Collaborative Work Environment for Operational Conjunction Assessment

François Laporte
Stéphane Christy
Monique Moury
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. Operational collision threat characterization is now an essential component of space mission operations. Most spacecraft operators have some sort of a process to evaluate and mitigate high-risk conjunction events. As the size of the space object catalog increases, satellite operators will be faced with more conjunction events to evaluate. Thus more sophisticated collision threat characterization and collision avoidance strategies must be implemented thought Middle Man entities.

CAESAR (Conjunction Analysis and Evaluation Service, Alerts and Recommendations) is the French Middle Man. CAESAR relies on a collaborative work environment between all members of CAESAR team and its subscribers. For CAESAR, the collaborative work environment is based on JAC software and a dedicated secure webserver SpOD "Space Operations Data". 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 a laptop by on-call teams or support dialogue between Middle Man and FD teams. The dedicated secure webserver is a key element to share data and information between actors.

This paper presents the main feedbacks from CAESAR team operational experience with regards to its collaborative work environment components:

- **JAC software which is not a classical Flight Dynamics software, its MMI is designed to be very quickly taken over (by teams not using it on daily basis) while also offering all the expertise levels required by the Middle Man team. JAC is used by CAESAR on-call team and all FD teams who subscribed to CAESAR. JAC is also distributed by CNES and therefore already used by some operational teams for Conjunction Assessment.**
- **The secure webserver dedicated to CAESAR, SpOD, is used to offer operational security in combination with functions provided by JAC. For instance, JAC manages "Team Data" such as operational procedures, templates, input data for analysis and so on. It guarantees that each member of the operational team always uses the common last version of the operational procedures, templates or input data.**

Collaborative work environment for Conjunction Assessment is essential to secure operations. CAESAR organization has been enriched and secured thanks to its declination of a collaborative work environment and is a concrete example of benefits in terms of security that can be achieved thanks to it.

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). 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. Between April and August 2014, JSpOC transitioned from CSM to the standardized format CDM (Conjunction Data Message, defined by the Consultative Committee for Space Data Systems, CCSDS, as in [1]).

Conjunction assessment with Conjunction Messages (CM) is described in [2]. CM, either CSM or CDM, 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.

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 CM 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

The Middle Man concept is described in [3]. The Middle Man is in charge of risk evaluation for collision avoidance decision (Step 2). CAESAR stands for "**C**onjunction **A**nalysis and **E**valuation **S**ervice: **A**lert and **R**ecommendations". 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 [3].

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, and can be used on laptops by on-call teams and supports dialogue between Middle Man and FD teams. JAC functions are described in [4].

The next chapters focus on the benefits for CAESAR of its collaborative work environment in terms of security and efficacy first through the Conjunction Assessment (CA) process (automated acquisition of CM, checks of the incoming CM, analysis of the incoming CM in order to detect High Interest Events (HIE) and determination of the avoidance action, when necessary) and then through the operational issues perspectives (huge amount of CM, 24/7 requirement, efficient spreading of process updates).

2. AUTOMATED ACQUISITION OF CDM FROM SPACE-TRACK WEBSITE

For CDM acquisition from Space-Track website, a dedicated API (Application Programming Interface) is available to request the server on regular basis (or after reception of a notification email from JSpOC). No CDM should be missed and the number of requests to the server should be minimized.

In order to avoid downloading the same CDM several times from Space-Track website by different members of the CAESAR team, all incoming CDM are downloaded only once by CAESAR main application software using the "FILE" predicate and uploaded on SpOD. Then, each CAESAR team member downloads the CDM from SpOD.

In order to secure acquisition of incoming CDM, a redundant acquisition is performed using the monitoring function of JAC software but without duplicating CDM acquisition. JAC first downloads all new CDM from SpOD using an optimized process thanks to a bookmark feature, then request Space-Track for the list of references (CDM_ID, MESSAGE_ID, TCA) of all the newly added CDM for which the CDM_ID is greater than the bookmark, the bookmark being the greater CDM_ID of the last request. Then JAC looks for new CDM on Space-Track website, most of the time there is none. If there are some new CDM in the list, JAC downloads them using the list of CDM_ID.

JAC monitoring function combined with SpOD secures acquisition of CDM and optimizes the number of requests from CAESAR to Space-Track website.

3. CHECKS OF THE INCOMING CDM

Different checks of incoming CDM must be performed. JAC realizes many checks. XML parsing is used for checking compliancy of the syntax of CDM. JAC checks the validity of covariance matrices, for instance JAC checks that the Eigen values are positive. To verify if the TCA is a real TCA, JAC checks if the relative velocity is perpendicular to the relative position vector. Since relative parameters can be computed with the data provided in CDM, JAC computes them and checks if there is a difference with the value provided inside the CDM for the relative parameters. Especially for small relative velocity encounters, JAC searches for closer approach around the provided TCA.

JAC manages 3 levels of inconsistency:

- <u>Error</u>: the CDM cannot be taken into account because the relative position cannot be computed (invalid file, no TCA, invalid position or velocity, …);
- <u>Warning</u>: there are some inconsistencies or missing data which can prevent the Probability of Collision (PoC) computation. For examples: PoC can be computed but the read TCA is not valid and has to be recomputed by JAC, or PoC cannot be computed because there is no dispersion or an inconsistent covariance matrix, etc;
- <u>Minor warning</u>: the analysis can be performed but the CDM is not completely as expected, either the read relative geometry is not correct or some obligatory fields are missing in the XML file.

JAC checking function guarantees that CDM with problems won’t be analyzed unless JAC has been able to correct the anomaly.

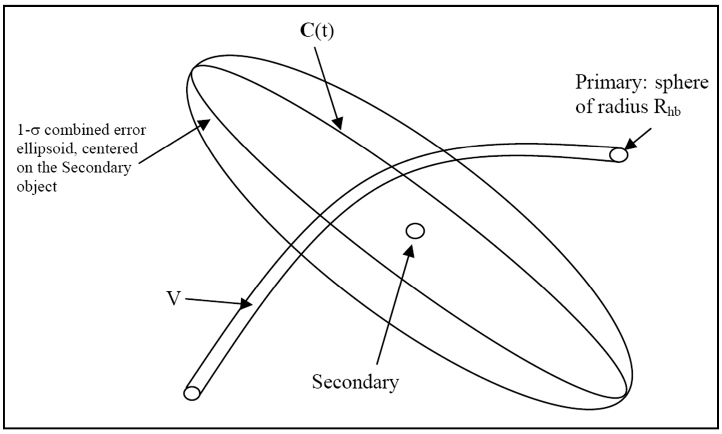
4. ANALYSIS OF CDM TO DETECT HIE

The criteria to detect High Interest Events (HIE) is the Probability of Collision (PoC). To compute PoC, the key factors are:

- V: integration volume which is a circular tube defined by the evolution of Position & Velocity of the 2 objects;
- C: combined covariance which is the sum of covariances of the 2 objects.

Therefore analysis of CDM implies to evaluate at TCA:

- Position & Velocity of the 2 objects,
- Covariance of the 2 objects,
- Radius of the englobing sphere of each object.



$$P_c = \frac{1}{\sqrt{(2\pi)^3|\mathbf{C}|}} \iiint_V e^{-\frac{1}{2}\bar{r}^T\mathbf{C}^{-1}\bar{r}}\, dXdYdZ$$

Figure 1: Probability of Collision

<u>Position and Velocity of the 2 objects:</u>

In many cases, JSpOC does not have information about planned maneuvers and therefore cannot take them into account. It means that there are “false alarms” in cases where an already planned maneuver will avoid the identified risk, but there are also “missed risks” when a planned maneuver generates a new risky conjunction. The issue is different depending of the orbit regime. Geostationary (GEO) satellites often perform maneuvers (typically every 2 weeks), they are supposed to be "packed" in boxes and there is a high percentage of maneuverable objects around GEO region. Low Earth Orbit (LEO) and Medium Earth Orbit (MEO) satellites perform fewer maneuvers, there is no notion of "reserved" orbit or position and the percentage of maneuverable object in those orbit regimes is very low.

How JAC software helps dealing with maneuvers is described in [2]. For primary object false alarms are detected patching Owner/Operator (O/O) ephemeris in CDM and missed risks are detected thanks to the large criteria to get CDM. For secondary object, maneuverability is detected: for MEO or LEO satellites a coordination is required each time the secondary object is maneuverable, for GEO satellites only, JAC helps to identify false alarms (satellites kept in their boxes) but coordination remains necessary if the maneuverable secondary is drifting.

<u>Covariance of the 2 objects:</u>

PoC is very sensitive to the covariance matrix (as shown in figure 1). Unfortunately, covariance in CDM is not always fully representative of reality. For both primary and secondary, covariance can either be too optimistic or too pessimistic. Figure 2 illustrates the 2 cases, first schematically and then with examples of real cases with CNES assets.

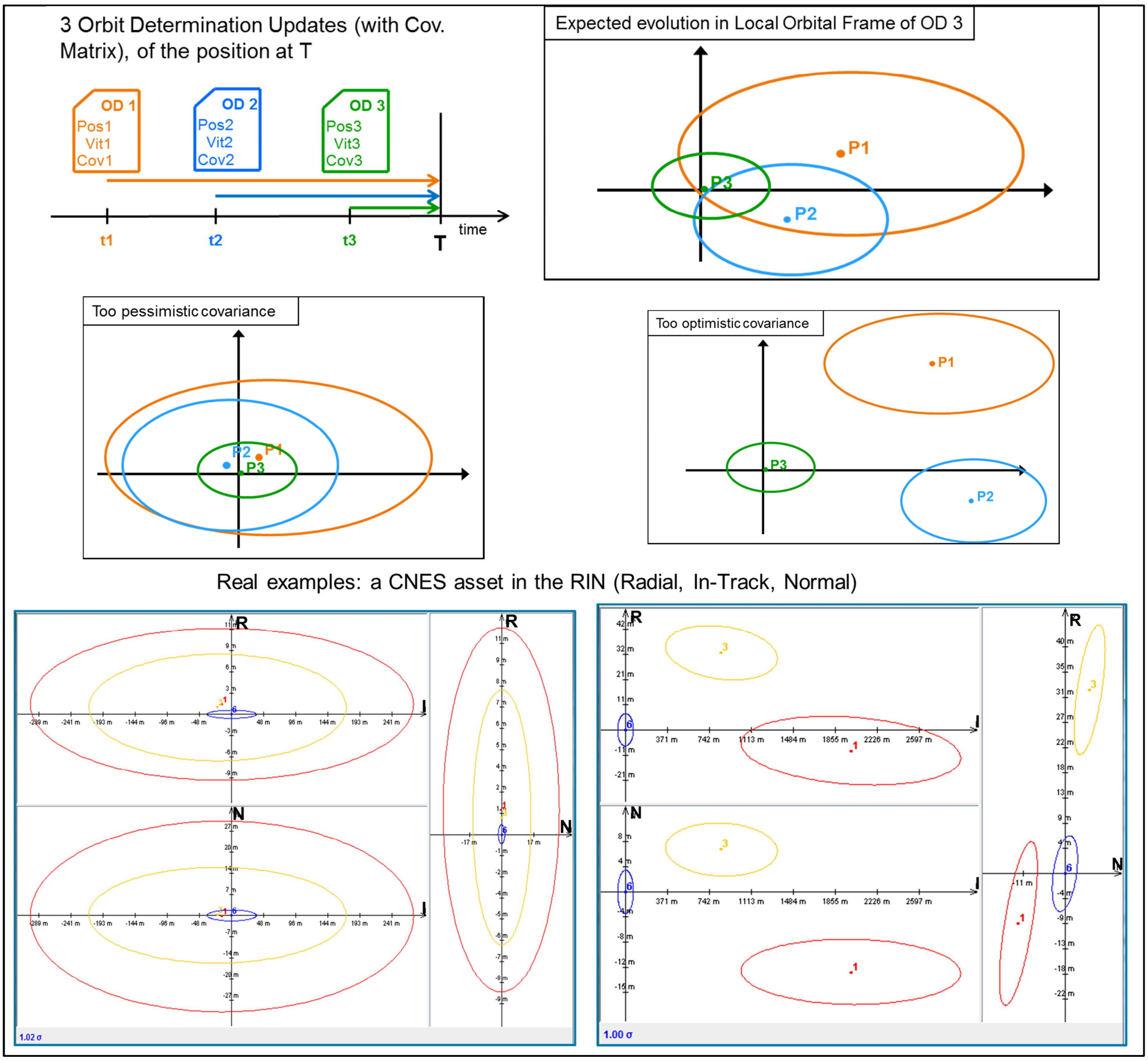


Figure 2: Covariance evolution through chronological CM in local orbital frame.

Covariance is a major contributor to PoC. As described in [2], dispersion on covariance can change PoC for the same conjunction from “no risk” to “very risky”. 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* and for all high PoC* a manual analysis is done in order to estimate the COPOC (which is always smaller than PoC*).

Radius of the englobing sphere of the 2 objects:
PoC is sensitive to Hard Body Radius (HBR) as a monotonically increasing function since it defines the volume of the integral. The maximum value of HBR gives the maximum value of PoC. Therefore there is no need to perform a sensitivity analysis.
HBR is the sum of the radius for the primary object and for the secondary object. For the secondary object, estimation of the radius can come from different sources of information:

- Internet: sometimes possible to find indication on the size of the secondary object, but not often and the process cannot be automated;
- DISCOS data base: the European Space Agency (ESA) provides access to the DISCOS database to registered users. DISCOS stands for Database and Information System Characterizing Objects in Space. It can be accessed at https://discosweb.esoc.esa.int. DISCOS provides information (Length, Height, Depth, …) and a variety of data associated with space activities. The service is provided by the European Space Operations Centre (ESOC from ESA, European Space Agency);
- JSpOC’s CDM: the <AREA_PC> field of CDM is actually populated with the RCS (Radar Cross Section) of the object. It means that the radius cannot be derived from CDM with the following formula: $R^2 = RCS / \pi$. Let’s take the example of SPOT5 satellite, RCS in CDM = 7.661 (the previous formula would lead to a radius of 1.5 meters) to be compared to the actual size of SPOT5 satellite: 3.1 * 5.7 * 10.0 meters. At CNES it is considered as 8 + 20% = 9.6 meters.

At CNES, CAESAR team uses real size for assets and otherwise DISCOS information when available and if not AREA_PC of the CDM to determine if the object is small, medium or large. By default, if information is not available, the object is considered as large.
As an improvement, CAESAR team is working on taking into account the real attitude of the asset at TCA in order to reduce the HBR and therefore reduce the computed PoC. The automated process will still consider the englobing sphere radius, but for HIE the analyst will compute the direction of the object in the asset local orbital frame and provide it to the Flight Dynamics team in charge of the station-keeping of the asset who would compute the “optimized” radius (according to real attitude at TCA using JAC).

JAC software combined with SpOD, DISCOS and internet access provides optimized tools for the analysis of CDM in order to detect HIE.

5. AVOIDANCE MANEUVER DETERMINATION

The goal of the avoidance action is to reduce the level of risk of the conjunction without creating new HIE. CAESAR process sizes avoidance action in order to reduce by a factor of 10 or 15 the COPOC of the conjunction. The process is in 3 steps:

- Evaluation of the necessary / feasible amplitude of the maneuver;
- Check the impact on the level of risk for the other conjunctions;
- Double-check with the O/O ephemeris.

The first 2 steps are iterative. Thanks to large criteria to get CDM from JSpOC and to JAC software, the first 2 steps can be automated and performed in-house very quickly.

In the CM analysis main window of JAC, the user is invited to tune the expanded coefficients independently for primary and secondary objects. Those coefficients determine the relative inflation or reduction on the 3 axis to be applied in the computation of the expanded PoC. Then the user has to enter the maneuver dispersion, to select the maneuver and to indicate on which CM of the conjunction the maneuver has to be applied. Figure 3 is a snapshot of the CM analysis main window of JAC.

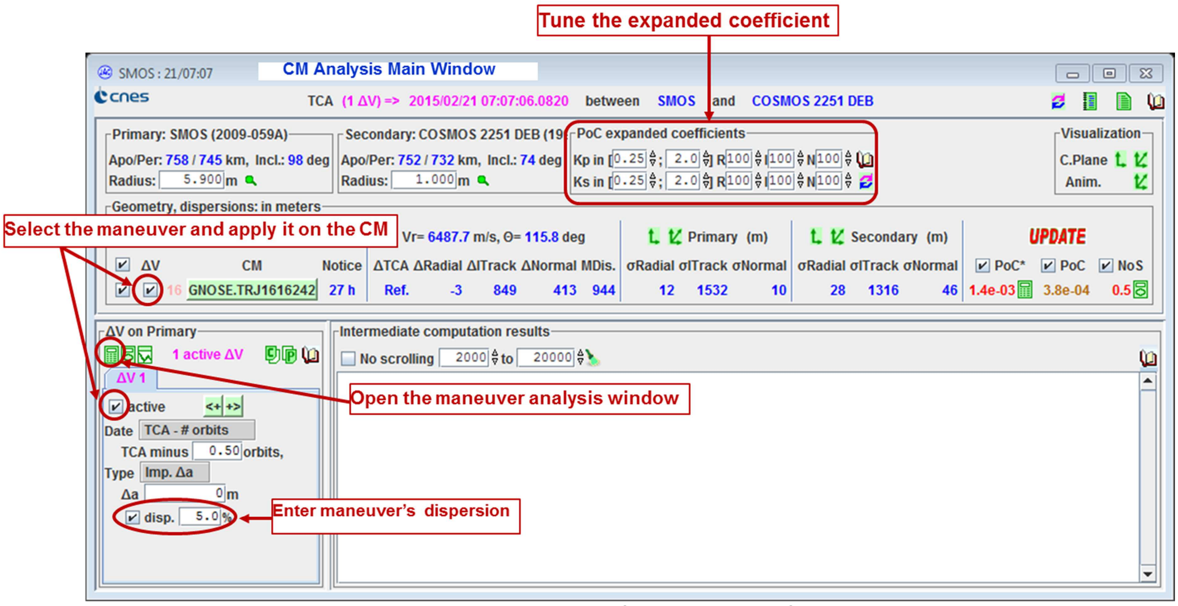


Figure 3: CM analysis main window in JAC for evaluation of the avoidance maneuver

Figure 4 shows the maneuver analysis window of JAC. When the frame of a cell is white, it means that PoC is above the indicated value (5 10^{-5} in the example). Definition of X and Y axis are given at the top of the window. The user can select to compute and display the expanded PoC (which is symbolized as PoC*). After a click on a cell in the graph, the window evolves and all the cells with a PoC greater than the PoC of the clicked cell are filled with a white square. The size of the square is proportional to the PoC of the cell.

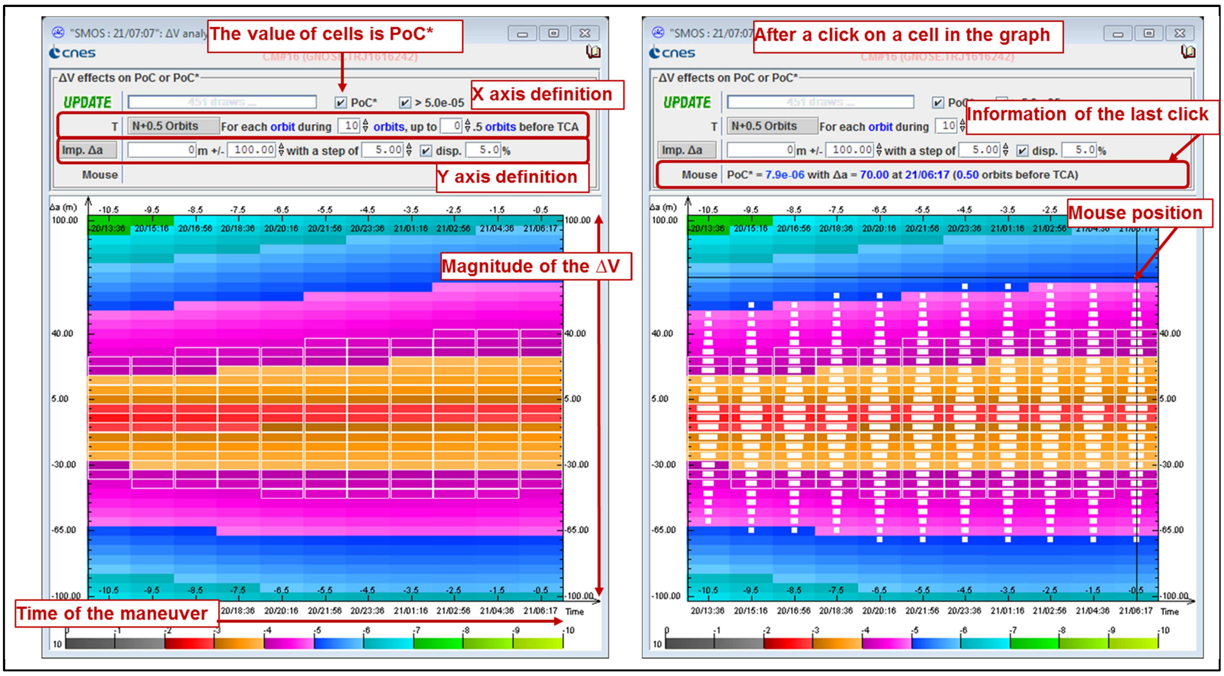


Figure 4: Maneuver analysis window of JAC

The next step is to check the impact of the avoidance maneuver with all the other conjunctions, in other words to check that the potential avoidance maneuver does not increase the level of risk of another conjunction above the threshold. JAC offers the possibility with few clicks to choose to apply a chosen maneuver to all already identified conjunctions (with the large criteria). JAC quickly identifies and provides to user a list of the conjunction with an increased risk level. The process is iterative to determine which avoidance maneuver to apply. The best way is that O/O provides an ephemeris including the chosen maneuver for double check with JAC.

The use of JAC software, as described above, enhances security of flights by an efficient choice of avoidance actions. SpOD also provides information on maneuverable satellites in order to secure analysis (to easily identify operational satellites).

6. HUGE AMOUNT OF CDM

The challenge with large JSpOC criteria (and therefore huge number of CM) 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 CM for CAESAR team. JAC provides a monitoring function which automates the first analysis of all incoming data and a synthetic presentation of results (CM list panel) which provides to user situation at a glance to identify which cases require manual analysis. Details are provided in [2].

7. 24/7 REQUIREMENT

Acquisition of CDM, analysis and detection of HIE must be done 24/7. It means that a first level of analysis has to be automated in order to identify all cases which require a manual analysis to be sure not to miss an HIE and to alert the analyst in case of emergency. 24/7 can be achieved with on-call process more easily when the analysis can also be performed outside the operational center (at home for the on-call analyst).

JAC sends emails to two recipients: MONITOR and ANALYST.

- MONITOR: it's a dedicated & shared email address to follow the process. JAC sends two kinds of messages to MONITOR:
    - Status email: this type of message contents a status of the last download of CDM, it includes provider, number of CM and so on … and it also confirms that the process is still running. When no status email is received, it means that the analyst has to investigate and cannot rely on the monitoring.
    - Error email: this type of message is for acquisition failure, erroneous CDMs, …
- ANALYST: at CNES each member of the CAESAR team is in the ANALYST list of email addresses. Those messages are warnings or alerts. For alerts messages, JAC also performs a "call action", a phone call to the on-call analyst (at CNES this done with SYGALE device which is a speech unit).

JAC monitoring is in charge every few minutes to download new (and only new) CM from either a local folder, or SpOD website or Space-Track website. It checks the consistency of the data and computes the PoC in order to estimate the risk level. The output of this monitoring is an email to ANALYST when the risk level is over the orange limit (warning), the value of the threshold defined in the preferences tab of JAC or an email combined with a "call action" to ANALYST when the risk level is over the red limit. JAC offers the possibility to define night periods when the "call action" can be delayed in order to optimize sleeping time according to remaining time before TCA.

8. EFFICIENT SPREADING OF PROCESS UPDATES

In JAC software, Team Data sharing function enables to easily share the same key data among a team and to be warned of the availability of updates.

Team Data for JAC include different kinds of data:

- <u>Data for the analysis:</u>

- HBR evaluation process parameters:
  - Large/medium/small definition,
  - Computation options to take into account JSpOC's exceptions;
- Geometric criteria:
  - Definition of "emergency" criteria when PoC cannot be computed;
  - Limit of realistic value for dispersions: below which a warning is set and PoC not computed.
- PoC thresholds: when the PoC label must be red & orange.
- PoC expanded (PoC*) default coefficients: intervals for Kp and Ks.

- Satellite dependent data
  - Satellite Preferences: for a list of assets some parameters will override the default ones. Examples:
    - Radius of englobing sphere;
    - PoC* criteria;
    - Geometric emergency criteria;
    - Analyst: reference of the analyst in charge of the asset;
    - …
  - Satellite Abacus: variance abacus which can be frequently updates (weekly at CNES).
- Templates

  A simple user-defined text file that can be updated with information from the current conjunction. Dedicated key-words will be replaced with the actual value. This can be useful to define typical email contents.
- HTML documentation.
  - operational description of concept of operation of the team;
  - includes operational contacts;
  - can be visualized from JAC main frame.

The goal of team Data sharing is to enable consistent analysis among a team, to be sure that all analysts are warned as soon as an update is available (need an internet connection) and after the update, the analyst doesn't need any more an internet connection: the data is locally copied. Figure 5 explains how JAC combined with SpOD enables efficient spreading of process updates.

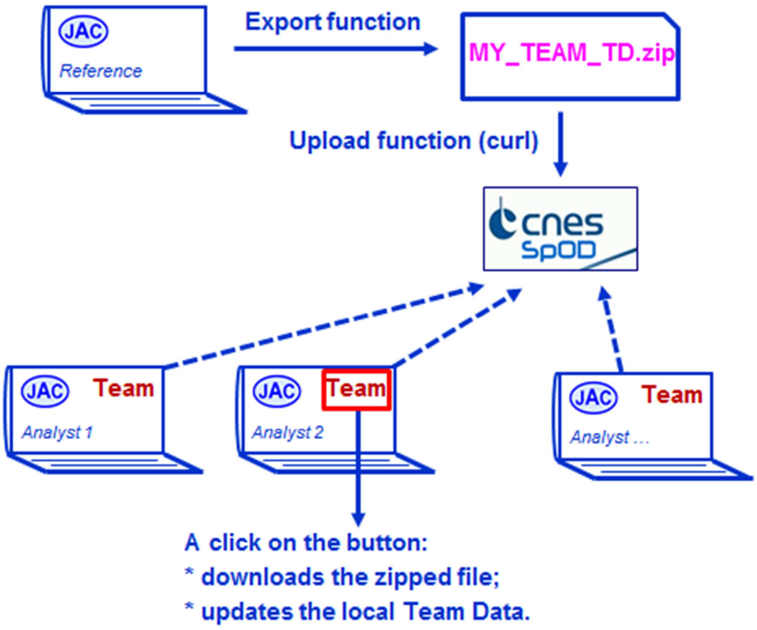


Figure 5: Team data process between JAC and SpOD

9. 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.
  - Team Data management through SpOD;
  - Automatic monitoring of incoming CM;
  - 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 distributes 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.

10. CONCLUSION

Collaborative work environment for Conjunction Assessment is essential to secure operations. CAESAR organization has been enriched and secured thanks to its declination of a collaborative work environment based on JAC software and SpOD website (https: (https://spod.cnes.fr). It is a concrete example of benefits in terms of security that can be achieved thanks to it for example the Team Data function.

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.

Both JAC software and SpOD website benefit from in-house capacity to evolve which provides an excellent reactivity either for corrections or evolutions. CAESAR in September 2015 is delivered to 22 satellites from which 12 are controlled at CNES. On daily basis, CAESAR deals with ~1000 CM per day. Analysis are done 24/7 thanks to two on-call teams (for redundancy and possibility to share analysis of difficult cases).

11. NOMENCLATURE

CA		
CAESAR	=	conjunction analysis and evaluation service, alerts and recommendations
COPOC	=	CAESAR Operational Probability Of Collision
CM	=	Conjunction Message
CDM	=	Conjucntion Data Message
CSM	=	Conjunction Summary Message
DISCOS	=	Database and Information System Characterizing Objects in Space
GEO	=	Geostationary
HBR	=	Hard Body Radius
HIE	=	high interest event
JAC	=	Java for Conjuction Assessment
JSpOC	=	Joint Space Operations Center
LEO	=	Low Earth Orbit
MM	=	Middle Man
PoC	=	Probability of Collision
PoC*	=	expanded PoC
O/O	=	Owner/Operator
OD	=	Orbit Determination
SpOD	=	Space Operations Data

12. REFERENCES

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