

JAC Software, Solving Conjunction Assessment Issues

François Laporte
CNES, France

Conjunction Messages (CM) provided by JSpOC are complete and valuable data to evaluate the level of risk of conjunctions, decide and choose avoidance actions. Nevertheless, conjunction assessment remains a difficult task which requires Middle Man between the CM provider (JSpOC) and Owner/Operators. CAESAR (Conjunction Analysis and Evaluation Service, Alerts and Recommendations) is the French Middle Man. CAESAR relies on a collaborative work environment between CAESAR team and its subscribers. For CAESAR, the collaborative work environment is based on JAC software and a dedicated secure webserver. JAC software is not the Main Flight Dynamics (FD) software used by CAESAR team, but it is a light friendly CM dedicated software to be used on laptops by on-call teams or support dialogue between Middle Man and FD teams.

This paper presents the main feedbacks from CAESAR team operational experience and how each new encountered issue has enriched JAC Software functions.

1. INTRODUCTION

Because of the ever-increasing amount of orbital debris, the possibility of a satellite collision with space debris or another satellite is becoming increasingly likely. This phenomenon concerns all orbit altitude regimes, particularly Low Earth Orbit (LEO) but also Geosynchronous Earth Orbit (GEO). Therefore Space Agencies, such as CNES, the French Space Agency, adopted operational collision risk monitoring. After the first collision of an operational satellite in February 2009, a major change occurred in USA: JSpOC started to predict close approaches for all the operational satellites and to send information messages describing close approach risks to operators worldwide. In July 2010, Conjunction Summary Messages (CSM) which are complete information to assess a collision alert, were made available for all by USSTRATCOM with a secured access on the Space Track website. In April 2014, JSpOC started transitioning from CSM to the standardized format CDM (Conjunction Data Message, defined by the Consultative Committee for Space Data Systems, CCSDS, as in [1]).

2. CONJUNCTION ASSESSMENT WITH CONJUNCTION MESSAGES

Conjunction Messages (CM), either CSMs or CDMs, are real satellite protection data provided by JSpOC for all active satellites. They are made available on Emergency Criteria which are Time of Closest Approach (TCA) within 72 hours combined with a miss distance criteria. For LEO the overall miss distance must be lower than 1km with radial miss distance lower than 200m, and for higher orbits (GEO and MEO) overall miss distance must be lower than 10km. CMs include: identification of the 2 objects, TCA, and for each object: position, velocity, dispersion and some orbit determination characteristics.

Nevertheless, CMs are advisory and informational messages only and are not directly actionable: they don't provide a direct recommendation to perform an avoidance action and of course they cannot take into account neither the operational constraints of the asset nor the maneuvers the asset plans or just performed.

Therefore, satellite Owner/Operators (O/O) must:

- Evaluate the level of risk of the conjunction according to their own criteria;
- Find a method to take into account maneuvers;
- Decide whether to perform an avoidance action, in other words detect among all conjunctions described with CMs the High Interest Events (HIE);
- Compute the avoidance action taking into account the operational constraints.

Conjunction Assessment using CMs is not so easy to perform, especially when a conjunction description is given through multiple CMs. While each CM provides sufficient information to compute a unique evaluation of the level of risk and can provide enough information to determine if O/O criteria for avoidance actions are met, multiple CMs do not always refine the description with consistent data. Each new CM comes from a new Orbit Determination

(OD) at JSpOC. Since OD is very sensitive to measurements (sensors distribution, dispersions, biases ...) and since realistic covariance is not easy to evaluate, successive OD are not always consistent. In such cases, it is not easy to evaluate if O/O criteria for avoidance action are met and which avoidance action should be chosen.

Conjunction Assessment using CMs implies:

- Consistency checks must be done using all CMs;
- O/O must be ready 24/7 to perform the analysis with very short notice;
- Difference (if any) between CMs must be explained : each CM must be double checked and JSpOC OD for primary object must be compared with the O/O OD;
- Variation of dispersion should be analyzed: “realistic” dispersion inflation or reduction, on primary and on secondary object, can lead to very significant increase of the Probability of Collision (PoC). “Realistic” depends on the OD characteristics and relies on experience feedback. A low PoC conjunction can hide a very risky one.

After conjunction assessment risk analysis, only very few CMs lead to an avoidance action, but those HIE conjunctions must not be missed.

Conjunction Assessment is a two-step process followed by a third step for collision avoidance action:

- Step 1 : close approach detection
It requires the maintenance of a catalog of space objects. The catalog is the main source to perform screening and detect close approaches for active satellites. It produces conjunction messages to notify O/O of potential risky conjunctions.
Today, JSpOC is the single 24/7 global provider.
- Step 2 : risk evaluation for collision avoidance decision
It consists of the analysis of all available CMs describing a conjunction with the capacity to do so 24/7. It produces an evaluation of the level of risk of the conjunction in order to detect HIE, alert and recommend avoidance action.
There is a need for few entities delivering to O/O Step 2 service; this is the Middle Man (MM) concept.
- Step 3 : collision avoidance action
Once both steps of Conjunction Assessment are completed, the O/O must evaluate the risk assessment, make the collision avoidance maneuver decision and realize the maneuver.

3. MIDDLE MAN CONCEPT AND CAESAR

The Middle Man (MM) is in charge of risk evaluation for collision avoidance decision (Step 2). The interface between provider of information messages describing detected close approaches and O/O evolves as described in Figure 1.

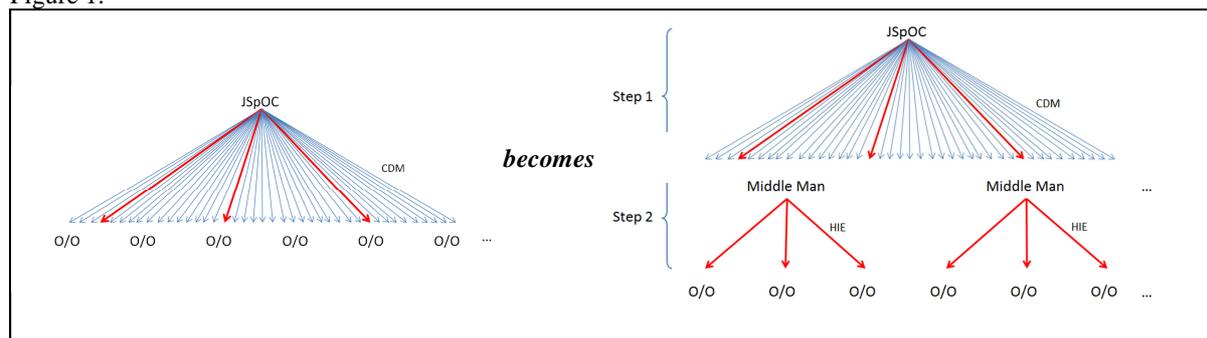


Figure 1: Interface evolution with Middle Man (MM).

In an organization that uses a Middle Man, the satellite O/O is only activated by MM for HIE, in other words when an avoidance action should be considered according to its own criteria (predefined with MM). MM is in charge of:

- Sending on daily basis O/O ephemeris to JSpOC;
- Analyzing all available CSMs;
- Finding the HIE conjunctions for which an avoidance action is needed according to O/O criteria;
- Sending collision alert to O/O in case of HIE;
- Providing elements to O/O in order to enable decision on an avoidance action;

- Supporting O/O to choose the avoidance action (to understand the level of the conjunction risk and to size the maneuver).

To enable fruitful dialogue between O/O and MM, a collaborative work environment between O/O and MM has to be established.

The collaborative work environment between O/O and MM has the following functions:

- Allow real time connections (phone, e-mail). The alert to O/O should be a closed loop process (acknowledgement of reception) and an interactive dialogue is necessary to ensure MM support;
- Ensure to share the same vision of the situation through the use of the same tool and secure exchange data means;
- Enable different levels of information visualization.

CAESAR stands for “Conjunction Analysis and Evaluation Service: Alert and Recommendations”. CAESAR is the French MM and a probative public service delivered by CNES using combined operational capacities of French defense and CNES. A description of CAESAR process is given in [2].

For CAESAR, the collaborative work environment is based on JAC software and on the dedicated secure webserver SpOD (<https://spod.cnes.fr>). JAC software is not the Main Flight Dynamics (FD) software used by CAESAR team, but it is light, friendly, CM dedicated, can be used on laptops by on-call teams and supports dialogue between Middle Man and FD teams. JAC functions are described in [3]. The next chapters focus on particularities of JAC to solve operational issues.

4. TAKING INTO ACCOUNT MANEUVERS

The first difficulty working with information data provided into CMs delivered by JSpOC is that maneuvers in close past or planned maneuvers are not taken into account. In close past, JSpOC cannot immediately have a good identification of the performed maneuver and of course has no idea of the O/O plan for maneuvers. This is particularly true for geostationary satellites (GEO) since on average they perform station-keeping maneuvers on fortnight basis or even more often with electrical propulsion, but this is also true for any controlled satellite.

It first means that close approaches detected by JSpOC after maneuvers of the asset are “false” ones up until JSpOC identifies the maneuver. For GEO satellites, false close approaches are therefore numerous since a close approach can be a false one either because there is a nearby maneuver for the asset but also because there is a nearby maneuver for the secondary. Indeed, GEO arc is unique and crowded (each asset has got quite close neighbors). For Low Earth Orbit (LEO) regime, the issue is also true but much less frequent.

Nevertheless the main issue is not that there are many false close approaches; the main issue is that JSpOC cannot provide real risky close approaches after maneuvers. Three major GEO operators created in 2009 Space Data Association (SDA) with the following goals: “seek and facilitate improvements in the safety and integrity of satellite operations through wider and improved coordination between satellite operators” and “seek and facilitate improved management of the shared resources of the Space Environment and the RF spectrum”. For CA purpose, SDA members share their operational ephemerides; it means that SDA can reliably detect true close approaches between SDA members. Unfortunately, this is only a small part of the potential conjunctions. For all non SDA members objects (either operational satellites or debris), SDA relies on Space Track website public data and therefore cannot solve the issue to detect close approaches after maneuvers, SDA efficiently detects close approaches between operational satellites which are members of SDA.

JSpOC provides a way to solve the issue: most any O/O can get CMs from JSpOC with 95% capture criteria instead of the emergency criteria. The 95% capture criteria are defined by orbit regime and come with 7 day notice for LEO and 14 day notice for GEO instead of 3 day notice. For instance, for LEO regime around 700km, the overall miss distance must be lower than 40km with radial miss distance lower than 800m to get CMs, and for GEO regime overall miss distance must be lower than 330km with radial miss distance lower than 7km. Middle Man (MM) with 95% capture criteria can perform in-house screening using O/O ephemerides including maneuvers against all the objects provided by JSpOC and therefore generates in-house CMs taking into account maneuvers. This solution has many advantages: ephemerides from O/O do not need to be sent to JSpOC neither on regular basis for routine screening nor to confirm a collision avoidance action. MM is autonomous as long as the maneuvers are not “too

big”, in other words this process works well and share the tasks between JSpOC and MM, except for non-routine maneuvers for which 95% capture criteria might be too small to guarantee that MM in-house screening is complete (for instance during end-of-life operations). Figure 2 illustrates the in-house screening which becomes possible with 95% capture criteria.

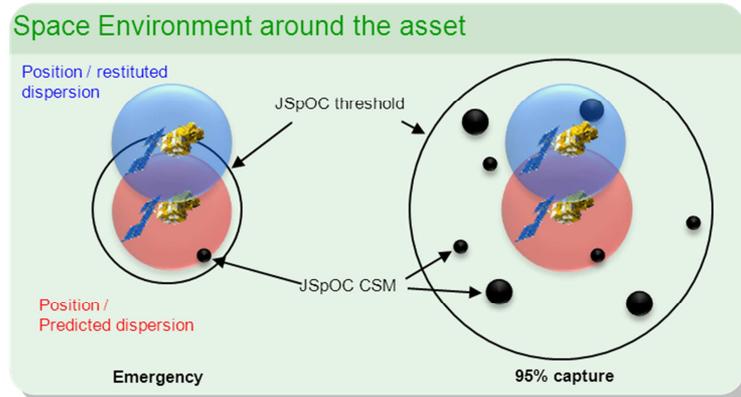


Figure 2: MM in-house screening taking into account maneuvers with 95% capture criteria.

95% capture criteria have an impact on the amount of data which has to be analyzed: while with Emergency criteria JSpOC provides few CMs, with 95% capture criteria the number of CMs is huge (more than 100 times more). In conclusion, MM concept enables to take into account maneuvers thanks to 95% capture criteria.

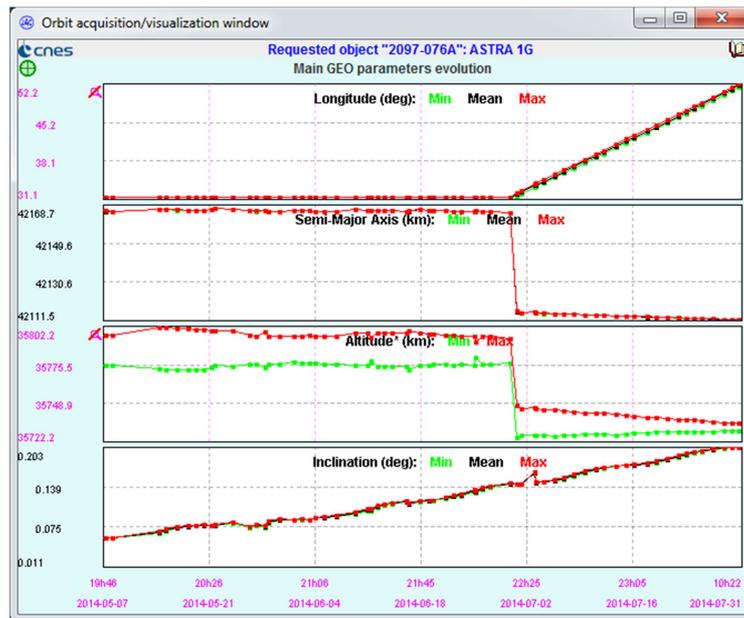


Figure 3: Maneuverability detection in JACsoftware

JAC is not used to perform CAESAR (as MM) in-house screening. This is done by the main FD system. All CMs (from JSpOC and all in-house generated ones) are posted on SpOD from where CAESAR team and O/O who subscribe to CAESAR can download them. Nevertheless, dealing with maneuvers, JAC is designed to identify maneuverability of secondary objects and to help to choose avoidance actions.

Before dealing with an avoidance action, it is important to know if the secondary is a maneuverable satellite since in that case coordination is mandatory. As long as JAC has an internet access, JAC offers the capacity to directly get from the public data on Space-Track.org a visualization of the evolution of the main orbital parameters of involved objects. Figure 4 is an example of the visualization in JAC of the evolution of orbital parameters of the GEO satellite ASTRA-1G. It becomes immediately possible to identify that ASTRA-1G performs relocation outside the GEO-protected arc and therefore will not be a threat for a controlled GEO satellite.

5. DEALING WITH HUGE AMOUNT OF CMs

The challenge with large criteria (and therefore huge number of CMs) is to have a process which automates a first level of analysis and identifies all the cases which require a manual analysis without missing any High Interest Event (HIE). JAC is a key component to manage huge number of CMs for CAESAR team. JAC provides a monitoring function which automates the first analysis of all incoming data and a synthetic presentation of results which provides to user situation at a glance to identify which cases require manual analysis.

Acquisition of CMs is easy with JAC: JAC parses xml files and performs checks (is the orbit realistic? is the covariance realistic? and so on). JAC re-computes TCA each time it is necessary. Acquisition of CMs is done through a dedicated panel with different choices for the User to select from where the data should be downloaded (website or local disk) and for which period of time (TCA in the future only, TCA in near past only or all available CMs). The local disk option is useful when several Users share a same database since it allows performing a unique download from the provider website and then each User of the group can have a local access to the updates. Options are available to optimize performance: PoC can be automatically computed after the parsing, download can only concern new CMs and filters can be applied to limit the data requested (filters on TCA, primary, miss distance...).

JAC Expert version provides a monitoring function. The monitoring function automates: acquisition of new CMs, first level of analysis and sending of messages when a conjunction can become risky according to an elaborated PoC criterion (PoC* described in [3]). For CAESAR, a dedicated device named SYGALE phones the on-call team whenever JAC Expert monitoring has detected an alert (the message read by SYGALE device is generated by JAC).

JAC presents in its CM panel a synthesis of all the conjunctions selected according to the different filters defined by the User. Figure 4 is an example of the CM panel with different legends. On each line, the status of the conjunction is summarized with a color-coded icon which immediately gives to the User the status on the risk level analysis without having to select and open a dedicated analysis window. Color-code is according to the parameters defined by the User for the different levels of risk.

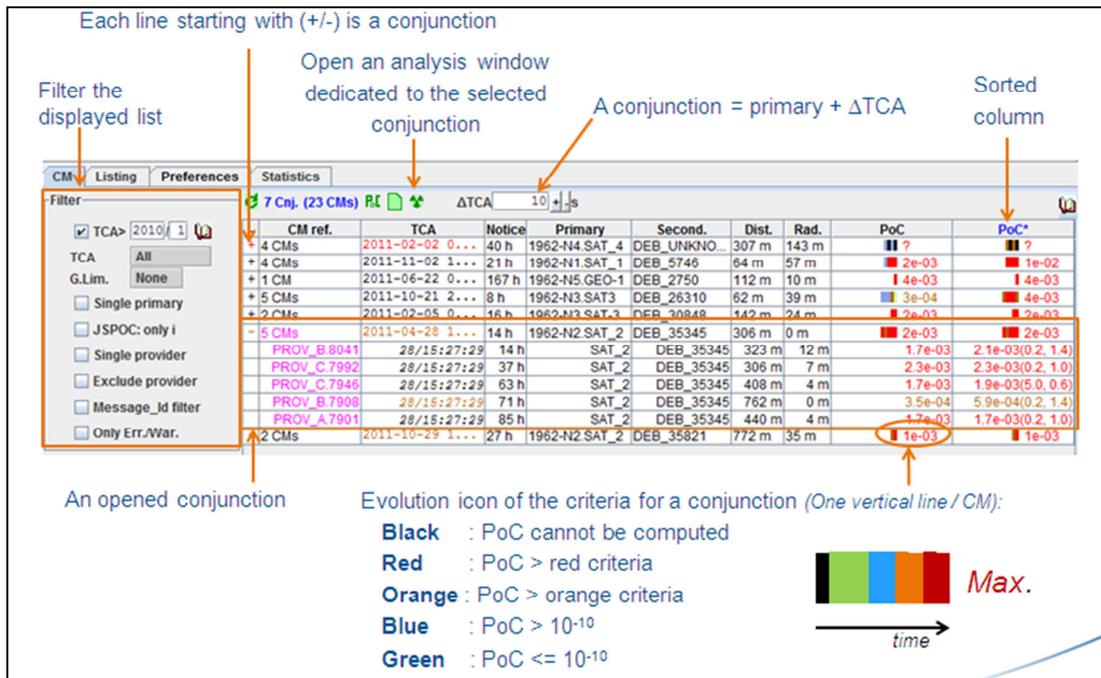


Figure 4: CM panel of JAC software

6. RISK LEVEL SENSITIVITY TO SMALL VARIATIONS OF INPUT DATA

Since any catastrophic in-orbit collision creates a cloud of debris that quickly spreads all over the earth, any catastrophic in-orbit collision is threat for space environment and for human use of space. The goal when analyzing close approaches is to correctly assess the level of risk and not to miss a required avoidance action. When assessing the level of risk, in other word when estimating the probability that the identified close approach becomes a collision, key data are used for the 2 objects: size, orbit parameters and covariance.

Size is known for assets and has to be estimated for secondary objects using information provided in CMs or from any other source. For this task, JAC helps to make realistic choices. CDMs include Radar Cross Section (RCS) values. Directly take this value for secondary would imply a minimization of the computed probability since physical size is most of the time bigger than size deduced from RCS. JAC proposes to filter object sizes in groups (small, medium and large) with values chosen by the User in preferences.

Covariance linked with orbit parameters is the key factor for the computation of the Probability of Collision (PoC). Figure 5 shows the PoC formula in the majority of cases when the 3D formula can be reduced to 2D one. The formula clearly shows the influence of covariance in the result. Realistic covariance is very difficult to estimate, JSPOC recommends considering that values provided in CMs are optimistic (at least 20%). Therefore it becomes clear that risk level cannot just be assessed with PoC computed with the values provided in CMs, risk level assessment should consider the sensitivity of a variation of covariance. The main idea is to check if one could be “at the edge of a cliff” since small variation of covariance in some configurations implies completely different risk level depending on the overall geometry of the close approach. In some cases covariance in CMs prove to be too optimistic and in other cases too pessimistic. JAC provides visualization in 3D and 2D in different planes of the evolutions of different solutions provided in CMs: combined with the information about Orbit Determination (OD) friendly displayed with JAC, it enables the User to get an idea about how representative covariance is likely to be.

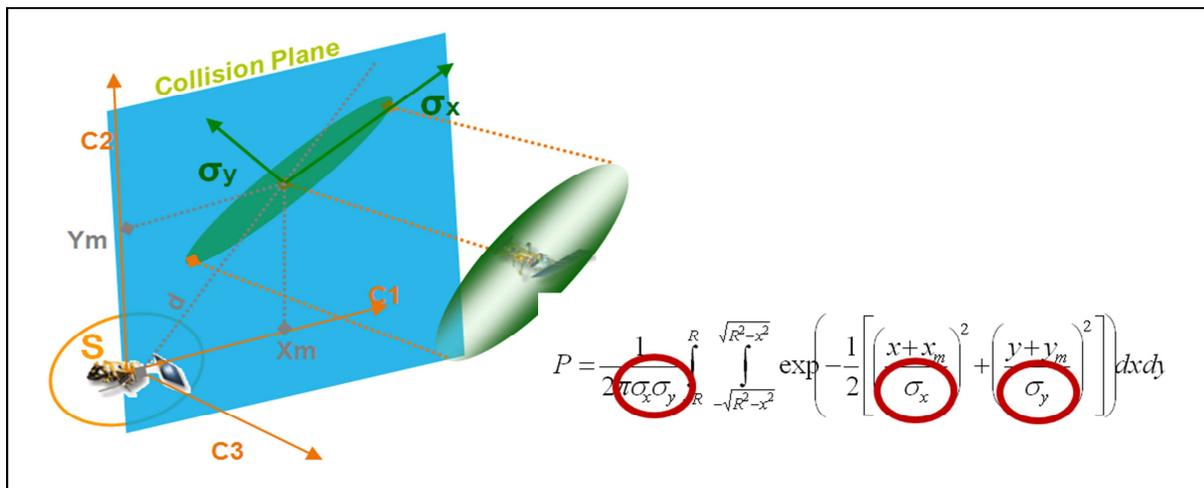


Figure 5: Covariance is the key factor to compute Probability of Collision

In figure 6, there are two examples using JAC displays from real cases: one with clearly too pessimistic covariance and one with too optimistic covariance.

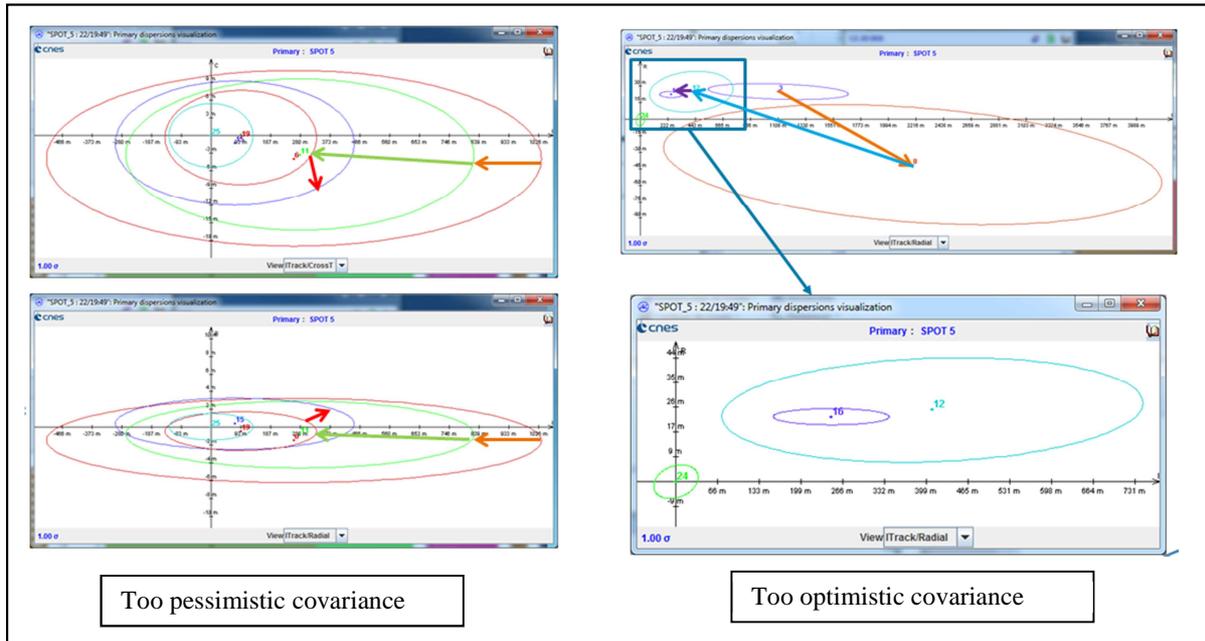


Figure 6: Real example (SPOT5) of covariance evolution through chronological CMs. In the orbital local frame of the reference orbit (very accurate O/O orbit) of SPOT5, each point figures the position of a CM with its covariance in In-Track/Cross-Track (top graphics) and In-Track/Radial (low graphics). The arrows go from oldest to newest (according to the numbers).

CAESAR uses CAESAR Operational Probability of Collision (COPOC) to assess risk level. The question is no more “What is the PoC” but becomes “Can the PoC becomes greater than the threshold?” or “Do the dispersions remain realistic to reach the threshold?”. Coefficients for magnitude of variation of dispersions for primary and for secondary have been chosen from a statistical analysis in the past. In JAC monitoring, a fixed range of variation of dispersions is applied and JAC computes PoC*, which is the expanded PoC or the maximum for PoC taking into account the magnitude of variation of dispersions. JAC displays PoC* (as can be seen in Figure 4) and for all high PoC* a manual analysis is done in order to estimate the COPOC (which can be smaller than PoC*).

C (covariance) = $k_p C_p + k_s C_s$ with k_p and k_s independent scale factors applied to respective covariance. The total covariance C is realistic when k_p and k_s are realistic. PoC* is the maximum value of PoC when k_p and k_s are in a realistic interval chosen after statistical analysis in the past. COPOC is the PoC* for a subset of variation of k_p and k_s , chosen by the analyst with the global context of the close approach (especially with all the other input data). COPOC also enables to anticipate a risky situation (when “at the edge of a cliff”).

PoC sensitivity analysis is displayed graphically with a friendly color-code in JAC as shown in Figure 7, first to assess the risk level and then to help choosing an avoidance action. Such analysis do not always conclude to the need to perform an avoidance action since CESAR works with COPOC and not with the automated result PoC*, but it guarantees that a real HIE won’t be missed.

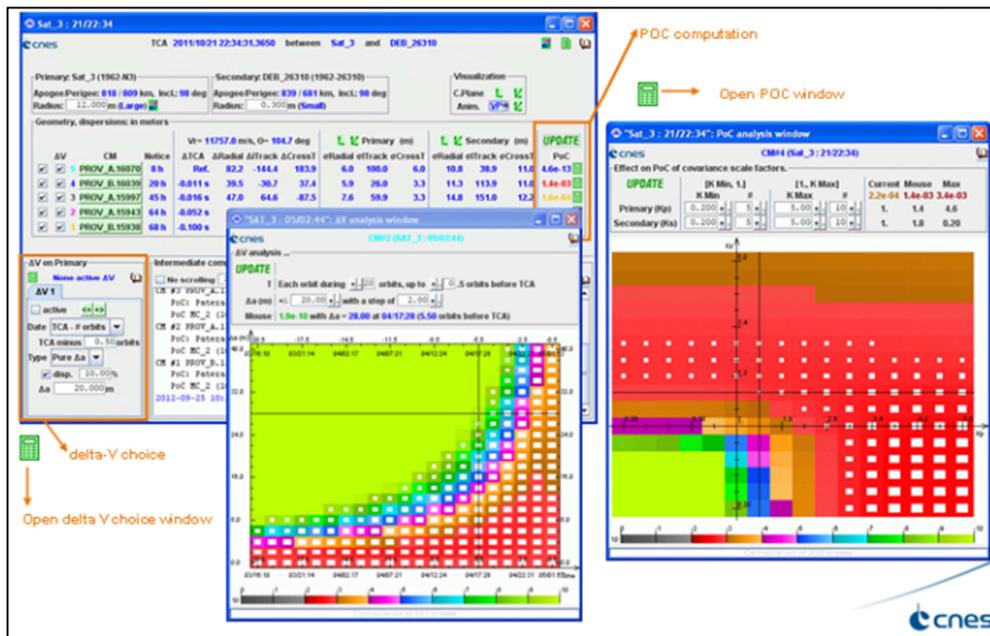


Figure 7: Sensitivity analysis displayed by JAC.

7. DISTRIBUTION OF JAC SOFTWARE

JAC addresses the needs of teams responsible for managing in-orbit collision risks for one or many satellites. JAC is modular software with two levels of use: Basic Modules and Expert Modules. JAC helps to retrieve and analyze close approach messages using CSM or CDM format by providing a synthetic vision of each close approach described by one or more CMs. It helps the User to evaluate the level of risk according to its own criteria.

The main functions of JAC are listed below:

- JAC Basic Modules: to be aware of the situation.
 - Automatic download of CM from websites with secure password management
 - Capacity to manage CM from different providers
 - Management of the downloaded CM database
 - Visualization of the key data given by the different CM related to each alert
 - Visualization of the evolution of those key data through tables, graphs, 3D animations
 - Capacity to copy/paste and edit CM data to illustrate sensibility of key parameters
 - Capacity to use several pre-defined dispersions for each primary
 - Printable summary of analysis
 - Statistics on CM in database
- JAC Expert Modules: to make and validate a decision.
 - Automatic monitoring of incoming CMs
 - Several methods to compute probability of collision
 - Threshold on the probability of collision is set by User
 - Simulation of maneuvers on the satellite of interest to determine their effect in terms of mitigation of the identified risk

JAC software is in Java, therefore JAC is naturally available on various platforms (Windows, Solaris, Linux, MacOS,...). JAC is accessible on SpOD, CNES secure website. JAC is distributed by CNES after signature of a license:

- JAC Basic Modules are distributed by CNES for free;
- JAC Expert Modules are distributed by CNES with an annual fee;

- JAC Expert Modules are included in CAESAR annual subscription.

JAC email contact for any questions on the use of the software: jac@cnes.fr.

8. CONCLUSION

Maneuvers need to be taken into account for close approach detection: this can be done with in-house screening at Middle Man level thanks to 95% capture criteria for JSpOC distribution of Conjunction Messages. A single existing entity is not likely to succeed in gathering all O/O ephemeris (neither JSpOC nor SDA), therefore it is pragmatic to engage in CA burden-sharing between JSpOC and Middle Man entities, each one gathering a group of O/O ephemeris. Fewer will be the MM entities, the more efficient the management of Conjunction Assessment. JAC software helps to deal with the great amount of data required at MM level (monitoring of in-coming data, friendly and synthetic display at a glance) and provides tools to perform sensitivity analysis on variation of covariance in order to secure assessment of conjunctions.

Thanks to its distribution since 2012, JAC takes advantage of the feedbacks of very different Users. It keeps on improving and will continue to do so. JAC will adapt to better take into account constraints such as on-board autonomous orbit control or low thrust propulsion or GEO specificities.

9. NOMENCLATURE

CAESAR	=	conjunction analysis and evaluation service, alerts and recommendations
CARA	=	conjunction assessment risk analysis
COPOC	=	CAESAR operational probability of collision
CSM	=	conjunction summary message
GEO	=	geostationary
HIE	=	high interest event
JSpOC	=	Joint Space Operations Center
LEO	=	Low Earth Orbit
PoC	=	probability of collision
PoC*	=	expanded PoC
O/O	=	owner/operator
OD	=	orbit determination
OSA	=	orbital safety analyst for CARA missions at JSpOC
MM	=	Middle Man
NDPP	=	non-traditional data pre processing
SP catalog	=	JSpOC precise (Special Perturbations) catalog which is not public
USSTRATCOM	=	United States Strategic Command

10. REFERENCES

1. CCSDS 508.0-B-1, "CONJUNCTION DATA MESSAGE", Recommended standard, BLUE BOOK June 2013, available at <http://public.ccsds.org/publications/BlueBooks.aspx>
2. Moury Monique, Newman Lauri and Laporte François, *Middle Man Concept for In-Orbit Collision Risks Mitigation, CAESAR and CARA example*, Proceedings of the *SpaceOps Conference 2014*, Pasadena, CA, May 5-9, 2014, AIAA 2014-1637
3. Laporte François, *JAC Software, Dedicated to the Analysis of Conjunction Messages*, Proceedings of the *SpaceOps Conference 2014*, Pasadena, CA, May 5-9, 2014, AIAA 2014-1774