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Operational Management of Collision Risks for LEO Satellites at CNES

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Because of the ever-increasing number of orbital debris, the possibility of a satellite collision with space debris or another satellite is becoming more likely. This phenomenon particularly concerns the LEO altitude regime, the most frequently used region in space, where the environment has reached a point in which collisions will become the dominant debris generating mechanism in the future. Today, CNES performs the station keeping of 16 spacecraft (14 LEO and 2 GEO) in its Operations Sub-directorate. In this context, CNES has placed an effort to evolve into a fully operational state of its collision risk monitoring activities for LEO satellites. These operational activities are gathered at OCC (Orbit Computation Center).

This paper presents the current OCC contingency operational procedure for collision risks management. This procedure is divided in five main stages: automated screening, manual risk assessment, dangerous conjunctions fine assessment, conjunction mitigation and formal end of conjunction mitigation. Collision risks automated screening involves the daily monitoring of close conjunctions of the 14 LEO spacecraft with all the USSTRATCOM catalogued objects. At this stage, fully automated computations are performed from the latest Two-Line Elements (TLE) data available using an in-house estimate of the orbital position uncertainty. Only close conjunctions which exceed a collision maximum probability threshold are short-listed for the next stage. The manual risk assessment stage identifies dangerous conjunctions with an empirical approach that considers several criteria, such as collision probability, trending miss distance and conjunction geometry. The dangerous conjunctions fine analysis is a much more complex procedure involving new orbit data and 3D visualization. When a high risk is corroborated, the risk mitigation stage is triggered. An avoidance maneuver is then calculated taking into account satellite mission and platform constraints, as well as new high-risk conjunction events in the post maneuver trajectory. This maneuver is eventually executed if the risk remains high while getting closer to the conjunction date. Finally, the formal end of conjunction mitigation capitalizes the case experience.

The CNES methodology is described with comprehensive justifications. A real case example is introduced to illustrate the whole operational procedure.

Nomenclature

A-TRAIN	=	Afternoon satellite constellation
CA	=	Collision Avoidance
CNES	=	Centre National d' Etudes Spatiales (French Space Agency)
DV	=	Delta Vitesse (in the paper it represents the avoidance maneuver)
GEO	=	Geosynchronous Earth Orbit

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GRAVES	=	French Air Force Space Surveillance System
LEO	=	Low Earth Orbit
NASA	=	National Aeronautics and Space Administration
OCC	=	Orbit Computation Center
OCG	=	Operational Coordination Group
OD	=	Orbit Determination
ONERA	=	Office National d' Etudes et de Recherché Aérospatiales
PoC	=	Probability of Collision
TCA	=	Time of Closest Approach
TLE	=	Two-Line Elements
VPO	=	Visualizations and Orbital Predictions (In-house CNES software)
2D, 3D	=	Two dimensions, three dimensions

I. Introduction

There are three recorded collisions with space debris. In December 1991, the Russian satellite COSMOS 1934 and a COSMOS 926 debris collided. 5 years later, on July 24^{th} 1996, the French satellite CERISE was hit by debris. The latest identified event was the January 2005 collision between THOR BURNER and debris from Long March.

Collision risks management is primarily constraint by the limited number of objects tracked: only 12,000 out of 100,000 potentially dangerous debris objects. Furthermore, the quality of the publicly available orbits of the regularly tracked objects is quite poor. In this context, CNES operations deal with a maximum number of available data sources, which can be divided in three different kinds:

- SpaceTrack database: the main TLE database. Due to its breadth and update frequency, it has been adopted as the primary source for the screening phase. Nevertheless, its accuracy and orbit propagation models are not fully available. Therefore, complex estimations are needed to measure and improve reliability.
- GRAVES database: the French Air Force Space Surveillance System (built by ONERA).
- Specific orbital data: radar measurements from CNES Guyana Launch Center and from French Defense. These sources produce very accurate measurements. However, due to their limited availability, they are only used to improve the orbit determination of dangerous objects.

II. History of Collision Risks Management at CNES

CNES has been managing collision risks for more than a decade. The experimental phase started in 1997 at the Orbit Computation Center (OCC) (part of the CNES 2GHz network). At that time, OCC had already 12 years of experience in operational orbit determination (routine, orbit positioning and operations) for LEO and GEO spacecraft. Besides, the OCC concurrent engineering approach facilitated the rapid implementation and evolution of collision risks management activities[1]. The key dates in this evolution of the operational process are:

- 1997: Experimental implementation phase[2]
  - Objectives:
    - Identify real cases and effects of theoretical parameters ;
    - Analyze the available means (reliability, integrity, availability, accuracy, …) ;
    - Define a methodology to realize an operational implementation (procedures, interfaces with other Control Centers, …);
    - Identify the required resources (software, man power, …);
  - Key event: an avoidance maneuver performed on SPOT 2 on July 27th 1997.
- 1999: Probabilistic approach: collision alert at a probability threshold of 10^{-3}.
- 2006: CNES-NASA cooperation for the A-TRAIN[3] involved major improvements of CNES tools[4].

[3] The Afternoon or "A-Train" satellite constellation consists of five satellites flying in formation around the earth: NASA's Aqua, CloudSat and Aura satellites and CNES' PARASOL and CALIPSO satellite. By combining the different satellites observations, scientists will be able to gain a better understanding of important parameters related to climate change.

- 2007: Operational phase: collision risks management of 14 CNES LEO satellites.
    - 2007/01: advance of an orbit control maneuver (NASA Alert);
    - 2007/02: avoidance maneuver;
    - 2007/06: avoidance maneuver;
    - 2007/07: planned avoidance maneuver cancelled (from external data);

III. CNES Contingency Operational Procedure

The CNES collision avoidance (CA) procedure is applied on all LEO satellites controlled by CNES. This procedure is mainly the same for all spacecraft. Some exceptions occur on particular satellites with specific mission constraints that require few CA operational adaptations. A collision risk can be treated at any time. There are two on-call teams of flight dynamics engineers that are available 24/7: one in charge of CA analyses and one in charge of the station-keeping of the LEO satellites controlled at CNES. Moreover, the CA procedure can benefit from all other on-call teams (vehicle, payload, ground segment, stations network …) as soon as an avoidance maneuver is considered.

The CNES procedure is divided into 5 stages as presented in Figure 1.

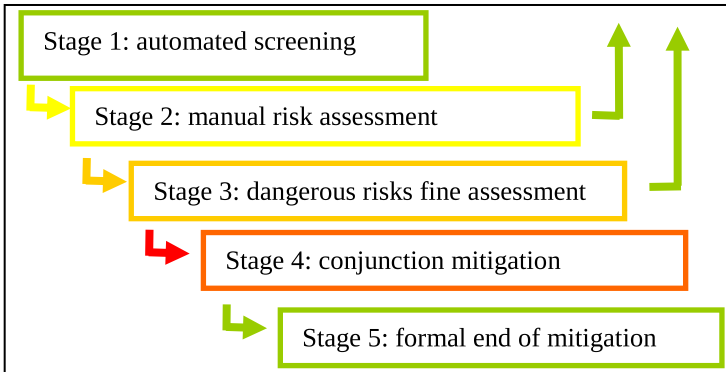


Figure 1*: The CNES contingency operational procedure in 5 stages*

Each of the first 4 stages represents an escalation in contingency and the fifth stage capitalizes the lessons learned. Basically, information provided by external databases is recorded and processed by in-house tools that screen the collision risks and produce collision assessments that are gradually refined. Eventually, an avoidance maneuver is considered. Figure 2 shows the global information flow of this process.

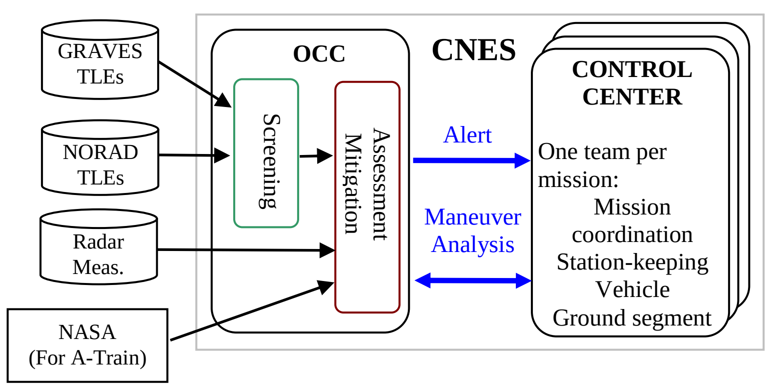


Figure 2*: The CNES collision avoidance information flow*

The following paragraphs describe the operational procedure stage by stage.

1. Automated Screening

Figure 3 presents a diagram of the automatic screening stage. This stage consists of a fully automated process which is performed daily at OCC. Collision risk predictions are made 7 days into the future.

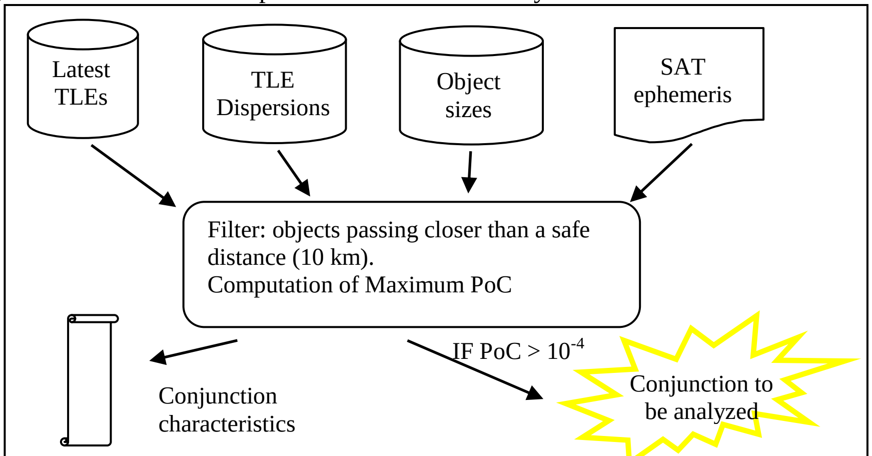


***Figure 3**: Automated Screening*

The orbits of the objects of interest are given by ephemeris provided by the corresponding control centers.
The secondary object information is retrieved from the latest update of the Public NORAD catalog (SpaceTrack database) and eventually completed by data from the GRAVES (French Air Force Space Surveillance System) catalog. Furthermore, in-house databases and varied tools are used to improve the knowledge of the input data: TLE history, object size estimation, orbit discrepancy, etc. The estimation of the orbital position uncertainty is a key element of the in-house modeling tools. For all objects considered, a statistical approach based on differences between extrapolated TLE bulletins of the same object elaborates an estimate of the orbit uncertainty for each axis of the local reference frame. As pictured in Figure 4, this estimate takes into account not only a consistent evaluation of differences between consecutive TLEs, but also an extrapolation accuracy evaluation that provides a statistical model of the orbit uncertainty evolution. However, it does not give an estimate of error biases.

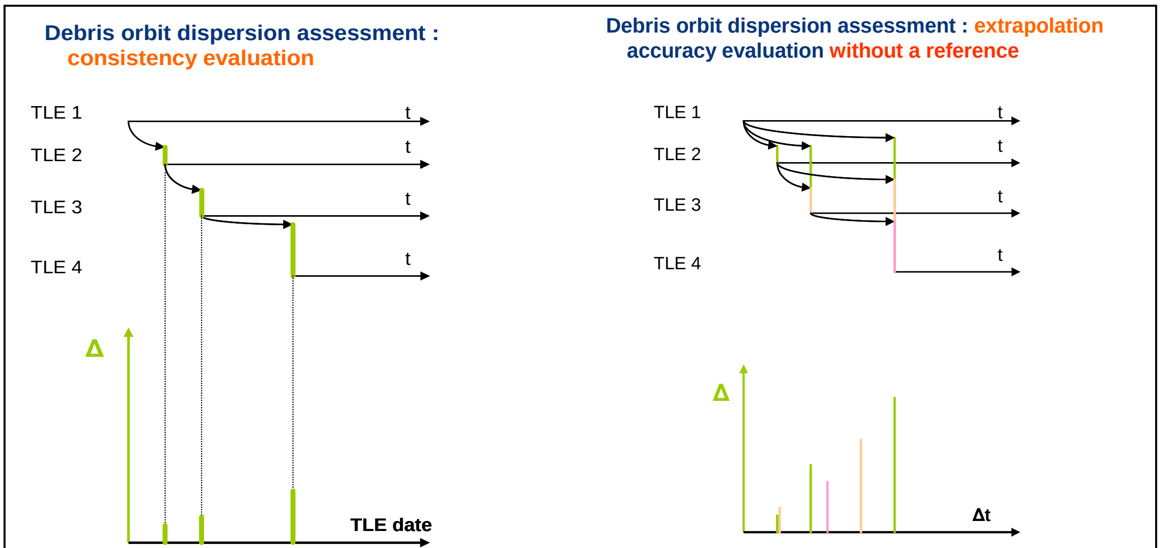


***Figure 4**: Dispersion Assessment*

This preprocessing is performed regularly so that OCC operational databases remain updated.
The automated screening process itself is divided into 3 steps. First, all conjunctions are filtered to keep the ones with secondary objects passing closer than a safe distance (10 km) to any primary object. Second, the real and “maximum” collision probabilities are computed with the method described in reference 3. And third, the on-call CA team is sent an automated report describing collision characteristics of all events with a maximum probability

exceeding 10^{-4}. This threshold has been arbitrarily chosen taking into account collision statistics and previous collision risks. It is a result of the experimental implementation phase.

2. Manual Risk Assessment

This stage consists of the manual assessment of the short-listed conjunctions reported by the automated screening and/or by the collision risks for the A-train constellation reported by NASA. The CA team updates all data related with the conjunctions to be assessed with the latest information available: spacecraft ephemeris extrapolation, latest TLEs from all databases, discrepancies refinement, etc. It is with the updated information that the screening process for each short-listed conjunction is manually started. The sensitivity analysis of this manual screening takes into account several criteria at the same time: collision probability, orbit uncertainties, miss distance on each axis, trending miss distance, conjunction geometry, conjunction date and object size. Each conjunction characteristic is important and that is why an empirical approach is necessary. The risk evaluation can be decomposed in two phases: trend analysis and statistical analysis.

The trend analysis studies the evolution of collision geometry and probability. Figure 5 is an example of the information produced by this phase. The primary object in plotted in the center of the collision plane. The evolution of the position of the secondary object closest approach is represented for input data received at different dates before TCA.

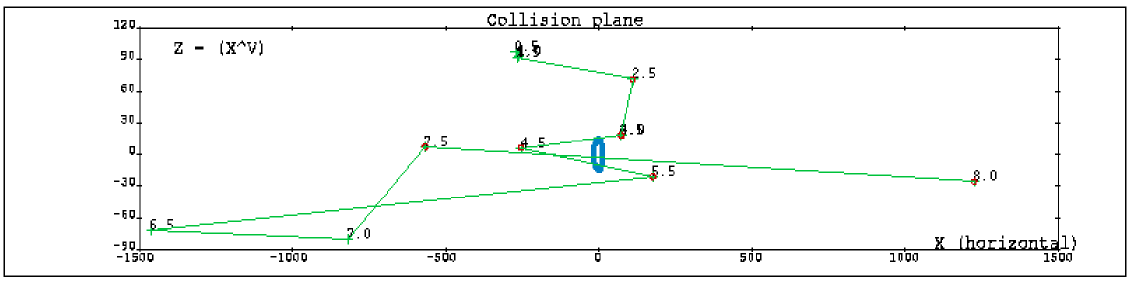


***Figure 5**: Trend analysis in the collision plane*

The statistical analysis studies the distribution of collision probabilities through different geometries. For instance, Figure 6 shows the projections of the secondary object TLE extrapolations in the collision plane. The blue circle in the center represents the projection of the collision sphere (combined hard body radius) and the red and green points stand for conjunctions with a collision probability > 10^{-3} and < 10^{-3} respectively. It is in this statistical analysis phase that different types of analytical and numerical probability calculations have been experienced.

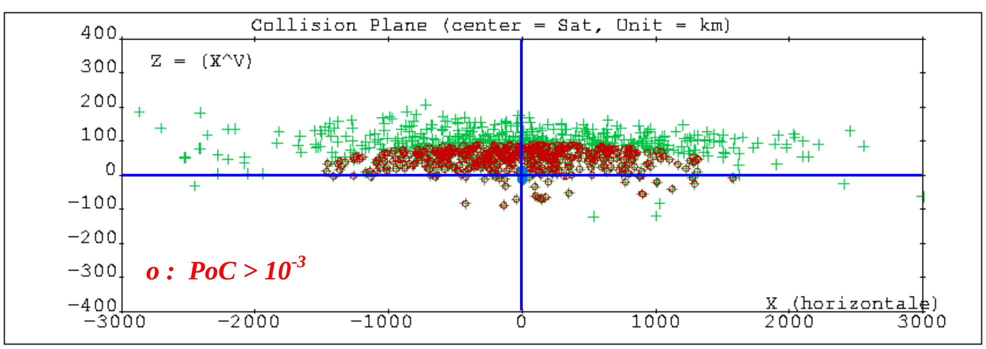


***Figure 6**: Sample discrepancies in the collision*

At present, an estimate of the probability which is called "operational probability" is a key element used to determine whether a conjunction is to be analyzed. Given that the number of collisions is proportional to the surface of the collision circle, this calculation performs an extension of the collision area (initially a circle with a radius equal to the sum of the conjunction bodies radii) to embrace more real discrepancy cases so that more varied and better statistical estimates can be obtained. The main advantages of this method are that it is based on real

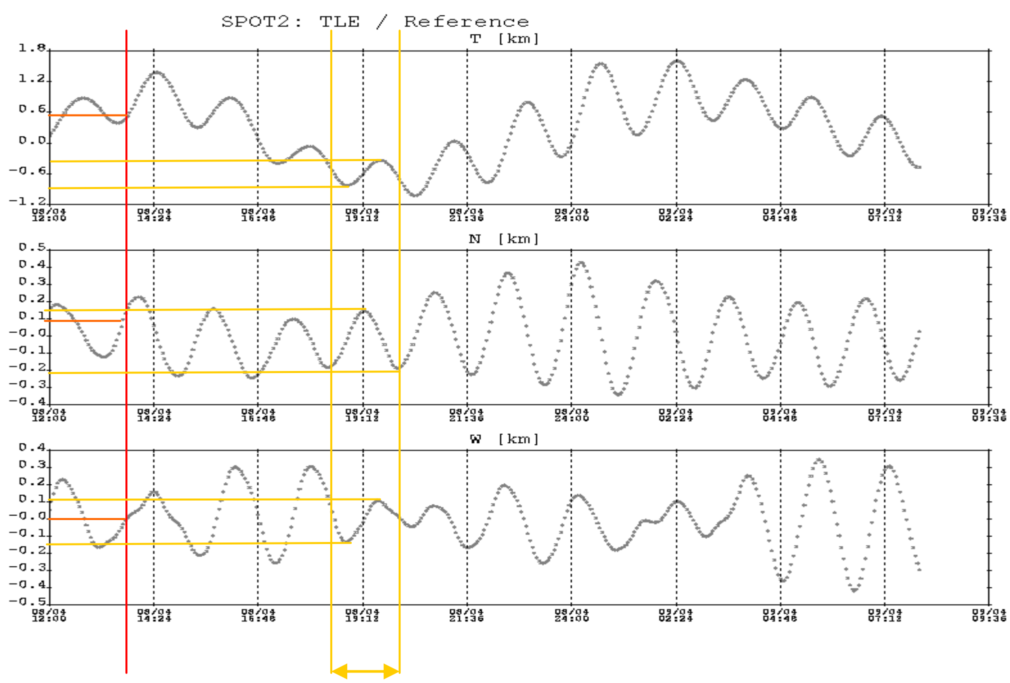
discrepancy cases and that it neither needs the Normal distribution of dispersions nor the constant relative velocity assumptions.
Only the criterion of operational probability of collision > 10^{-3} automatically selects a conjunction for the next stage. This threshold has been set through experience.

3. Dangerous Conjunctions Fine Assessment

The objective of this stage is to determine the dangerous conjunctions that need to be mitigated. This is a manual procedure that requires experience and knowledge of OCC tools and collision risks management theory. First, all inputs are updated again and refined as much as possible. This involves getting new orbit data from radar measurements which are specifically requested for each dangerous debris objects. In-house models process known radii and radar-equivalent equivalent surfaces to produce estimates of the secondary objects radii. The complete TLE histories of the secondary objects are updated, carefully analyzed and processed to yield fine dispersions. Indeed, the method used to compute orbit dispersions differs slightly from the first two stages. Whereas in the previous stages dispersions are computed by TLE extrapolation differences on several points over the orbital period, the fine assessment focuses on calculating dispersions at the on-orbit-position of the dangerous conjunction. This is a more accurate estimate that requires the conjunction position and is therefore exclusively adapted for this fine assessment step. Figure 7 highlights the dispersion differences between different on-orbit-positions for the CNES controlled satellite SPOT2.

CNES – Xtrace V5.10

Figure 7: *On-orbit-position dispersion differences in the orbital local frame*
(T = in-track direction ; N = radial direction; W = cross-track direction)



Once all inputs have been optimized the CA team deals with the risk evaluation again, and therefore produces updated results for the trend and statistical analyses. There are three common cases of dangerous conjunctions selected for the next stage: when the secondary object orbit is corroborated by radar measurements and the operational collision probability exceeds 10^{-3}, when the secondary object orbit is NOT corroborated by radar measurements and the operational collision probability exceeds 10^{-2}, or when the risk is confirmed by NASA (only in the particular case of the joint collaboration for the A-train constellation). In parallel, a 3D visualization of the conjunction with an in-house visualization tool helps to fully understand the geometry of the problem and validate computation results. Figure 8 shows a SPOT satellite with its uncertainty volume in red, in a close approach configuration with an object (yellow sphere) with its uncertainty volume in green.

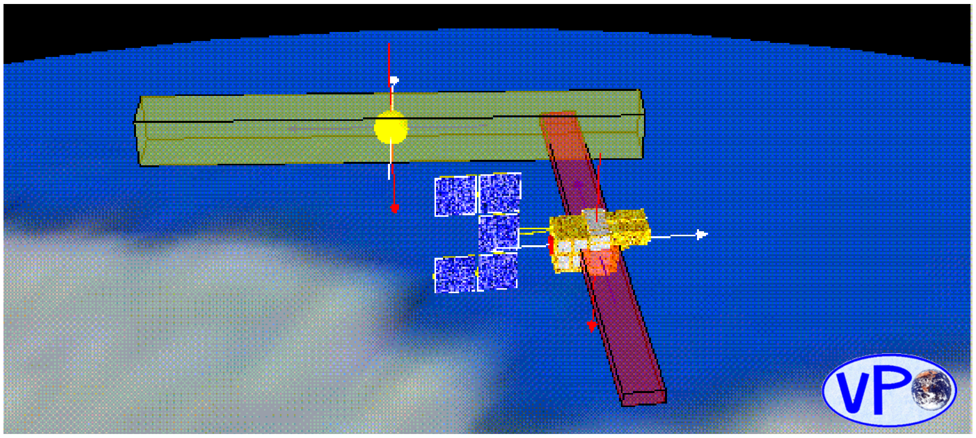


Figure 8*: Example of 3D visualization*

Figure 9 summarizes in a diagram of the main phases and dependencies of this stage.

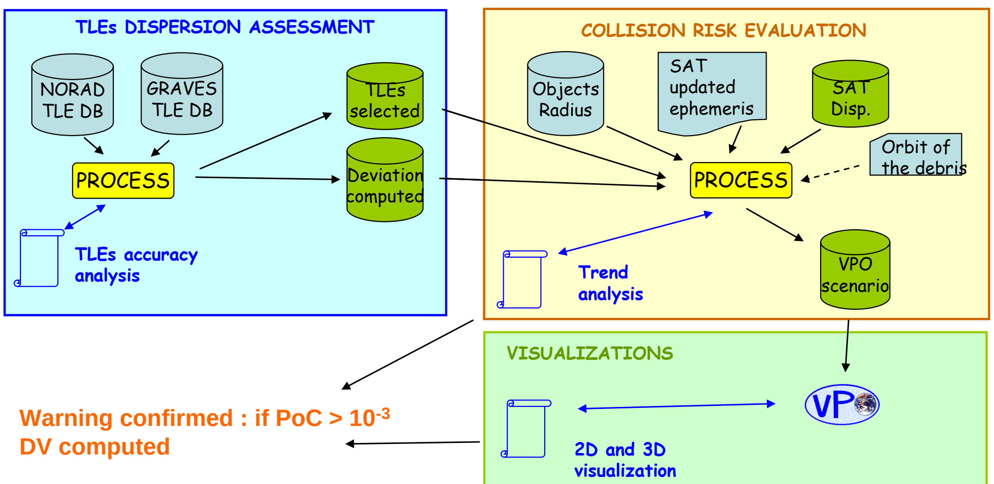


Figure 9*: Fine analysis process*

4. Conjunction Mitigation

The conjunction mitigation is coordinated by the on-call mission representative. Exceptional Operational Coordination Group (OCG) meetings are scheduled, in which all important actions and decisions are discussed and eventually approved. Regardless of the maneuvering decision, the CA team will continue to analyze the conjunction risk if any new data becomes available so that any increase or decrease in the collision risk is quickly detected. In parallel, possible avoidance maneuvers are calculated in cooperation with the station-keeping team taking into account satellite mission, platform and operational constraints, as well as potentially new high-risk conjunction events in the post maneuver trajectory. The final decision criteria are the evolution of the operational probability, trends in the collision plane, spacecraft mission specificities and capacity to perform a required avoidance maneuver. If it is decided to perform a maneuver, OCG determines whether a “come-back” maneuver is required.

5. Formal End of Conjunction Mitigation

Once the conjunction risk has been mitigated, an analysis of the lessons learned is initiated in order to improve our knowledge and operational procedures. Therefore we capitalize a maximum of information from each risk. All data exchanged and decisions taken during the corresponding conjunction risk management are compiled, debriefing documents are issued and presentations are undertaken in exploitation reviews.

IV. Real Operational Case Example

This section describes a real close approach between a SPOT satellite and a FENGYUN-1C debris (number 29773) that occurred on July 22nd 2007 at 05h49.

Stage 1: Automated Screening
This conjunction was firstly identified in the morning of July 18th thanks to the screening process of the previous night. The automatic screening output provided the main characteristics of the close approach:

- time of closest approach: July 22nd 2007 at 05h49;
- Maximum probability exceeding 10^{-4};
- Radar cross section of the debris had been in the interval of [0.011 ; 0.043] during the previous 34 weeks, which produces an estimation of the body radius < 2m;
- The conjunction geometry:
  - Miss distance = 125 m;
  - In-track separation = 90 m;
  - Radial separation = 50 m;
  - Cross-track separation = 70 m.

Stage 2: Manual Risk Assessment
This conjunction was manually analyzed every day from July 18th till the conjunction date. Once all new data was updated and pre-processed, the first task consisted in determining, thanks to the latest TLEs received, the evolution of both the probability of collision and the objects relative position in the collision plane. Figure 10 pictures these evolutions.

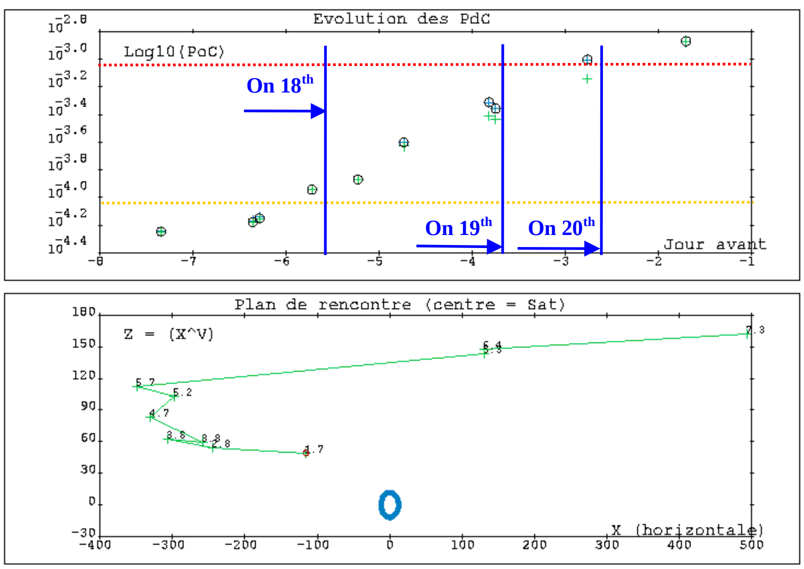


Figure 10*: Evolution of PoC and relative position in collision plane*

In the top graph, the green crosses and black circles correspond to the real and maximum probabilities respectively. The blue lines show the evolution of the graphic from July 18 to 20. The whole graphic was elaborated in the evening of July 20th, after the acquisition of the latest debris TLEs. It can be observed that the probability of collision was gradually increasing. These results gave the expert the feeling of a highly probable critical evolution of the conjunction. Those elements were suggesting a request for external measurements. Figure 11 completes the information of Figure 10 but with some TLEs acquired days after the conjunction date. It confirmed the critical evolution “a posteriori”. The CA team has to forecast this evolution before the conjunction date.

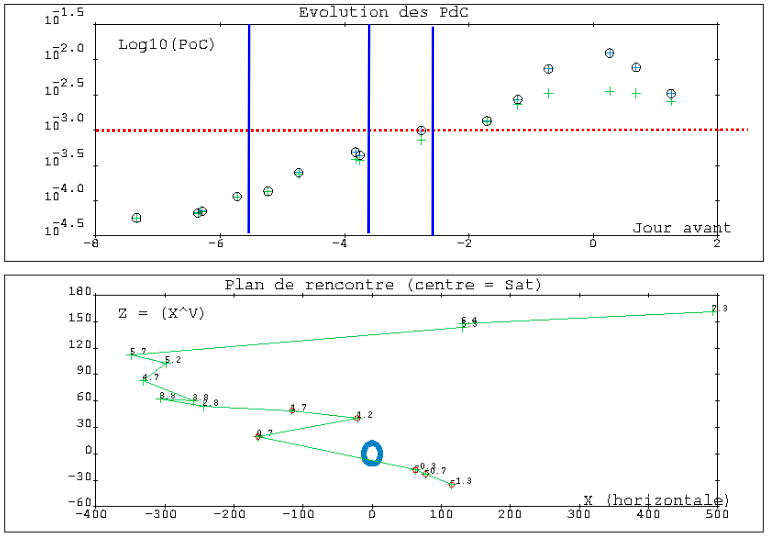
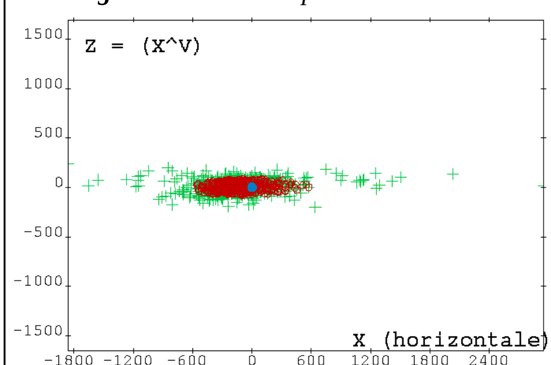


***Figure 11**: Confirmation of the critical tendency*

Another task of this stage is the computation of the operational probability and the statistical distribution of the probability of collision. Figure 12 shows the statistical distribution of the debris position in the collision plane at the time of the closest approach. Each cross is a real discrepancy case of the debris TLE observed in the past and applied to this case. The probability of collision is analytically computed for all points with two approximations: a Normal distribution hypothesis for the TLEs dispersions and a constant relative velocity at a reduced interval of closest approach. When the PoC is greater than 10^{-3} the crosses are red circled. In our example, 75% of the 630 cases gave a PoC exceeding 10^{-3}. This was another condition that suggested asking for radar measurements.

***Figure 12**: Collision plane: with TLE*



The following action was the computation of the operational probability of collision. In our current example this probability was equal to 2.5 10^{-3}. This figure was greater than 10^{-3}, which was another reason for the CA team to ask for radar measurements in order to improve the orbit knowledge of the debris.

Stage 3: Dangerous Risk Fine Assessment
As shown in Figure 13, radar measurements of two passes were acquired from one of the DGA (French Defense) radars: the first on July 20th at 16h27 and the second on July 21st at 6h20 (one day before TCA).

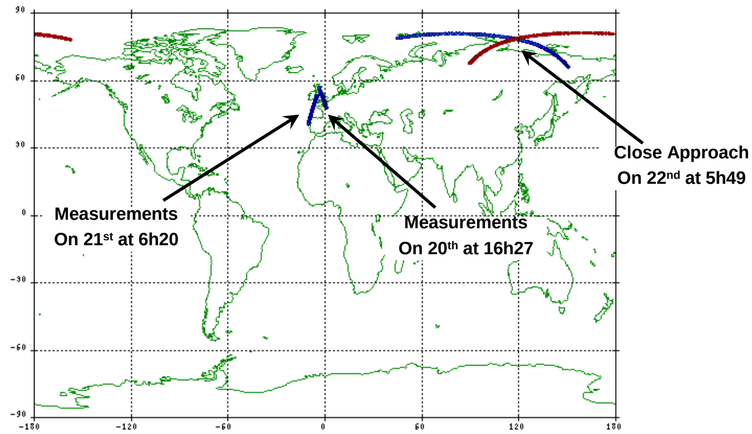


***Figure 13**: Pass Configuration*

The angular and ranging measurements processing allowed correction the secondary object orbit as follows:

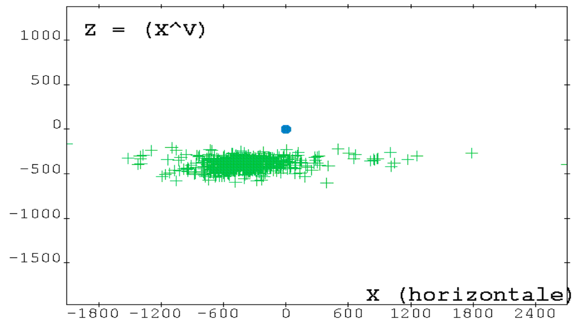
- Semi major axis: 2 m;
- Inclination: 0.003 deg;
- Ascending node: 0.002 deg;
- On orbit position: 0.001 deg.

Given this updated orbit, the new conjunction geometry was quite different:

- In-track separation = 290 m;
- Radial separation = 360 m;
- Cross-track separation = 225 m.

The alarming results from stage 2 were updated: in 100% of the cases the analytical probability of collision was lower than 10^{-3} and the operational probability of collision was equal to $7*10^{-5}$. Figure 14 presents the new statistical distribution of discrepancies in the collision plane. Therefore, in the morning of July 21st we were able to cancel the avoidance maneuver before its on-board execution.

***Figure 14**: Collision plane after OD*



Stage 4: Conjunction Mitigation
The conjunction risk did not reach this stage.

Stage 5: Formal End of Conjunction Mitigation
This example enhanced the need of radar measurements to improve orbit knowledge of debris before any collision avoidance maneuver decision. TLE catalog is the best mean to detect dangerous conjunctions but not accurate enough to compute avoidance maneuvers.

V. Conclusion

Today, the CNES collision avoidance procedure is operational for the 14 (15 soon) LEO satellites controlled at CNES. Operational qualifications have been undertaken involving all teams (mission, payload, on-board, station-keeping …).

For the last 12 months, 977 collision alerts for 405 conjunctions were handled in the stage-2 process (output of stage 1): among those 405 potentially dangerous close approaches 37 had an "automatic" probability of collision greater than 10^{-3}, and 19 greater than 10^{-2}. Seven cases needed a stage-3 analysis with a request for radar measurements: none of them required an avoidance maneuver.

This process is in permanent improvement from operational feedback. One of the main lessons learned is the need of external measurements to confirm a maneuver decision.

Some areas of further studies have already been identified: computation of a more realistic probability of collision without the Normal distribution hypothesis, better estimations of TLE dispersions[5] and access to other measurements such as FGAN radars.

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