CNES OPERATIONAL EXPERIENCES IN COLLISION AVOIDANCE FOR LEO SATELLITES

Xavier PENA(1) and Monique MOURY(2)

CNES DCT/OP/MO, 18 av. Edouard Belin, 31401 Toulouse cedex 9, France,
(1) Email: xavier.pena@cnes.fr,
(2) Email:monique.moury@cnes.fr

ABSTRACT

CNES (French Space Agency) performs collision risks monitoring for the 15 LEO (Low Earth Orbit) satellites it controls. Most of the operational collision avoidance (CA) activities are gathered at OCC (Orbit Computation Centre) in the CNES Operations Sub-directorate.

First this paper briefly presents the current CNES Collision Avoidance Process which includes OCC contingency operational procedure for collision risks management partially put to test with the recent IRIDIUM and COSMOS collision case. Then the key results since the beginning of the operational activities are introduced : number of alerts, number of avoidance manoeuvres and the most often encountered debris.

In order to give an idea of the variety of situations which needs to be handled some examples of real encountered cases are discussed: a typical close approach, a close approach between two controlled satellites and finally a close approach between an operational satellite with a non-operational one which is on almost the same orbit.

1. INTRODUCTION

There are four recorded collisions with space debris. In December 1991, the Russian satellite COSMOS 1934 and a COSMOS 926 debris collided. 5 years later, on July 24th 1996, the French satellite CERISE was hit by a debris. On January 17th 2005 there was a collision between THOR BURNER and a debris from Long March. And recently, on February 10th 2009, an operational IRIDIUM collided with a non operational COSMOS.

One difficulty of the collision risks management is the limited number of objects tracked: only 13,000 out of 100,000 potentially dangerous debris. Another difficulty is the lack of availability of the accuracy of the publicly available data to properly monitor collision risks. CNES uses different data sources :

- SpaceTrack database: the main Two Lines Elements (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 required to estimate and improve consistency.
- GRAVES database: the French Air Force Space Surveillance System (built by ONERA).
- Specific orbital data: radar measurements from CNES Guyana Launch Centre, French Defence facilities and German TIRA (FGAN) radar. These sources produce very accurate measurements but they are only used to improve the orbit determination of dangerous objects due to their limited availability.

2. CNES COLLISION AVOIDANCE PROCESS

The CNES collision avoidance process is operational since July 2007 on all LEO satellites controlled by CNES. In order to be capable of handling a collision risk whenever it occurs, on-call teams in each speciality are in place. Two on-call teams of flight dynamics engineers are available 24/7: one in charge of CA analyses (CA team) and one in charge of the station-keeping of the LEO satellites controlled at CNES. Obviously, when an avoidance manoeuvre is considered, the CA procedure also relies on all the other on-call teams (vehicle, payload, ground segment, stations network …). The CNES procedure is divided in 5 stages as presented in Fig. 1, each stage being an escalation in the contingency.

The automated screening stage consists of a fully automated process which is performed daily at OCC. Collision risk predictions are made within an horizon of 7 days. The orbits of the CNES satellites are given by ephemeris provided by the dedicated control centres. The secondary object information comes from the Public NORAD (North American Aerospace Defence Command) catalogue (SpaceTrack database) and is eventually completed with data from the GRAVES catalogue. The estimation of the orbital position uncertainty is performed using in-house tools as described in [1]..

The manual risk assessment stage consists of the manual analysis of the risks detected by the previous stage. This stage cannot be completely automated since

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each conjunction characteristic (collision probability, geometry and date, orbit uncertainties, miss distance on each axis, trending miss distance and object size) is important and has to be analyzed and taken into account to evaluate the risk.

The aim of the dangerous conjunctions fine assessment stage is to determine the conjunctions that need to be mitigated. This is also a manual stage and it involves requesting radar data in order to improve the knowledge of the object orbit. At this stage, three kinds of risks can lead to conjunction mitigation:

- if the secondary object orbit is confirmed by radar measurements and the operational collision probability exceeds 10^{-3},
- if radar measurements are not available and the operational collision probability exceeds 10^{-2},
- if the risk is confirmed by NASA (when the conjunction concerns one of the CNES satellites involved in the Aqua-Train).

During the conjunction mitigation stage CA team keeps on analyzing the risk so that any change in the collision risk can be detected. At the same time, possible avoidance manoeuvres are computed 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 manoeuvre trajectory. This stage is coordinated by the on-call mission representative through exceptional Operational Coordination Group (OCG) meetings which decide if an avoidance manoeuvre has to be performed.

The final stage is the formal end of conjunction mitigation. At this stage, the CA team tries to analyze the lessons learned in order to improve the process. Post collision avoidance reports summarizing the risk management are produced and presentations are performed in annual exploitation reviews.

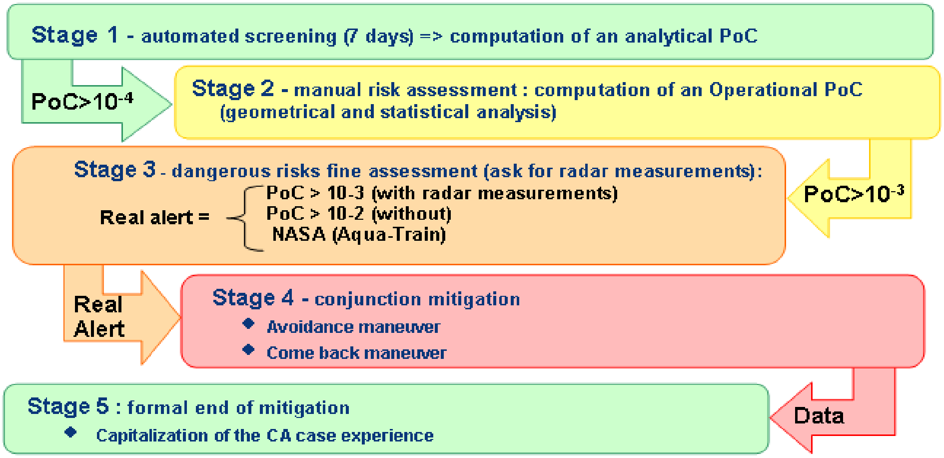

Figure 1.Five stages procedure

2.1. Application to the IRIDIUM/COSMOS collision case

The operational US satellite IRIDIUM 33 and the non-operational Russian satellite COSMOS 2251 collided in orbit on February 10th 2009 at 16h56 UT. Around 200 debris of IRIDIUM and 450 of COSMOS are catalogued in the Space Track database.

In order to experiment the efficiency of the CNES process this collision case was applied to the automated screening stage taking IRIDIUM as the satellite of interest (as it was one of the satellites controlled by CNES).

Since IRIDIUM accurate orbit is not available at OCC, the experiment was performed using the two Space Track TLEs available before and after the collision. For COSMOS, all the TLEs available up to seven days before the collision were considered.

Orbit dispersion associated to available TLEs of both IRIDIUM and COSMOS were estimated with the same method than the one described in [1] and used in daily operational activities. Orbit dispersion estimation has two phases: the orbit consistency evaluation and the extrapolation accuracy estimation.

The orbit consistency evaluation is performed by the extrapolation of each TLE of the concerned object to the following one and then by comparing them at the on-orbit-position of the conjunction. The results of this phase are the differences between contiguous TLEs in

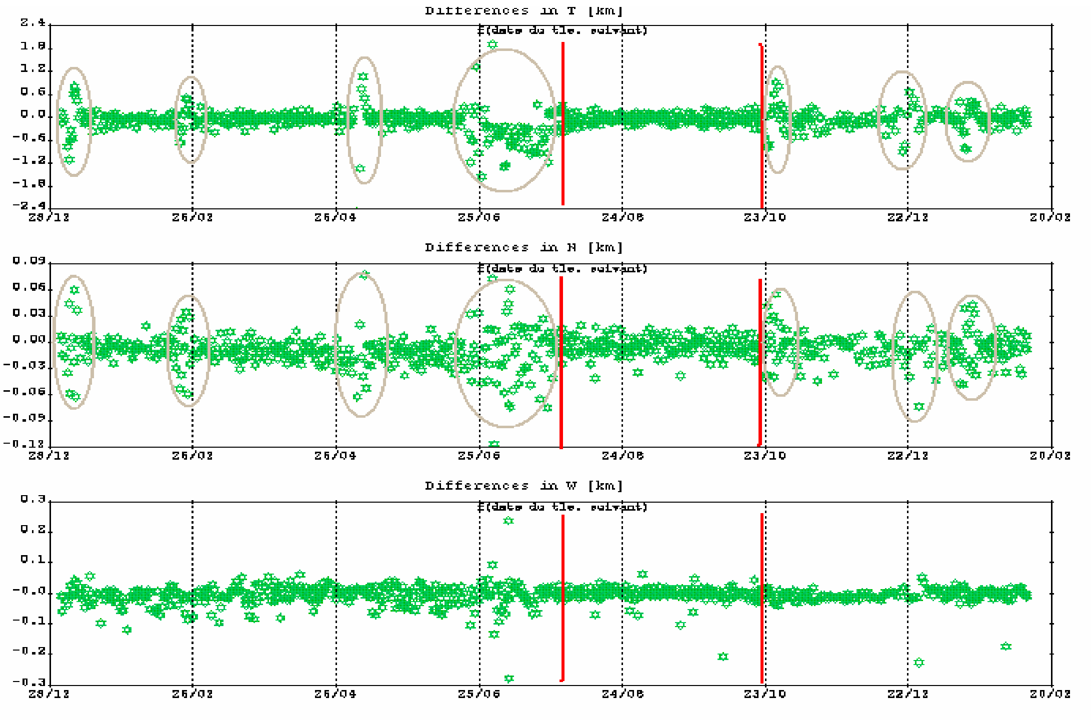

Figure 2 .IRIDIUM TLEs consistency

the three axis of the local reference frame over a given time interval. The analysis of these differences is used to identify and eliminate anomalous TLEs, to filter manoeuvres and to define the best period for the next phase. Fig. 2 shows the result of this treatment applied to IRIDIUM in T(in-Track), N (Radial) and W (Cross-Track) axes. Y axis represents the differences between TLEs and X axis represents the TLE date. Manoeuvres are clearly identified with observed differences in In-Track and Radial directions (grey ellipses). As IRIDIUM is supposed to be one of the CNES satellites, dispersion estimation should not take into account manoeuvres so the TLEs chosen for the next phase were those within the time interval delimited by the red lines (approximately 200 TLEs).

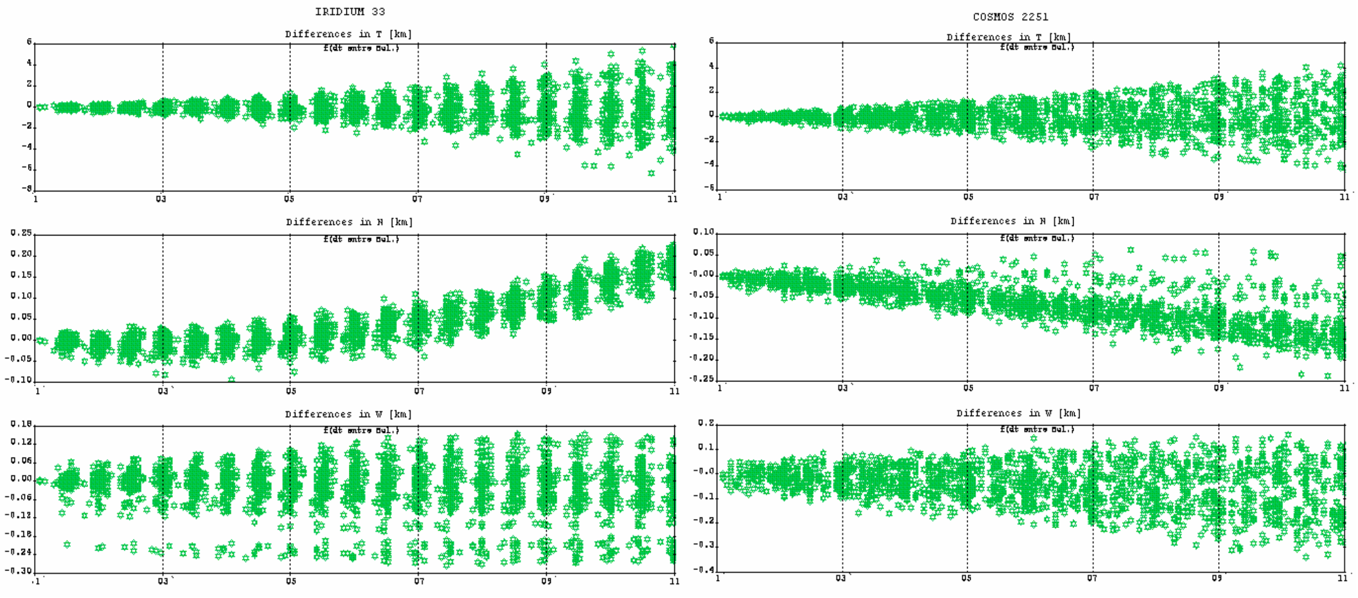

Figure 3 .IRIDIUM and COSMOS extrapolation estimation accuracy

The extrapolation estimation accuracy is performed by comparing at the on-orbit-position of the conjunction each TLE with the following ones that are within a given extrapolation horizon. The results of this computation represent the expected dispersions when extrapolating a TLE. Fig. 3 is the graphical representation of this estimation for COSMOS and IRIDIUM in the three local reference frame axes. Y axis is the difference between TLEs and X axis represents the extrapolation duration. For instance, when extrapolating during 7 days a COSMOS TLE we expect a dispersion of 2 kilometres in In-Track direction, around 150 meters in Radial direction and 250 meters in Cross-Track direction. The limitation of this method is that it does not estimate possible TLEs biases.

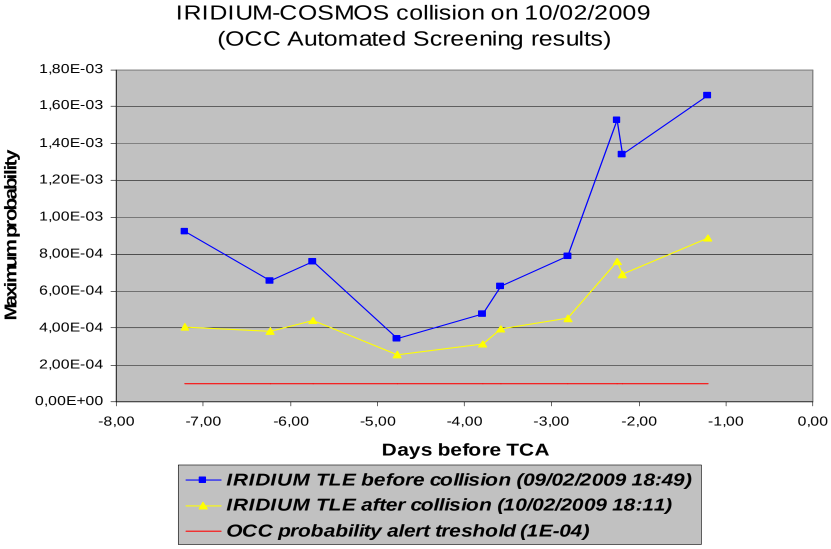

Figure 4. OCC automated screening applied to the IRIDIUM-COSMOS collision

These dispersions were used as input data for the automated screening in order to compute the maximum probability of collision, Fig 4 shows the obtained values. One can see that maximum probability of collision (our detection criterion) using either IRIDIUM TLEs before or after the TCA is higher than the alert threshold each day within the screening horizon which means that the risk would have been daily analyzed.

This exercise is mainly constrained by the miss-knowledge of the IRIDIUM accurate orbit. Proceeding to the next stages without that information is not relevant so the entire process has not been experimented.

3. OPERATIONAL KEY RESULTS

The aim of this section is to present the main operational results since the operational kick-off of the collision avoidance process (since July 2007).

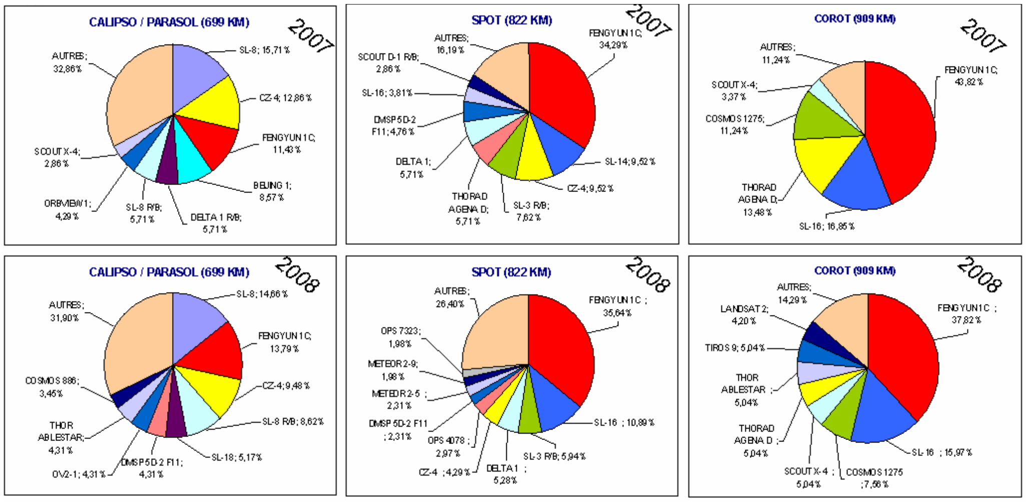

Figure 5. Most dangerous debris families by orbit altitude

CA team considers a collision risk as a close approach between a satellite controlled by CNES and an object when the minimal distance is lower than 10 km and the maximum probability of collision is higher than 10^{-4}. A single risk generally gives place to several successive alerts in the daily report of the automatic screening. During the 6 months of operational activities of 2007 CA team handled 428 alerts corresponding to 179 risks in stage-2. Three cases needed a stage-3 analysis with a request for radar data and 1 risk needed to be mitigated by programming an avoidance manoeuvre that was finally cancelled few hours before its execution thanks to radar measurements.

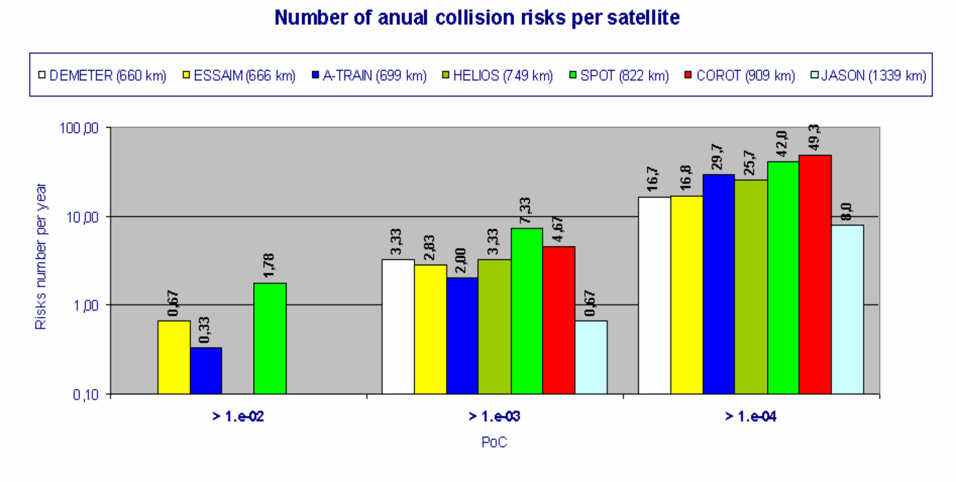

Figure 6. Number of annual collision risks per satellite and probability threshold

In 2008, 881 alerts corresponding to 344 risks were analyzed in stage-2. These values represent almost the same average number of alerts (2.4) and risks (1) per day than in 2007. During 2008, 13 cases were analyzed on the stage-3, 4 of them triggered by NASA and 2 confirmed risks were mitigated by anticipating a coming station keeping manoeuvre.

Fig. 3 shows the most dangerous debris for each CNES orbit family (700km, 800km and 900 km). For orbits between 800 and 900 km Fenyung 1C debris represent the largest proportion of alerts. In 700 km orbits, alerts are mostly generated by Sea-Lunch, CZ-4 and Fengyung debris in equal shares.

Risk distribution by satellite family can also be represented versus the chosen threshold for the probability of collision. In Fig. 4 we can find the number of collision risks per year and per satellite for each family depending on the probability threshold considered for the screening. SPOT, ESSAIM and A-TRAIN (CALIPSO and PARASOL) families are the most dangerous ones which is consistent with the risks treated at stage-3 and the avoidance and advanced station-keeping manoeuvres performed.

4. EXAMPLES OF REAL CASES

This section describes some real cases handled by CNES CA team since the beginning of its operational activities. The objective is to illustrate the variety of situations encountered, firstly describing a typical case and then presenting two special cases for which the involvement of several CNES entities was required.

4.1. Typical close approach

On July 18th the automatic screening provided the following information concerning a new collision risk:

- time of closest approach (TCA): July 22nd 2007 at 05h49;
- maximum probability exceeding 10-4;
- the conjunction geometry:
  - miss distance = 125 m;
  - in-track separation = 90 m;
  - radial separation = 50 m;
  - cross-track separation = 70 m.

The risk was manually analyzed (stage-2 of the CNES procedure). The first task consisted in determining the evolution of the probability of collision, the object's relative position in the collision plane (plane perpendicular to relative velocity of both objects at the time of close approach) and the statistical distribution of the debris position as shown in Fig 7. It can be observed that on July 20th the probability of collision exceeded 10-3. The risk went to stage-3 analysis and the CA team requested for radar tracking data.

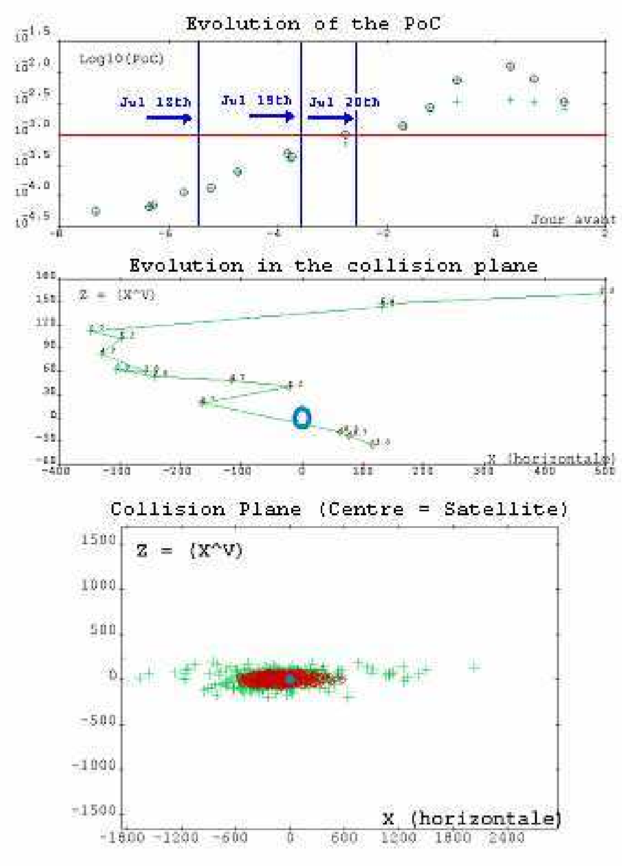

Figure 7. Evolution of PoC, relative position in collision plane and distribution of the debris position

One of the French Defence radars provided two passes, the first one on July 20th at 16h27 and the second one on July 21st at 6h20. Using these data the debris orbit could be affined giving a quite different conjunction :

- in-track separation = 290 m;
- radial separation = 360 m;
- cross-track separation = 225 m.

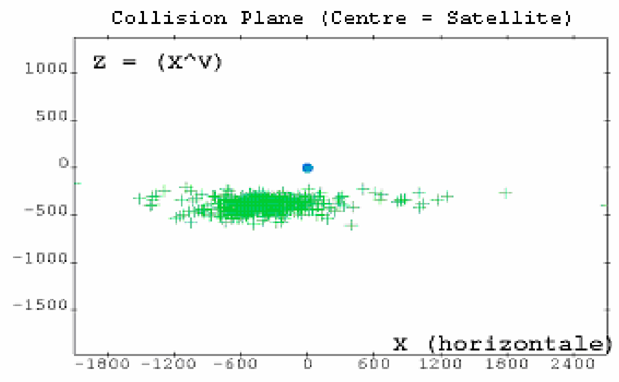

Figure 8. Distribution of the debris position after the orbit determination

With these new data CA Team computed the statistical distribution of the debris position. The result is shown in Fig 8.
The new probability of collision was 7*10-5, therefore the uploaded avoidance manoeuvre was cancelled before its execution. Complete information about the management of this risk can be found in [1].

4.2. Close approach between controlled satellites

In the beginning of 2006 the orbit of CNES satellite DEMETER was decreased for missions management purpose but unfortunately created a periodical dangerous configuration with ESSAIM constellation (also controlled by CNES). The semi major axes of DEMETER and ESSAIM differed only by 1.7 km causing a relative drift in argument of latitude. This fact, added to the variations of eccentricities, produced both DEMETER and ESSAIM constellation orbits to intersect twice a year.

CNES managed this risk by considering the precision of the orbits and the operational constraints related to the effective realization of possible avoidance manoeuvres. The difference with a classical case was that the concerned satellites were both controlled by CNES and their orbits were well-known, therefore risky periods could be identified long time before the close approach (with the limitation of orbit propagation uncertainties) and then gradually characterised. The priority was to prepare an avoidance strategy but only perform a DEMETER avoidance manoeuvre if it was really needed.

While for typical close approaches (conjunctions with non-operational satellites) the criterion is the probability of collision, in this case CNES preferred to consider geometrical criterion and define exclusion volumes around each satellite. The idea was to guarantee that collision was not possible (no intersection of the defined exclusion volumes). Detailed information about the management of these close approaches and how the exclusion volumes were estimated can be found in [2].

CNES managed four close approaches (every 6 months) from January 2006 to January 2008. The first close approach, on June 2006, needed an avoidance manoeuvre on DEMETER, for the other close approaches the risk was managed using the autonomous orbit control of DEMETER.

The periodical risk was finally cancelled in early 2008 with the decision to decrease the orbit of DEMETER by 1.7 km which froze the relative drift between the satellites.

4.3. Close approach between a controlled satellite and a non-controlled one which are in a close orbit (JASON-1/TOPEX)

Launched in 1992, TOPEX was a common project of NASA and CNES to measure the surface of the global ocean. This project was followed-on by JASON-1 satellite, launched in 2001 and placed on the same orbit.

TOPEX mission ended in October 2005 due to attitude control troubles and the satellite was finally decommissioned in January 2006 losing manoeuvre capability. As both TOPEX and JASON shared the same low-drag orbit, the non-controlled TOPEX became a dangerous debris for JASON. Some studies were carried out in order to predict the period of close approach and the relative position of the satellites was periodically monitored by CNES and NASA teams.

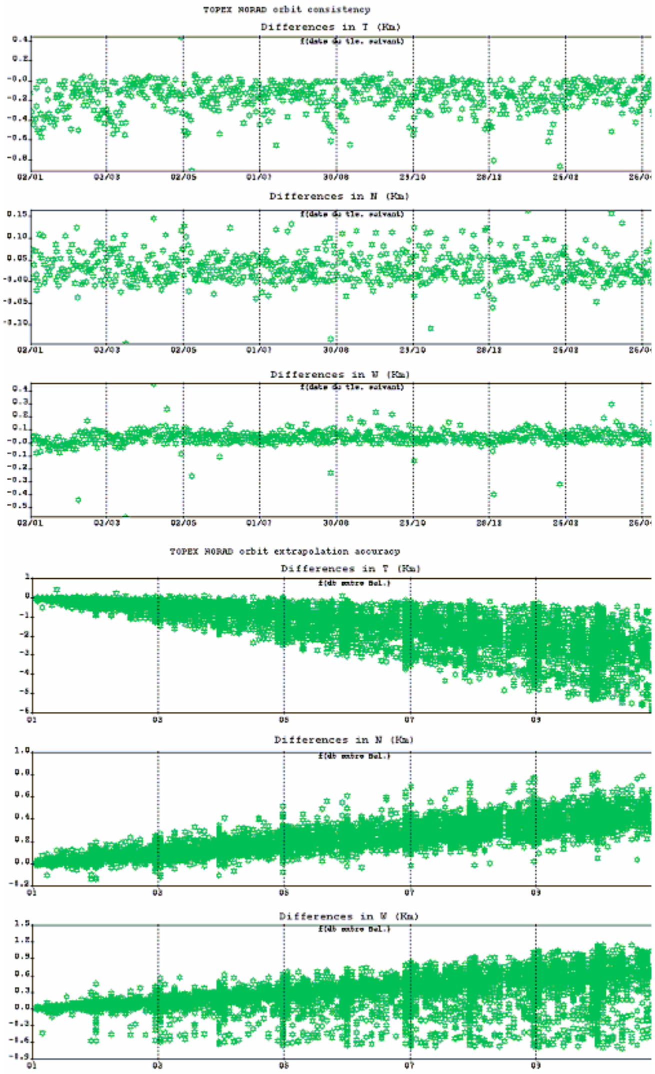

Figure 9. Evolution of PoC, relative position in collision plane and distribution of the debris position

CNES CA team operational activity began one month before the conjunction when the period of close approach (from May 5th to May 10th 2008) was precisely identified. The first task was to estimate TOPEX orbit consistency and extrapolation accuracy from NORAD and GRAVES TLEs as described in section 2.1. Fig. 9 shows the results of these computations using the NORAD TLEs (for GRAVES TLEs the results were quite similar). One can see that for a 5 days extrapolation radial dispersion was around 400 meters.

Whereas in a classical close approach the avoidance manoeuvre is chosen to mitigate a well-defined conjunction (in terms of time), in this case the avoidance manoeuvre should have eliminated several risks since the close approach period lasted around 5 days. It implies that a come back manoeuvre would have been necessary, at least, 5 days after the avoidance manoeuvre. Due to mission constraints, a typical semi-major axis avoidance manoeuvre would have implied to perform two come back manoeuvres in order to come back to the same on-orbit-position than the one before the avoidance manoeuvre (Fig 10). It would have meant a mission interruption of 10 days. Other manoeuvres types, like eccentricity manoeuvres, were analysed too but, in all cases, a mission interruption of at least 1 week would have been necessary.

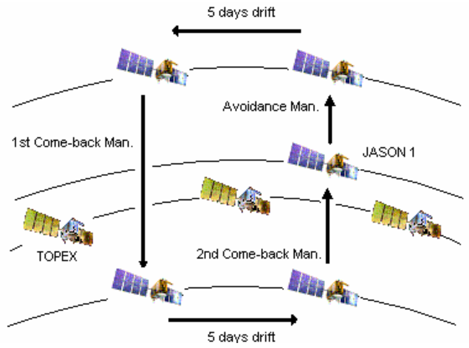

Figure 10. Classical avoidance strategy

Taking into account all this information the CA team chosen strategy was the one disturbing the less possible JASON mission : to compute a precise TOPEX orbit in order to perform the avoidance manoeuvre only if it was absolutely necessary.

Therefore two weeks before the identified risky period a measurement campaign was organized with the support of German TIRA (FGAN) and French Defence (Monge vessel) radars. In total 10 radar passes were received :

- 5 FGAN passes from 23/04 to 25/04
- 1 Monge pass on 30/04
- 3 FGAN passes from 06/05 to 07/05
- 1 Monge pass on 07/05

The first orbit computation was made on April 28th. The minimal radial miss distance obtained using this orbit was around 400 meters in the evening of May 8th. The orbits determined the following days confirmed those results (minimal radial miss-distance and closest approach date). Taking into account the estimated orbit dispersions respectively for TOPEX and JASON satellites, CNES considered that this radial miss distance ensured a sufficient radial separation. The last orbit determination on May 7th again confirmed the minimal radial miss-distance around 400 meters on May 9th at 4h32.

Decision was taken between CNES and NASA JPL that no avoidance manoeuvre was required.

5. CONLUSION

Today, the CNES collision avoidance process has been operational since almost 2 years for the 15 LEO satellites controlled by CNES.

The process depends on :

- Completeness and reliability of catalogues for detection. The US catalogue is more complete and publicly available. The accuracy of the GRAVES one is available at OCC.
- Capacity to determine the orbit of the threatening secondary object for mitigation. Therefore, tracking radar access improvement is the priority to improve the process.

With a controlled knowledge of orbits, avoidance manoeuvre will be rare and small and only when absolutely needed.

The CNES collision process cannot guarantee there will be no collision for the satellites of interest, it tries to guarantee that the detectable ones will be mitigated.

6. REFERENCES

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