CO-LOCATION OF SIX ASTRA SATELLITES : ASSESSMENT AFTER ONE YEAR OF OPERATIONS

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ABSTRACT

This paper presents the developments realised by Société Européenne des Satellites in order to co-locate up to six satellites at the same orbital position. We emphasise the latest developments in terms of methods, software and hardware motivated by the will to simplify the operations and to be able to operate more efficiently a larger number of satellites. We finally summarise our co-location experience with special emphasis on the case of six satellites since June 1996.

1. INTRODUCTION

Société Européenne des Satellites (SES) is currently co-locating six geostationary satellites in a longitude and latitude window of ±0.1 degrees; a picture of the six spacecraft in orbit can be seen in figure 1. The co-location method used is based on eccentricity and inclination separations [1]. Actual implementation of this strategy called for adaptations and refinements of control algorithms [2] and the operational environment [3], which allow to maintain at all times a safe inter-satellite separation whilst coping with satellite constraints and minimising operational complexity.

The present paper reviews four main aspects considered in our previous work [2,3], namely (i) the definition of separation safety, (ii) the determination of eccentricity and inclination configurations, (iii) the scheduling of manoeuvres and the strategy applied to maintain these configurations over the entire mission and (iv) the operational hardware and software. In particular we stress the improvements realised in the light of our current experience with the co-location of six satellites and in preparation of the insertion of two additional satellites into the constellation.

Chapter 2 reviews the concept of separation safety which accounts for uncertainties of current and predicted satellite positions. We describe our new developments wherein separations are analysed based on covariance matrix propagation involving orbit estimation errors and manoeuvre performance statistics.

In chapter 3 we describe the configuration modifications that were required by the insertion of new satellites. We show in particular how the eccentricity and inclination configurations have been adjusted by means of numerical simulations [4], and how the actual implementation of successive configurations closely followed the plans.

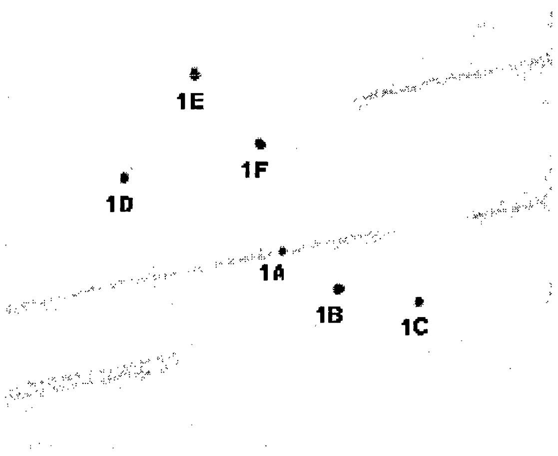

Figure 1. Picture of the ASTRA satellites constellation taken from Betzdorf, Luxembourg, on June 4th, 1996 using a 35cm telescope. The field covered by the picture is about 0.185° *squared*

Chapter 4 presents improvements in manoeuvre scheduling and eccentricity and inclination configuration control algorithms realised to maintain safe and efficient operations. In particular it is shown how long-term North/South manoeuvres planning has been decoupled from East/West manoeuvres planning. In addition a new long-term eccentricity targeting method is introduced.

Chapter 5 presents the tools that were implemented in order to efficiently handle the co-location and operations of more satellites. New developments include an automatic co-location management system, im-

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proved manoeuvre targeting and computation algorithms, a configuration recovery system and a new version of our quasi real-time orbit determination and monitoring system. In addition improvements in tracking data quality have been realised by the procurement of accurate spread-spectrum ranging units and by the reduction of systematic tracking errors caused by thermal distortions of the antenna.

Operational experience with the co-location of six satellites since June 1996 is presented in chapter 6. We illustrate how the developments introduced in previous chapters are used in operations and we compare actual results with those of numerical simulations. Finally chapter 7 contains our conclusions.

2. DEFINITION OF THE SEPARATION SAFETY

Central to the development of the ASTRA co-location strategy [2] was the requirement to maintain a safe spatial separation between the co-located satellites, taking into account statistical errors associated with the orbit estimation and manoeuvre realisation processes. Assuming these statistical errors to have Gaussian distributions, the complete statistical properties of the orbit state vectors can be obtained at any point in time by propagating the covariance matrices of the various satellites, through coast and powered arcs. Essentially the orbit estimation statistics contribute to the initial value of the covariance matrices whereas the manoeuvre performance errors affect solely the component of the acceleration vector during the powered arcs, and both error sources are assumed to be statistically independent. For each pair of satellites the instantaneous covariance matrix associated with the separation can be obtained by summing the covariance matrices of the individual satellites, assuming that no correlation exists between the statistical errors of the two satellites. Diagonalisation of this matrix allows to determine the 3 principal directions $\vec{u}_i$, $i = 1, 2, 3$ and the semi-axes σ_i, $i = 1, 2, 3$ of the relative position error ellipsoid. In the frame defined by the axes $\vec{u}_i$, $i = 1, 2, 3$, a statistical measure of the separation associated with the intersatellite vector $\vec{\Delta r}$ is given by the formula

$$d = \sqrt{\sum_{i=1}^{3} \frac{\Delta r_i^2}{\sigma_i^2}}.$$

The separation is considered to be safe if $d > 9/\sqrt{2}$ or $\Delta(3 \times 3\sigma) \equiv d\sqrt{2}/9 > 1$ in accordance with the concept of $3 \times 3\sigma$ separation introduced in [2]. Note that the above equation reduces to equation (1) of reference [2] in the limiting case where the principal axes $\vec{u}_i$ of the relative position error ellipsoid are aligned with the satellite local frame.

Figures 2 and 3 illustrate the typical evolution of the error ellipsoid associated with the separation between two satellites, seen in the reference frame of one of the satellites. Ellipsoids are shown at one hour time intervals in the radial-normal plane, in the absence of manoeuvre (figure 2) and in the presence of a North/South manoeuvre (figure 3).

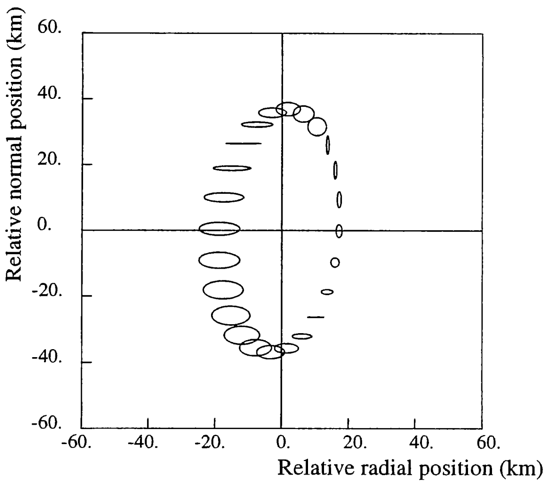

Figure 2. Propagation of the relative position error ellipsoid of two satellites projected in the radial-normal plane of the local frame of one satellite; ellipsoids are represented at one hour time intervals over one day. Initial covariances have been exaggerated for illustration purpose.

3. REVIEW OF THE ECCENTRICITY AND INCLINATION CONFIGURATIONS

In our previous work [2] we have defined the optimum reference eccentricity and inclination configurations which allow to maintain a safe separation, even in the unlikely case of large manoeuvre errors, while satisfying the station-keeping constraints of the ASTRA satellites and minimising the propellant consumption. In addition the proposed strategy took into account the constraints associated with configuration changes required by the insertion of new satellites. Such constraints include the minimisation of propellant losses and of the number of additional manoeuvres required to realise the transition between configurations involving different numbers of spacecraft. They also include the requirement to guarantee a co-ordinated change of the eccentricity and inclina-

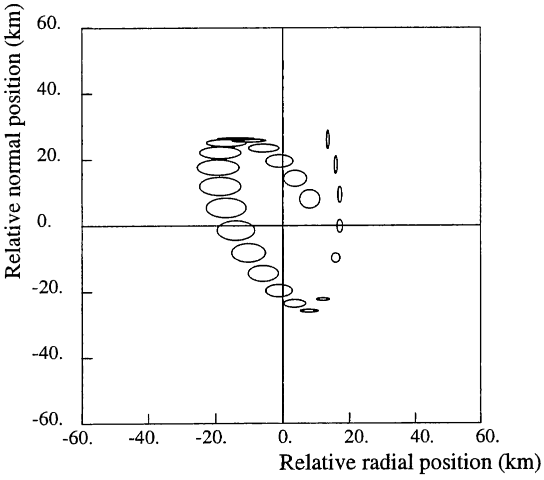

Figure 3. Same as figure 2 but with a North/South manoeuvre taking place after 6 hours of propagation. Manoeuvre errors have been exaggerated for illustration purpose.

Satellite to be inserted	Initial configu-ration	Target configu-ration	Transi-tion duration	Min. $3 \times 3\sigma$ value
1C	2	4	-	4.0
1D	3	4	-	3.8
1E	4	5	5 months	3.4
1F	5	6	4 months	3.3

Table 1. Summary of the successive transitions applied to the ASTRA constellation. The second and third columns indicate the number of satellites in the initial and target configurations. The fourth column shows the duration of the transition; note that no transition was required to realise the 4 spacecraft configuration. The last column shows the minimum $3 \times 3\sigma$ value up to the insertion of the new satellite.

tion configurations in such a way that the transient configurations do not result in a degradation of the minimum separation, compared with the target configuration.

The proposed methodology [2] has been applied to co-locate successively 3, 4, 5 and 6 satellites. The transitions were planned well in advance and both the transition plan and the target configurations were adjusted and validated by means of numerical simulations [4], using control algorithms and models identical to those used in operations and taking into account observed in-orbit performance of existing satellites as well as predicted manoeuvre performance of future satellites.

The summary of the successive transitions applied to the ASTRA constellation can be found in table 1. It can be seen that the average transition duration was 4.5 months, which is enough to allow a progressive correction of eccentricity and inclination configurations, with deviations of North/South manoeuvres right ascension not larger than a couple of degrees and a maximum of three double East/West manoeuvres. As an example, figure 4 shows the actual evolution of the minimum $3 \times 3\sigma$ separation (all spacecraft pairs combined) for the 6 satellites configuration preparation.

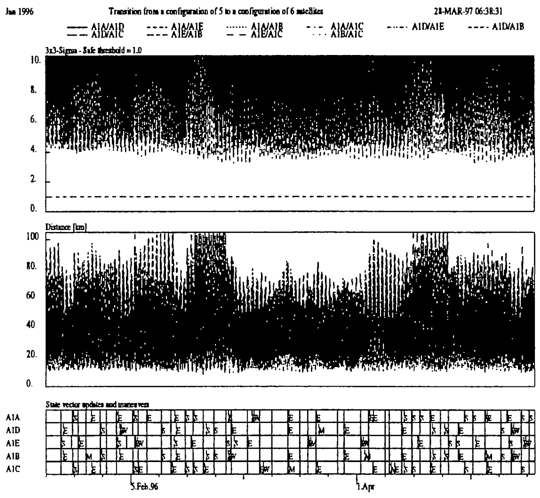

Figure 4. Transition from a configuration of 5 to a configuration of 6 satellites. The figure shows the $\Delta(3 \times 3\sigma)$ separations and intersatellite distances for all spacecraft pairs as a function of time, and the occurrence of manoeuvres.

4. REVIEW OF THE CONFIGURATION CONTROL STRATEGIES

Based on co-location experience and in order to maintain safe and efficient operations of an increasing number of satellites the manoeuvre scheduling has been tailored and the eccentricity and inclination configurations control algorithms revised. Firstly, according to the general planning scheme defined previously [2], the six-satellites manoeuvre schedule that proved the most convenient operationally has been selected and used as input to generate a yearly planning of all spacecraft manoeuvres.

Next, a more robust inclination targeting algorithm has been implemented, which makes the sequencing of the inclination corrections on the various groups of satellites [2] independent from the conventional notion of station-keeping cycle associated with each individual satellite. This is realised by defining in the yearly manoeuvres planning a set of reference dates called "Inclination Cycle Boundaries" (ICB hereafter) at which the reference inclination configuration as defined in reference [2] has to be restored. The targeting algorithm aims at restoring the reference configuration while maximising the size of inclination corrections, taking into account propulsion subsystem and station-keeping constraints. Appropriate algorithms are then used to map the inclination targets obtained at the ICB epochs back to the epochs corresponding to the standard station-keeping cycle end of the individual satellites. As in previous work [2], an additional optimisation of the inclination correction direction is carried out.

In parallel, a new long-term eccentricity targeting method has been developed. By contrast to the inclination configuration control algorithm described above, this method can be applied independently to each satellite, provided that some tolerances around the nominal Sun-pointing perigee eccentricity targets are given. For each station-keeping cycle, the target eccentricity within the tolerance window is selected so as to minimise the East/West propellant consumption and the number of double East/West manoeuvres required over a given period (typically six months), considering the future evolution of North/South manoeuvres cross-coupling effects as a function of manoeuvre mode and time.

5. NEW OPERATIONAL TOOLS

The methods described in the previous chapter have been integrated into a new co-location configuration management software. This tool retrieves the latest orbital and manoeuvre assessment information stored in databases, performs eccentricity and inclination targeting for all manoeuvres during a prescribed period of time, optionally computes all orbit corrections manoeuvres and ultimately applies the co-location monitoring function to validate the manoeuvre plan.

The algorithms used for manoeuvre computation have also been considerably improved with the capability to handle time-dependent cross-coupling coefficients, burn duration constraints, arbitrary number of North/South manoeuvres within a station-keeping cycle and the possibility to apply non-linear optimisation techniques. In parallel our co-location monitoring module has been improved to support the covariance matrix propagation techniques described in chapter 2, along with several enhancements in the accuracy of our models. Our software also includes methods developed to handle the unlikely case of unplanned large disturbances of the configurations, by restoring the nominal situation in a minimum time and with minimum propellant requirements while reducing the risk of close approaches.

In order to increase the separation safety margins, improvements in tracking data quality have been realised. Our former TV-ranging system [3] has been replaced by SATRE spread-spectrum ranging units [5] which provide a continuous flow of data with an accuracy better that one metre and are compatible with both analogic and digital TV signals. Besides, continuous efforts at hardware level have been made in order to reduce systematic angular measurement errors resulting from the thermal distortion of our tracking antenna.

These improvements in data quality, combined with continuous enhancements of the data acquisition software and of the quasi-real time orbit determination system (QRTOD hereafter) [3] have provided a very stable autonomous orbit determination system. In addition, closer integration of the QRTOD system with the other station-keeping and co-location tools and databases allows to automatically maintain continuous consistency between the latest orbit and manoeuvre assessment and planning information.

6. OPERATIONAL EXPERIENCE

We now describe the simplification of operations that resulted from the introduction of the revised control strategies of chapter 4 and their software implementation discussed in chapter 5. Firstly, the new long-term inclination and eccentricity control strategies have considerably improved our capability to accurately take into account the time-varying spacecraft constraints in the validation of the yearly manoeuvre planning. For instance, this proves very useful to plan the manoeuvres required at the entry and exit of the eclipse seasons, where no North/South

Number of satellites co-located	Minimum $3 \times 3\sigma$ separation	Minimum intersatellite distance (km)
3	3.8	9.7
4	3.6	8.9
5	3.3	8.1
6	2.9	6.9

Table 2. Minimum $3 \times 3\sigma$ separation and intersatellite distance for the successive configurations of the ASTRA constellation

manoeuvre is performed, as mentioned in a previous work [2]. The basic commonality of our simulator and planning tool on one hand and our day-to-day operational software on the other hand guarantees a smooth implementation of the manoeuvre plan, where only minor adjustments to the long-term predictions are required to cope with random effects in the manoeuvre realisation.

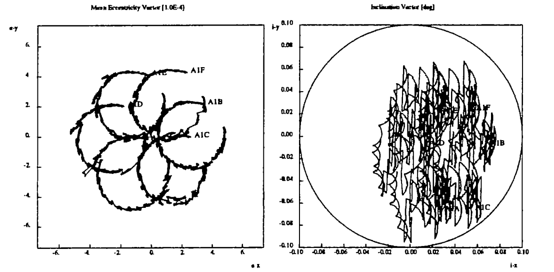

Figure 5. Eccentricity and Inclination strategy for the six ASTRA satellites from June 1996 to March 1997. The plot shows the eccentricity (left) and inclination (right) configurations.

Secondly, the decoupling of the inclination control from the eccentricity control allowed to restrict the requirements for centralised configuration management to inclination targeting only, while longitude and eccentricity corrections can be performed independently on each satellite. Of course the co-location management software described in chapter 5 would also support a fully centralised station-keeping control if required, thereby providing additional flexibility in the organisation of operations.

Improvements in operations efficiency similar to those concerning manoeuvre planning and computation have been experienced in the field of orbit estimation and manoeuvre assessment. For instance the latest version of our QRTOD system described in the previous chapter allows an instantaneous assessment of the health of tracking systems, orbit estimation quality and manoeuvre performances.

Table 2 summarises our experience with the co-location of 3, 4, 5 and 6 satellites. It can be seen that safe operations have been maintained at all times with a $3\times3\sigma$ separation value always higher than 2.9. This confirms the validity of the methods and tools introduced in previous chapters and shows that safe co-location of six satellites is feasible using a single tracking station. It is worth mentioning that insertion of new satellites into the fleet was each time realised promptly after completion of the In-Orbit Test phase. This was made possible by station-keeping performances of new satellites meeting the stringent specifications imposed upon the manufacturer.

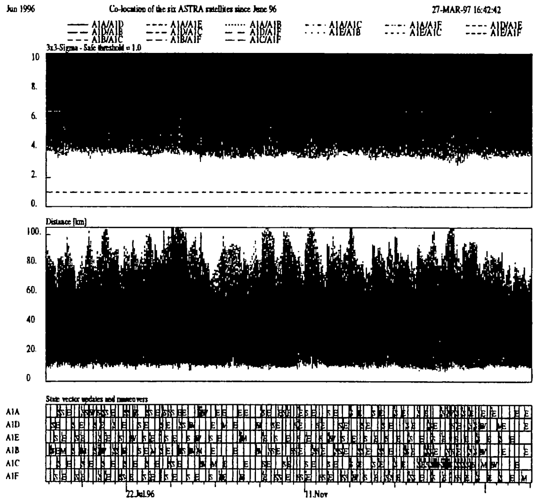

Figure 6. Eccentricity and Inclination strategy for the six ASTRA satellites from June 1996 to March 1997. The plot shows the $\Delta(3 \times 3\sigma)$ separations and intersatellite distances as a function of time, and the occurrence of manoeuvres.

Co-location of 6 satellites since June 1996 is now presented in more details. The evolution of the inclination and eccentricity configurations are shown in figure 5. It can be seen on this figure that, as explained in chapter 4, the strategy always attempts to maximise the size of inclination vector corrections, thereby keeping the configuration most of the time in the lower part of the inclination window. The larger excursions along the positive i_y axis mainly took place during the eclipse seasons.

Figure 6 shows the typical evolution of the $3 \times 3\sigma$

separation and the intersatellite distance for all pairs of satellites. It can again be seen that the absolute minimum $3 \times 3\sigma$ separation is larger than 2.9. A different representation of this separation is provided by figure 7 which shows the evolution of the 3σ separation error ellipsoids of ASTRA 1B,...1F relative to ASTRA 1A over a station keeping cycle of 14 days. The white area in the centre of the figure shows that a safe separation is maintained at all times in the radial-normal plane of a co-moving reference frame.

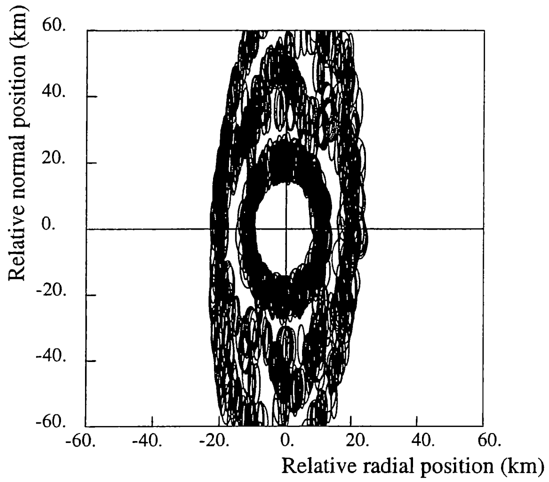

Figure 7. Evolution of the relative 3σ position error ellipsoids of ASTRA 1B, 1C, 1D, 1E and 1F relative to ASTRA 1A over 14 days, projected in the radial-normal plane of the spacecraft local frame.

Figure 8 shows the comparison of the actual distribution of minimum $3 \times 3\sigma$ separation with the results of numerical simulations [4]. It can be seen that the observed values are in good agreement with the 3σ confidence interval resulting from the simulations.

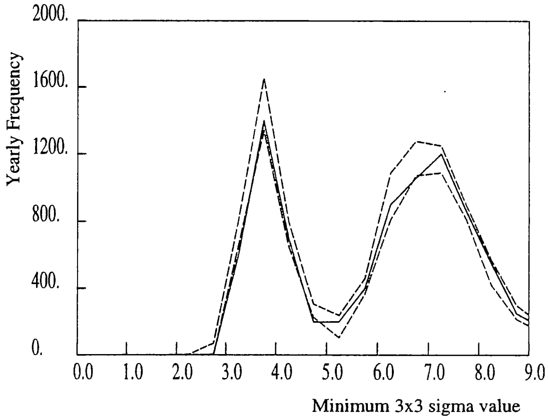

Figure 8. Comparison between the minimum $3 \times 3\sigma$ separation values resulting from numerical simulations over a cumulated period of 50 years (the dotted lines depict the bounds of the corresponding 3σ confidence interval) and actual monitoring of the 6 ASTRA satellites since June 1996 (solid line).

7. CONCLUSIONS

Successive co-location of 3, 4, 5 and 6 satellites using a single tracking station has confirmed the validity of the strategy designed for the ASTRA satellites and the results of previous numerical simulations. Continuous improvements of methods, software and hardware have allowed to maintain safe and efficient operations of an increasing number of co-located satellites.

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