could be considered to perform a modified station-keeping manoeuvre that fulfils both objectives of station-keeping and avoidance.
- Even if there was no planned station-keeping manoeuvre, the operator could perform a combined station-keeping / avoidance manoeuvre.
- The optimal manoeuvre is not recommended as it would pose additional threats to the satellite as the post-manoeuvre orbit may result in additional close encounters with other objects.

In these cases, an optimal solution is no longer achieved by just minimising the fuel expenditure. In many cases, this is often done with no optimisation (i.e., by choosing a “good enough” manoeuvre).

As a general summary of the literature review the found references provide a good understanding of the conjunction avoidance manoeuvre optimization problem, especially in the following aspects:

- Formation flying (including GEO collocation)
- Simplified methods for fast manoeuvre optimisation
- Parametric/analytical solutions for specific manoeuvre directions

A relevant aspect of the conjunction avoidance manoeuvring analysis is related to the constraints to be applied to the optimisation problem of computing the most optimum manoeuvre. Constraints might be imposed on the trajectory geometry, but also on the manoeuvre parameters (execution time and direction), and on the conjunction (which is, in any case, the objective of the mitigation manoeuvres). In the optimisation problem the control variables are the parameters defining the manoeuvres (time and 3-D vector), which might be restricted due to operational timeline or attitude constraints. In addition, other constraints can be applied to the manoeuvre directions resulting from the effect on the orbit. For example, only tangential manoeuvres might be desired (resulting in a manoeuvre parallel to the velocity vector), or manoeuvres not changing the orbital period (which results in manoeuvres perpendicular to the velocity vector). It must be remarked that, in order to reduce the required time for computing the solutions during optimisation, it is preferable to reduce the number of free variables with a correct parameterisation.

Some “operational trajectory constraints” may be imposed on the trajectory. These trajectory constraints are fulfilled during normal SC operations, while their fulfilment during the collision avoidance operations depends on the mission. For example, GEO satellites must always be within their assigned longitude slot (to keep own and neighbouring satellites safe), while for some Earth-observing LEOs the respective constraints might be less safety-critical (but, in any case, may be required in the optimisation problem).

The need to fulfil the trajectory constraints requires propagating the orbit forward up to the point/s where the constraint/s need to be evaluated in the optimisation process. However, it may require the inclusion of additional manoeuvres in order to have controllability of the constraint fulfilment. The resulting problem depends strongly on the mission.

2.8 Communication Approaches

The most commonly used SSA provider, previously JSpOC, now 18th Space Control Squadron (18SCS) uses a very particular type of communication protocol. They communicate using standard format message warnings for upcoming conjunctions. This makes it easy for operators to autonomously receive and digest the content. Conjunction Messages, either Conjunction Data

Messages (CDMs) or Conjunction Summary Messages (CSMs) are provided by 18SCS. Before 18SCS took over SST operations in July 2016, JSpOC transitioned from providing CSMs to CDMs as the messages were standardised to allow greater interoperability and automation, nonetheless the information included in the messages largely didn't change.

Conjunction messages are strictly advisory only and don't provide avoidance actions. They are typically provided within 72 hours of the TCA. The criterion for LEO events is an overall miss distance of 1km with a radial miss distance lower than 200m; and for GEO an overall miss distance of 10km. Each message contains the object ID for each collider, the TCA and some orbital characteristics for both objects, such as position and velocity [30].

TLE information generated by 18SCS can also be accessed via an API built into the Space-Track website, which is a public website owned by the US Strategic Command (USSTRATCOM), managed by the Joint Force Space Component Command (JFSCC) and populated by 18SCS. The Space-Track website gives free access to historical and current TLE, allowing users to search the catalogue and download data. Being freely and publicly available, this website has become a primary data source for the space industry.

Other providers use Secure File Transfer Protocol (SFTP) and email to exchange data, for example tools like CRASS (Collision Risk Assessment Software) and SCARF (Spacecraft Conjunction Assessment and Risk Frontend) can produce automated warning reports and services such as CAESAR (Conjunction Analysis and Evaluation Service, Alerts and Recommendations) and CARA (Conjunction Assessment and Risk Analysis) provide summary reports via email to user specified addresses.

In the frame of EUSST, Conjunction data is provided through the EUSST web portal, but additional direct contact in between users (satellite operators) and NOCs (National Operations Centres) are considered when needed. This information exchange is done through email or by telephone for particular cases.

It is also worth mentioning the case of last conjunction warning event between ESA's AEOLUS satellite and a SpaceX Starlink satellite. This event, one of the few cases where both objects involved in a conjunction case are operational, draws attention to the lack of a clear communication between the different stakeholders for such events. In this case, ESA operators considered the event as a high risk one, requiring the execution of an avoidance manoeuvre. In order to coordinate with the operators of the chaser, contact with Starlink flight dynamics team was initiated. The coordination was not achieved as the first contact through email apparently never reached the relevant team. This case highlights the need of a clearer protocol and communication channel, not only among SST providers and operators, but among the different operators themselves.

2.9 Available Conjunction Analysis Tools and Services

The following list contains a summary of the various tools and methods available for use in SSA, SST and CA.

- **18SCS** (USSTRATCOM) - Primary data source for CA services, tools and methods.
- **MASTER** (ESA) - MASTERs primary purpose is to describe the debris environment in Earth orbit.
- **DRAMA** (ESA) - To enable users to assess debris mitigation standard compliance.
- **DISCOS** (ESA) - DISCOS is a database containing physical object properties for the space population, such as mass, materials etc. along with launch dates, registration information and much more.
- **CRASS** (ESA) - CRASS can be used to predict conjunctions and the associated collision risk.
- **ODIN** (ESA) - is useful in improving knowledge of objects involve in high-risk conjunctions.
- **CORAM** (ESA) - contains refined algorithms for computing collision risks and can compute the most appropriate avoidance manoeuvres.
- **SCARF** (ESA) - SCARF is a front-end service providing a concise, user friendly interface allowing users to easily understand potential conjunction events.
- **CAESAR** (CNES) - Screens for conjunctions using O/O provided ephemeris, via an internally held space object catalogue and via CDMs provided by JSpOC. Identifies HIE based on criteria agreed with O/O. Supports decision making process for conjunction mitigation strategies.
- **ORDEM** (NASA) - ORDEM is NASAs tool akin to MASTER, it describes the debris environment.
- **CARA** (NASA) - Equivalent to French CAESAR service, and working closely with the CAESAR team. Analyses JSpOC close approach predictions from CDMs and O/O ephemerides to calculate the probability of collision. Refines the conjunction assessment providing geometry and covariance analysis. Supports collision avoidance manoeuvre planning. Acts as an intermediary, contacting chaser objects owners to facilitate data exchange. Provides a daily summary report of close approach data. In case high interest (typically high risk) events are identified, an email notification is sent to the customer.
- **CAM** (NASA) - Provides conjunction analysis, and tools for calculation of collision probability. Also provides a tool for analysis of historical trends and a collision avoidance manoeuvre planning tool.
- **STK** (AGI) - Software for simulation in general, it is a physics-based software package that can be used to

simulate almost any environment.

- **SOCRATES** (CSSI) - SOCRATES is a service that provides twice daily updates on upcoming conjunctions.
- **FocusSuite** (GMV) - Focussuite is a customisable COTS end-to-end tool kit for flight dynamics engineers.

3 STAKEHOLDERS SURVEY RESULTS ANALYSIS

Due to the broad community impacted by CA activities, retrieving information on CA processes and methodologies through interviews would have required a lot of time and require addressing people around the globe. Therefore, prior to any videoconference or in person interviews stakeholders were asked to fill out an online survey. These surveys addressed questions on processes, methodologies, communication protocols, current best-practises, recommendations, but also main drawbacks of current approaches and wishes or expected needs for the future of CA activities. Dedicated surveys were developed depending on the target responder; Satellite Operators, SSA/SST Providers and Developers of Methods and Tools. It was thought that these three groups would have very distinct needs and views on CA aspects. Each survey participant was also asked at the end of the survey if they would like a follow up interview. The following sections summarise the outcomes of the survey. Some graphics of this data are available in the corresponding presentation, however, for more details on these survey results please feel free to contact the authors.

3.1 Summary of the Operators survey results

There were 10 responses to the Operators survey.

In summary, all the operators providing feedback declared a well-defined procedure for conjunction avoidance activities within the operational tasks. The majority of responses came from operators with GEO spacecraft (70% of the responses), though operators with LEO spacecraft were also well represented (50% of the responses). Most of them use in-house tools or COTS tailored to their systems.

Although most of the operators use in-house or customized tools for CA activities, it seems that a tool endorsed by external entities in charge of SSA would be appreciated. The majority of operators prefer a government-based solution, only one respondent said they would prefer a commercial-based solution.

All the operators responded that the SSA provider they receive information from is 18SCS, and some from other systems, among them EUSST, and other commercial solutions.

In regards to conjunction avoidance algorithms, the most widely used are Alfriend & Akella, Maximum Collision Risk and the Scaled PoC algorithm (mostly those that have worked with FR-CNES system for a long time).

Operators who do not manoeuvre on the basis of PoC refer to the lack of reliability of covariance information as the cause to use miss-distance.

There is a trend to include in the future complex geometries and low-velocities algorithms for conjunction risk evaluation with considerable interest in Machine Learning-based technologies also.

There is a consensus on not receiving manoeuvring guidelines from the SSA providers, as there are a number of operational constraints which make it less optimum. All operators compute their own avoidance manoeuvres, mainly reporting lack of proper configuration or optimisation of manoeuvres recommended by SSA providers.

Regarding interfaces, operators seem to be happy both in the format and process, with a clear trend to use API approaches instead of emails.

No matter the orbital regime (GEO or LEO), all operators refer to less than 3 manoeuvres per satellite and year, with 60% saying less than 1. Operators are split 60%/40% saying there is/is not, respectively, a trend of increasing numbers of events.

A small majority, 55.5%, of operators say their CA process is mostly automatic with intermediate manual steps, with the other 44.4% saying their CA process is mostly manual supported by tools operated by an analyst.

Regarding the needs for improvement in the process, there is a large consensus on the interest on improvement of data quality and timeliness, there is also significant interest in improving cataloguing of space objects.

In regards to the concern about future population evolution, it is notable that there is no major concern in regards to the miniaturization of satellites. However, as expected, there is concern over the general increase in space population, large constellation deployment and deployment of satellites without manoeuvring capability.

3.2 Summary of the Providers survey results

There were 5 responses to the Providers survey.

Most providers (4 of 5 respondents) support services in the GEO and MEO regions, with 2 providers supporting LEO and 1 supporting the HEO region.

All providers (1 no response) answered that their activities are most autonomous with some steps reviewed by analysts, 2 of the 4 plan to move to a fully autonomous system, while the other 2 plan to keep an analyst in the loop.

All providers who responded currently provide or plan to provide autonomous warning of CA events (4 current, 1 future), geometric features of the events (5 current), collision probability (4 current, 1 future), and orbital information and accuracy at TCA (5 current). Only 2 of the 5 respondents say they currently provide manoeuvre recommendations, another 2 say they plan to provide this in the future.

Most also support SSA/SST activities beyond CA, including raw measurement provision (4 providers), space object cataloguing (4 providers), operational support (5 providers), launch support (4 providers) and space traffic management support (4 providers), among others.

All providers answered that they have their own in-house tools for screening and 2 responded that they also use commercial off-the-shelf tools. There was no consensus on the tools used though. Most methods rely on both exclusion volume and collision risk for decision making.

All providers answered that they use in-house information in their CA analysis, and 3 of the 5 providers also use external information.

Most providers provide (3) or plan to provide (1) recommendations on triggering manoeuvres, only 1 provider does not ever plan to provide recommendations on manoeuvres. Though most providers give guidance on triggering manoeuvres, only 1 currently provides a recommendation on the manoeuvre to be performed, another 3 providers plan to do so in the future. 4 responses (1 no response) suggest that they receive (3) or sometimes receive (1) the planned manoeuvre information, allowing them to check for new potential conjunctions.

All providers trigger observations for at least some conjunctions, 3 responded they only trigger observations for high risk events or for conjunctions with objects of interest, while 2 trigger observations for all events.

There is a range of data used in evaluating events on the operational satellite side, but most providers use external ephemeris and operation ephemeris from flight dynamics operations. On the chaser side there is no consensus on the data used, each provider uses a different type. On the contrary, there was a consensus on the propagator type used; all providers use numerical propagators to generate ephemeris.

All providers say they consider data from the 18SCS, and a few use other sources such as EUSST. There is a consensus among providers that the communication protocols are generally sufficient and are not a priority for improvement. Data quality is, however, a concern for improvement, with all providers agreeing that it is important (3) or very important (2). Typically, providers use email, and web-based services and APIs to share data.

Unlike the operators, the providers are not in agreement on the concerns for the future, only 2 providers are most concerned about the general increase of the space population, another 2 think it will have little impact. 3 providers are very concerned about large constellations, 1 thinks they will have little impact. 3 are concerned about the miniaturisation of satellites but again 1 thinks it will have little impact. Interestingly, it was always the same respondent who was unconcerned, that respondent was, however, concerned about large constellations.

3.3 Summary of the Developers survey results

There were 7 responses to the Developers survey.

Of the 7 respondents, 6 said they have already developed, 3 are currently developing, and 4 have plans to develop tools or methods for CA. Most (5 current) are involved in developing tools for cataloguing space objects. Most (5) also say they plan to support space traffic management, among other areas of SSA.

Among the areas of CA, tools for modelling orbital accuracy at TCA are the most common, with 5 responding that they had already developed tools for this use. Other common tools already developed are autonomous warnings for CA event (4), event features tools (4), collision probability tools (4) and tools for calculating orbit information at TCA (4). The most common tools under development are manoeuvre recommendation tools (3) and collision probability tools (3).

Funding sources for development are equally split with 3 answering to each, personal (personal research grants), company (internal funding by employer) and customer (customer requests and pays for specific developments) funding. Likewise, the orbital regimes for which tools are developed are well split, 4 for LEO, 5 for GEO, 4 for MEO and 3 for HEO.

Unlike the providers, developers have no clear partiality in propagator type; 5 have developed numerical propagators, 4 have developed semi-analytical propagators, 4 have developed analytical propagators and 3 have developed TLE propagators.

Unexpectedly, all developers have access to in-house data, all 7 use in-house data, with 5 also using external data sources for developing their tools.

As with the providers there is no consensus of the types of tools used to compute conjunctions, event features or collision risk.

Developers are split on recommendation of avoidance manoeuvres, 2 do not plan to provide these, 1 already does and 1 plans to provide these.

Developers are also split on the information used to develop tools for evaluating encounters on the target side, and on the chaser side with many different types of data used.

Most (4 of 5) developers receive data from 18SCS, and some receive data from a range of other sources including EUSST and ComSpOC.

As with both the operators and the providers, developers collectively feel improvement in the quality of SSA data is the most important priority for future advancement. Unlike the others timeliness of data is not a priority, this is to be expected as developers tend to rely more on historical data than current. Instead, their priorities are improvement in cataloguing and collision risk assessment.

Most (66.7%) answered that their tools are mostly automatic with some analyst input, while the remaining 33.3% answered that their tools are mostly manual. Interestingly, only 33.3% of developers plan to make their tools completely automatic, while 66.7% plan to keep their tools mostly automatic.

4 CONCLUSIONS AND RECOMMENDATIONS

Overall, CA services are functional, however it seems there is still a lot of room for improvement. The following subsections discuss the outcomes of the literature review and stakeholder survey and any recommendations for improvement for each step of the CA process.

4.1 Conjunction Identification

Conjunction identification takes place in three steps; first data on space objects' positions is acquired; next, that data is propagated to predict the future positions of objects; finally, those future positions are screening for potential conjunctions.

4.1.1 Data used in Screening

Status: Room for Improvement.

Recommendation: Investigate new data sources.

The whole CA process starts with data and one of the most prominent results of both the literature survey and the stakeholder survey is that there is a general dissatisfaction with the current SSA data quality and timeliness. All three groups surveyed (Method and tool developers, CA providers and Satellite Operators) agree that the most important priority for improvement is data quality. While developers are not concerned with data timeliness, operators and providers both rate it as one of the most important priorities for improvement. While timeliness is of great importance for those involved in the operational real time conjunction avoidance activities, it is not relevant for those working on the development tasks. It is clear that improvements need to be made in how data is gathered and processed in order to improve the quality of the data. Most of the survey participants say they get their data from 18SCS. This suggests that while 18SCS maintains the most complete catalogue, it is not of sufficient quality for today's market. It is therefore recommended that research is carried out to find alternative data sources of better quality and timeliness.

One of the major components of the data that needs to be improved is the covariance information. Currently, not all data sets include covariance, which is an essential part of identifying and characterising conjunctions. With large assumed covariances, larger numbers of conjunctions are predicted; if covariances could be provided and refined, the automated screening process could eliminate many more conjunctions freeing up resources to deal with the true conjunctions, and prevent many unnecessary avoidance manoeuvres. This is particularly relevant in light of the projected increase in space population; assuming that increase there will be significantly more conjunctions predicted and the analysis load will be great. Therefore, it will be more important than ever to have the screening process automated to remove all but the most certain of conjunctions.

4.1.2 Propagation of Ephemeris

Status: Room for Improvement.

Recommendation: Continue fundamental research.

It was also clear from both the literature and the stakeholder survey that there are still a lot of fundamental research questions in the field of conjunction analysis to be answered, as well as some underpinning problems in astrodynamics as a whole. In particular for propagating orbits; the atmospheric density modelling problem, this is the largest error contributor in orbit determination and propagation of low Earth orbiting space objects. Similarly, the case of propagation of covariance information shall also be addressed. Covariance realism at the time of orbit determination, and its propagation is one of the major limitations in current conjunction avoidance capabilities. Methods for orbit determination and propagation could generally be improved with better modelling techniques. However, much of the improvement in this area is hampered by the lack of good quality, freely available data for researchers. One suggestion which could solve this problem is that providers with high quality data make historical data (for example ephemerides from several months ago) available, this would be less sensitive and therefore should not be a problem to release to academics and method developers. Beyond satellite ephemerides, more detail is also needed on the space environment as a whole, there are a lot of unanswered research questions around atmospheric density and space weather effects; including around satellite-killing events such as Carrington-type solar events. These questions will not be answered in the short term, but it is important that fundamental research continues to be supported.

4.1.3 Screening for Conjunctions

Status: Good enough at present.

Recommendation: Monitor and reassess needs as space object population grows. Develop most run-time efficient approaches or define architectural solutions that can handle with a larger population catalogue.

Once the data has been acquired, and objects positions have been propagated the final step in conjunction identification is screening for potential collisions, assuming the data problem is resolved the current screening processes are adequate to find potential conjunctions. However, it should be noted that a large increase in the space object population is forecast, therefore in the future screening processes may need to be adapted to deal with larger volumes of data.

4.2 Evaluation of Identified Conjunction

Status: Room for Improvement.

Recommendation: Complete comprehensive review of techniques and tools and have governments endorse the best ones.

Once potential conjunctions have been identified the next step is evaluating them and from the surveys it is clear that operators, providers and developers are undecided still on the best metrics, methods and tools for evaluating conjunctions. There was no consensus in the stakeholder surveys on the best tools for computing conjunctions. There was also no consensus on the best method for computing event features. The majority of stakeholders also use multiple metrics to evaluate events, i.e., using both miss distance and risk. This all suggests that more research needs to be done in order to find the best methods, tools and metrics. It was clear in the survey that a tool endorsed by external entities would be appreciated, with the majority of operators saying they would prefer to have a government-based solution. A wide range of techniques are available in the literature; however, no studies were found containing a comprehensive review of each techniques' ability to capture and effectively model conjunctions.

It is therefore recommended that a program of research is undertaken to investigate further the available CA tools and techniques and provide guidance on or even an endorsed method for use across the sector. This endorsement would of course need to be kept up-to-date with any advancements made in the field.

4.3 Refinement of Risk Assessment

Status: Good enough at present.

Recommendation: Monitor and reassess as conjunction evaluation methods improve.

Refinement of the conjunction is an area of lesser concern. Generally, SST providers are responding to the need for refinement of conjunction data through further observations. This process is well defined and does not need alteration at present. However, it does suffer the same lack of direction as the initial risk assessment. So, it is recommended that as further research into the best methods for risk assessment and event characterisation is carried out this step is also reassessed. Most of the concern is related to the lack of realism of the covariance information, which may vary largely from one orbital update to another, forcing to use empirical approaches as the Scaled PoC algorithm.

4.4 Collision Avoidance Actions

There are two areas to consider when discussing collision avoidance procedures; first the communication between stakeholders; and secondly the avoidance manoeuvre planning.

4.4.1 Communication Protocols

Status: Room for Improvement.

Recommendation: Investigation into regulating communications.

Surprisingly, the communication protocols were not an area that stakeholders feel needs further investment. Most are satisfied with the current approach of emails and web-based services such as API for data sharing. However, if the space population grows as predicted, the average number of conjunctions predicted per day will also grow and these protocols may need to be re-evaluated and made more efficient.

There is, however, conflicting evidence in the literature, suggesting that communication protocols are not sufficient. The example of the ESA/SpaceX conjunction suggests that while current protocols may be sufficient in some cases it is not always so. This is not an easily solved problem; when operators are willing to cooperate, the current protocols are sufficient. Updating the protocols will not change this willingness to cooperate, therefore a more comprehensive strategy is needed. This would likely need to be a change in the law and regulations that operators must follow. One option might be that a designated point of contact should be established when applying for license to launch objects. With stipulations that this point of contact must be maintained for the whole of the objects life and that any communications received must be responded to. However, as has been seen with space debris regulations, it is difficult to get all parties to agree to a regulation that may hamper their activities, and implementing such a regulation in a single country would not be sufficient, it would need to be sector wide. It is therefore recommended that further investigation of possible changes to regulations be investigated by an experienced space lawyer with a good understanding of international politics.

4.4.2 Collision Avoidance Manoeuvre Planning

Status: Good enough at present.

Recommendation: Recommend checking proposed orbit for conjunctions prior to manoeuvring.

Collision avoidance manoeuvre planning is not an area of concern for stakeholders presently, each stakeholder will always have their own priorities when it comes to manoeuvre planning (i.e., minimum delta-v requirement, or coordinating with station keeping manoeuvres), therefore it is unlikely that a sector-wide approach will ever be necessary. The current tools and techniques for mission analysis are sufficiently advanced to provide for needs. There is, however, one change that would be helpful; parties manoeuvring to avoid conjunctions should be recommended to check their new orbital path for new potential conjunctions prior to manoeuvring. Currently, not all parties are completing this additional step. At present there is no way to enforce such a measure, but it could potentially form part of space traffic management regulations if such a thing is realised.

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