COLLISION AVOIDANCE PRACTICES FOR GEO SATELLITES IN AN OPERATIONAL CONTROL CENTRE

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ABSTRACT

The protection of the geostationary ring has always been a big concern for CNES, in charge of geostationary station-keeping since 1974. In particular, protecting this unique resource implies to absolutely avoid any collision in this region, as it could generate debris that would pollute on a long term basis the whole geostationary ring and so threaten all current and future missions.
This paper will focus on CNES recent experience concerning on-orbit collision avoidance for operational geostationary satellites. The different stages of risk mitigation will be discussed : specific practices to increase safety during longitude drift phases, daily screening for conjunctions detection, analysis of risk and decision of performing an avoidance manoeuvre with respect to mission constraints. This process will be illustrated by two examples of operational management for proximity situations.

1. OPERATIONAL CONTEXT

CNES has controlled geostationary (GEO) satellites since 1974 and began to care for space debris mitigation in geostationary area in 1983 when the first reorbitation process was achieved for SYMPHONY satellites. Studies and improvements for end-of-life have been made ever since for every new satellite generation : raising the end-of-life altitude above 250 km in 1996 and achieving a complete tank depressurization in 1999.
Meanwhile, coordination between in-orbit satellites became a preoccupation : from 1985, drifting satellites during relocations had to avoid the station-keeping corridor. This preoccupation increased with the necessity of having satellites sharing the same window : from 1990 to 1999, four satellites belonging to ESA, France and Germany and controlled by three different control centres were collocated at the same longitude with regular orbit and manoeuvre coordination.
Since 2000, insertion into or departure from collocation situations were managed, as well as controlled proximity of satellites in order to ensure an easy change of satellite for the payload final customers. A coordination process is now also proposed as a baseline to neighbouring satellites operators.

More recently, daily collision risk assessment was set up for GEO satellites as well as LEO ones. This process allows to detect objects belonging to NORAD public catalogue passing near our controlled satellites, in particular all old satellites left on geostationary orbit. A few risks were identified and manually studied among which two led to an avoidance manoeuvre.
These collision risks mitigation practices developed over the years and described hereafter are today applied for the two last geostationary satellites controlled by CNES : Telecom 2C (TC2C) and Telecom 2D (TC2D) which have at the moment regular station keeping cycles consisting of one east manoeuvre every 2 or 6 weeks, without inclination's control.

2. PRACTICES TO INCREASE SAFETY DURING LONGITUDE DRIFT PHASES

During a GEO satellite's life, many situations can require a drift phase : Launch and Early Orbit Phase (LEOP), relocations and end of life manoeuvres. With the drastic increase of objects number in the GEO zone, these moves become more and more delicate, as they can generate dangerous conjunctions. In order to mitigate the risk of pollution of the GEO ring due to a collision in this zone, CNES developed over the years guidelines for longitude drift phases.

2.1. Recommended Strategies for Longitude Drift Phases

The GEO protected region is defined as the geostationary altitude +/- 200 km, i= ± 15° and consists in practice of two distinct zones :

- Zone 1 : this is the operational station-keeping region including satellites station-keeping boxes, usually defined as shown on Fig.1. North/South limits can be larger for satellites not controlled in inclination. Radial limits are defined by altitude variations due to eccentricity (~70 km) and semi-major axis variations (~ 5 km).

Proc. '5th European Conference on Space Debris', Darmstadt, Germany 30 March – 2 April 2009, (ESA SP-672, July 2009)

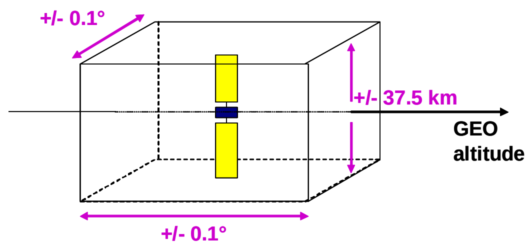

Figure 1 Definition of the operational station-keeping zone

- Zone 2 : drift and manoeuvre corridors are delimited by the high limit of zone 1 on one side and the low limit of graveyard region on the other side, which corresponds to the GEO altitude ± 200 km (2.5° / day drift rate). This zone shown on Fig.2 should be used for longitude drift phases, for example at the end of LEOP or for relocations.

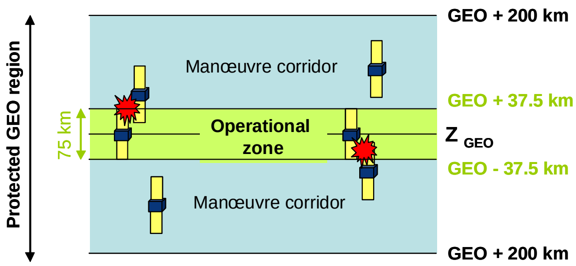

Figure 2 Definition of the manoeuvre corridors for longitude drift phases

Respect for these two separate zones is the first step towards collisions risks mitigation.
The simplest method for a relocation consists in initiating the drift by performing 2 manoeuvres at 12 hours interval. With such a method, the eccentricity during the drift is the same as during station-keeping, implying high daily altitude variations as shown on Fig.3 and Fig.4. These variations often cause violations of the GEO operational zone, threatening other satellites, unless initial manoeuvres are big enough to totally avoid this zone, which means a high cost.

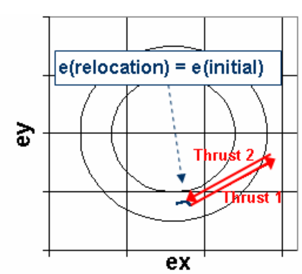

Figure 3 Eccentricity during simple relocation

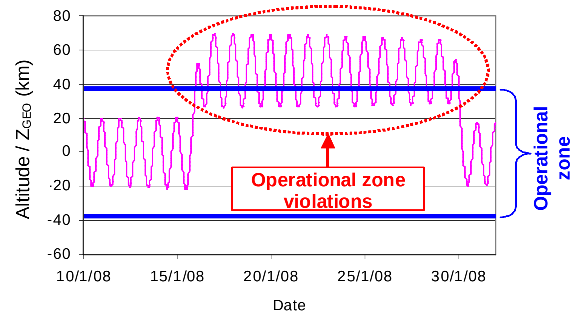

Figure 4 GEO ring violations during a simple relocation

As the cost always is a big concern in such cases, a recommended solution to preserve the GEO ring without over-consumption is to reduce the eccentricity during the drift by optimizing the time of start manoeuvres, as shown on Fig.5 and Fig.6.

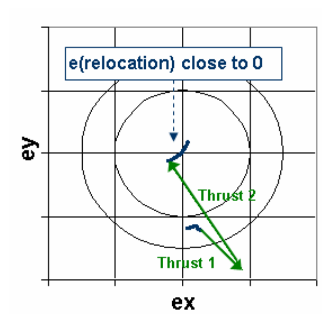

Figure 5 Eccentricity during optimized relocation

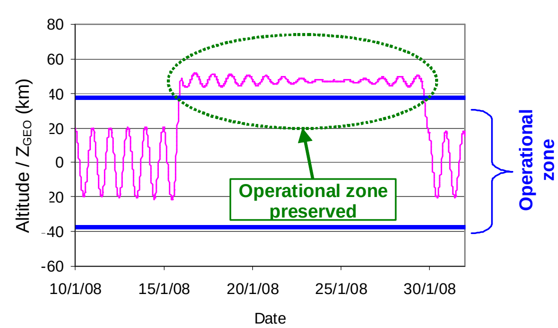

Figure 6 Protection of the GEO ring thanks to minimization of eccentricity

This simple adaptation of relocation strategy allows to mitigate collisions risks without any additional cost.
During LEOP, it is recommended first to target an apogee lower than the operational station-keeping zone to avoid dangerous oscillations in this zone and then to apply the same principle as during relocations for the final drift phase.

2.2. Operational Coordination

Even if the nominal strategy allows to avoid the operational zone, a contingency can occur and cause dangerous incursions in the GEO region. Manoeuvres can be postponed or aborted for a lot of different reasons (for example : satellite's failure or ground station's failure) and such events can quickly result in a violation of the operational zone. An example of such contingencies studied for TC2 relocation is shown on Fig. 7.

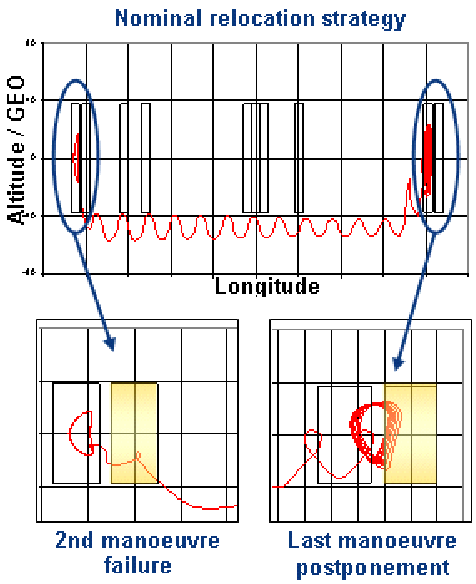

Figure 7 Violation of neighbours station-keeping boxes in contingency cases

In this example, there is a close neighbour at start position and at targeted position, which results in two possible violations of station-keeping boxes.
In such cases, the principle applied by CNES is to systematically set up coordination with closest neighbours. The aim of coordination is to anticipate the most probable emergency cases, in order to react as fast and as efficiently as possible.
Before operations, neighbouring satellites operators are informed of the relocation strategy and of its critical phases. Interfaces are defined and validated: orbit parameters and foreseen manoeuvres exchange protocol, contingency procedures, contacts for coordination and decision authorities. These definitions are described and agreed in an Interface Control Document (ICD), or at least thanks to informal exchanges depending on the wishes of the concerned operator.
During operations, orbital parameters and foreseen manoeuvres are regularly exchanged, especially during identified critical phases. Concerned operators are thus informed of any change in the relocation strategy. The minimum distance between satellites is monitored and an alert is triggered if this distance becomes lower than the threshold defined in the ICD or agreed between both parties.
Of course, this coordination can require specific tools for orbital parameters conversion, distance computation or avoidance manoeuvre research. These tools have been developed over the years in TC2 Control Centre.

3. CNES COLLISION RISKS MONITORING FOR GEO SATELLITES

With the increase of orbiting objects, CNES has developed and improved since about fifteen years a process to assess collisions risks for LEO satellites. This process described in [1] is now fully operational and leads to a few avoidance manoeuvres per year. In order to adapt this process to GEO satellites, an experimental phase is in progress using the main principles of the LEO process to monitor collisions risks for TC2 satellites. This chapter presents the main results of this experimental phase started about 2 years ago.
Based on the process implemented for LEO satellites, the monitoring method for GEO satellites has been divided into 3 steps presented on Fig.8. These 3 steps are detailed hereafter.

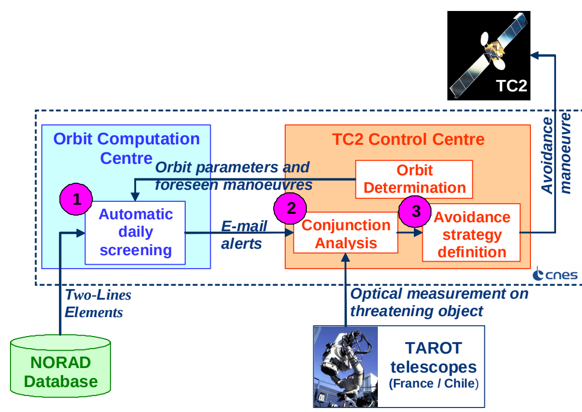

Figure 8 GEO collisions risks monitoring process

3.1. Step 1 : Automatic Daily Screening

The aim of this step is to detect any object referenced in the NORAD catalogue passing nearer from TC2 satellites than a fixed threshold during the 7 next days. The geometrical threshold is completed by a probability threshold allowing to quantify the risk level associated to the conjunction. This detection step is not performed in TC2 control centre but in the Orbit Computation Centre (OCC) which is in charge of operational daily conjunction risks assessment for all satellites controlled by CNES. OCC uploads daily updated NORAD catalogue and receives regularly TC2 determined orbit from Flight Dynamics Office. Each closest approach nearer than the geometrical threshold is summarized in an e-mail automatically sent to Flight Dynamics Team.

This alert also contains information about collision probability and estimated accuracy of orbit parameters for the threatening object. One conjunction generally causes several alerts, one per day until the conjunction is over or Two Line Elements (TLE) are updated.
For this experimental phase, the geometrical threshold determining if an alert should be triggered has been set to 50 km without any limit in probability. Statistics resulting from 15 months of screening with these thresholds are given in Tab.1. This table does not take into account closest approaches with closest controlled neighbours for which a special coordination is set up.

	Number of conjunctions	Number of alerts	Number of involved objects
TC2C	38	271	15
TC2D	37	205	20
Total	75	476	33 *(2 objects in common)*

Table 1 Number of alerts detected for a threshold of 50 km during 15 months of daily screening

Among these 75 conjunctions, 23 had a miss distance lower than 10 km, as shown on Fig.9.

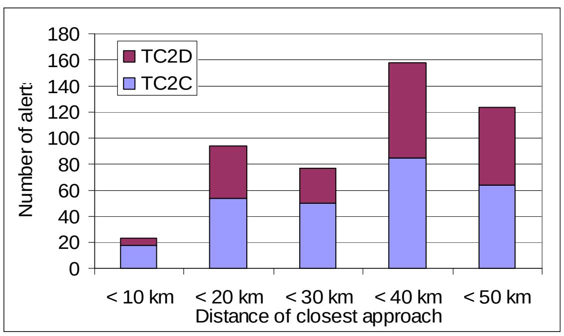

Figure 9 Number of alerts as a function of the distance of closest approach

The repartition of risks according to object type spresented on Fig.10 shows that more than one third of risks are due to operational satellites, probably during LEOP or relocations, which emphasizes the importance of operational coordination during such longitude drift phases. Another third of conjunctions is due to out of service satellites drifting on the GEO ring, which confirms that end-of-life management is essential to preserve the GEO ring from a drastic overpopulation of uncontrolled debris. Objects types were determined thanks to [2].

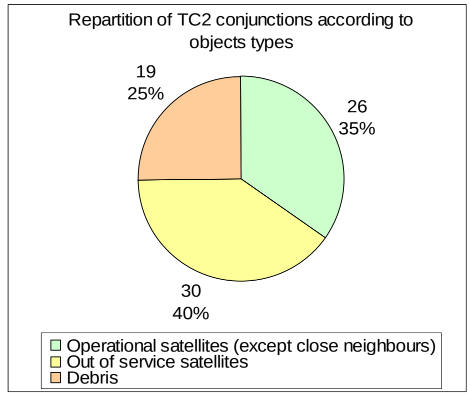

Figure 10 Repartition of TC2 conjunctions according to objects types

One of the aims of this experimental phase is to adjust the probability and distance thresholds used to trigger an alert. Fig.11 shows probability as a function of miss distance for detected risks.

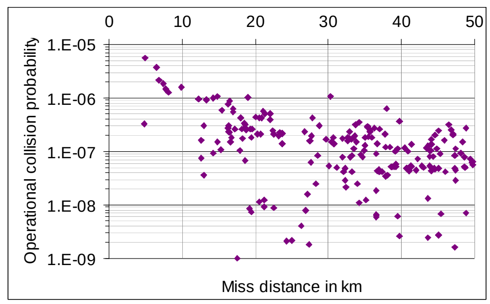

Figure 11 Probability of collision as a function of miss distance

Further analyses are in progress to improve knowledge of orbit accuracy which is essential to obtain a pertinent probability of collision and to tune thresholds triggering an alert.

3.2. Step 2 : Analysis of Detected Conjunctions

Among all alerts detected by automatic daily screening, only a few are analyzed by the Flight Dynamics Team. In practice, all alerts showing a miss distance lower than 10 km and/or a probability of collision higher than 10^{-6} were manually analyzed by the Flight Dynamics Team during this experimental phase. Furthermore, all conjunctions considered as unusual, such as conjunctions with satellites supposed to be controlled far from TC2 satellite or with satellites supposed to be in LEOP were monitored.
Analysis of an alert consists in the following tasks. The type of object is first determined. If threatening object is known to be a satellite in LEOP or relocation, the conjunction will not be processed with the same priority as if it is a drifting uncontrolled object. In the second case, a specific study is performed by OCC to see if this

object is well known, if it is regularly tracked and if its TLE are consistent. This study allows OCC to give a confidence level to the threatening object parameters used to compute characteristics of the conjunction. A tracking campaign with TAROT (Rapid Action Telescope for Transient Objects) telescopes can also be programmed. Thanks to a secured web interface, Flight Dynamics Team can directly schedule observations and a new orbit can be determined after a few nights depending on weather conditions. The conjunction geometry is graphically visualized, thanks to specific tools implemented in TC2 control centre or in OCC. The conjunction evolution is monitored over the days, taking into account updated TLE or new determined orbit if any.

Considering analysis results and its own experience, TC2 Flight Dynamics Team confirms or invalidates the risks with the support of OCC collisions management analysts and of precise orbit specialists.

3.3. Step 3 : Avoidance Manoeuvres

When the previous step confirms the risk, an avoidance strategy must be quickly worked out. For TC2 satellites, the considered avoidance strategies are always build thanks to tangential (East/West) manoeuvres. This kind of manoeuvres can as well result in a radial separation as in a separation in longitude due to the drift induced by the radial separation. The advantage is also a minimum of risk, as operational teams are performing this kind of manoeuvres every 2 weeks. The possibility of a North/South avoidance manoeuvre could be considered but it would generally be much more expensive and it would require procedures not used since several years.

Finding a suitable avoidance manoeuvre can be a tricky job : the ideal manoeuvre will cancel the risky situation without causing any other dangerous conjunction, disturbing the mission or consuming too much fuel. This complex equation must often be solved in quite a short time. In order to help dealing with all these constraints, a tool has been developed to assess quickly the impact of a large number of different manoeuvres on the close approach, so that the Flight Dynamics Team can have very quickly an idea of the cost and the date of a possible suitable manoeuvre.

The first considered solution is to modify a foreseen station-keeping manoeuvre. This solution can allow to mitigate risk at a lower cost and without adding any critical operations.

If this solution is not applicable, an algorithm exploring a large number of solutions is used. This specific algorithm has been implemented in TC2 control centre and computes minimum distances between objects for different manoeuvres. The operator selects the maximum delta-V admissible ΔV_{max}, the positions on orbit in which these manoeuvres should be applied and the step to go from $-\Delta V_{max}$ to $+\Delta V_{max}$. This software takes into account the time slots when manoeuvres are forbidden because of platform constraints and the transversal effects caused by the position of thrusters on TC2 platforms. Results are miss distances for each feasible manoeuvre.

The best solution in terms of distance and cost is then manually refined and proposed to the satellite's owner.

4. EXAMPLES OF OPERATIONAL COLLISION RISKS MANAGEMENT FOR GEO SATELLITES

Here are two examples of collision risks managements for Telecom 2 satellites.

4.1. Example 1 : Collision Risk during TC2C Relocation

This example illustrates practices used for drift phases as well as collision risks management. One can note that this risk was managed in 2006, when the process described in chapter 3 was not yet fully implemented. Nevertheless, conjunctions with objects referenced in the NORAD catalogue were detected before each foreseen move (without probability computation).

The risk was detected during relocation of TC2C from 5.2° W towards 3° E in may 2006. The nominal planned strategy consisted in 3 West manoeuvres in 24 hours to quickly go out of the geostationary ring, targeting a minimized eccentricity to keep a nearly constant altitude during drift, as described in chapter 2.1. Four braking manoeuvres and a final smaller one were planned to stop the drift at targeted longitude with a good accuracy. Coordination with closest neighbours (ASTRA, EUTELSAT) was set up to anticipate potential contingencies. Longitude and eccentricity during relocation for the nominal strategy are shown on Fig.12 and Fig.13. On Fig.13, E stands for "East Manoeuvre" and W for "West manoeuvre". One can note that the foreseen eccentricity during drift showed on Fig.13 is not equal to 0. This is due to constraints on manoeuvre times imposed by satellites characteristics. Nevertheless, Fig.12 shows that this eccentricity is small enough to avoid oscillations in the GEO operational zone, represented by satellites control boxes on the scheme.

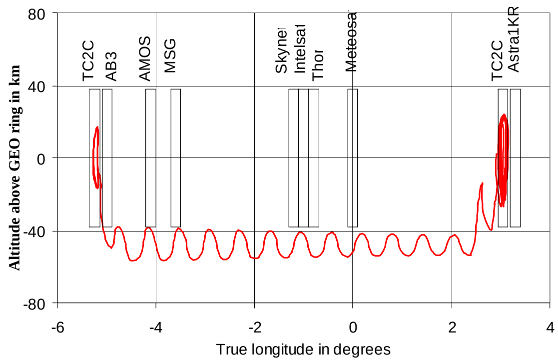

Figure 12 Longitude and altitude above the GEO ring during TC2C nominal relocation strategy

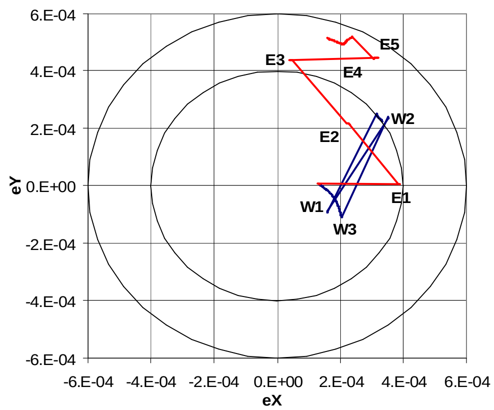

Figure 13 Eccentricity during TC2C nominal relocation strategy

After start manoeuvres, a conjunction between TC2C and Telecom 1B (TC1B, out of service since February 1988) was detected. This conjunction were foreseen during braking manoeuvres for a miss distance of about 10 km. The only data source for TC1B orbital parameters was the NORAD database, as TAROT telescopes were not yet available.

A modification of stop manoeuvres was quickly considered to mitigate risk at a lower cost. The best solution was to plan first stop manoeuvres one day earlier to drift more slowly, and then to create a separation in longitude when the satellites are at the same latitude and at the same distance from Earth. Stop manoeuvres times were kept to reach the targeted eccentricity. With this adapted strategy, the new distance of closest approach was about 100 km for the same cost as the nominal one. Fig.14 and Fig.15 show longitude and eccentricity evolutions with this new strategy.

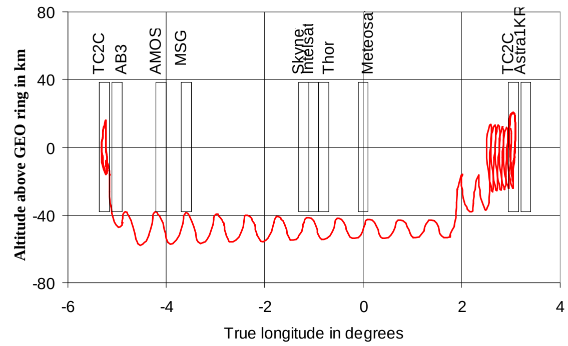

Figure 14 Longitude and altitude above GEO ring during TC2C relocation adapted to avoid conjunction with TC1B

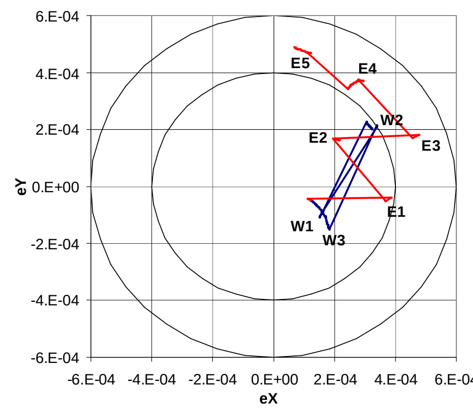

Figure 15 Eccentricity during TC2C relocation adapted to avoid conjunction with TC1B

The strategy modification was decided on May 15 late evening for a first stop manoeuvre on May 16 in the early morning. It entailed a 5 day long drift in GEO ring as shown on Fig.15. It was of course possible because there was no satellite on the way**.** The final drift at 3° East was stopped 4 days later than in the nominal strategy with no impact on payload restarting date.

4.2. Example 2 : Conjunction with Intelsat IVA F-6

This conjunction was detected thanks to the process described in chapter 3.

The screening performed on October 6 detected a closest approach for TC2C on October 15 with a miss distance lower than 6 km (Along track = 34 m; Radial = 5.6 km; Normal = 3 m) and a probability of collision of about 2.4 10^{-6}. The threatening object was Intelsat IVA F-6, an out of service satellite in a libration's orbit around the Eastern stable point (longitude 75°E). Analysis of TLE consistency showed a dispersion of about 7.5 km in radial for a propagation of 11 days as shown on Fig.16.

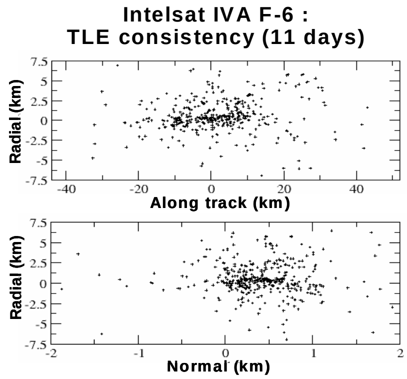

Figure 16 Intelsat IVA F-6 TLE consistency at 11 days

As the next station keeping manoeuvre was foreseen on October 7, a modification of this manoeuvre was quickly computed to mitigate this risk at a lower cost. In this case, the avoidance strategy was engaged without waiting for confirmation of the orbit with TAROT telescope to benefit from the possibility of avoiding this object thanks to a simple modification of a foreseen manoeuvre. The commanded delta-V of the foreseen station-keeping manoeuvre was increased by 0.01m/s to increase the radial separation and to induce an along-track separation. The delta-V increase was limited to stay within the station-keeping box. Thanks to this adaptation, the new miss distance was about 16.5 km (Along track = 15.4 km; Radial = 5.9 km; Normal = 1.6 km) with a probability of collision of $9\ 10^{-7}$.

In parallel with this modification, a tracking campaign was programmed on TAROT telescopes to help monitoring risk evolution. Only 2 nights of observation were performed because of bad weather. These tracking data allowed to determine an orbit which was quite consistent with previous predictions but not considered as reliable because of the lack of measurements.

5. CONCLUSION

Collision risks mitigation for GEO satellites have been included in CNES operational procedures at a lower cost. Use of optimized strategies during drift phases allows to preserve the operational GEO zone without additional cost. Simple adaptation of the process applied for LEO satellites allows to daily monitor GEO collisions risks with all referenced objects. This experimental process have been set up without considerable investment or additional manpower. 9 dangerous conjunctions were manually analysed during 15 months. Two of them led to avoidance manoeuvres and demonstrate that risks can be mitigated without impacting the mission or the satellite lifetime. Finally, this is a good starting point for further studies and developments which become more and more necessary with increasing population in the GEO region.

6. REFERENCES

1. Laporte, F. (2008). Operational management of collision risks for LEO satellites at CNES, Space OPS 08, Darmstadt, Germany.

2. Choc, R. & Jehn, R. (2009). Classification of Geosynchronous Objects Issue 11, ESA/ESOC, Robert-Bosch-Str. 5, 64293 Darmstadt, Germany.