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Collocation Assessment between GEO and GSO Satellites

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***Abstract*—**The change in orbit evolution between collocated satellites (X, Y) inside +/-0.09° E/W and +/- 0.07° N/S cluster, after one of these satellites is placed in an inclined orbit (satellite X) and the effect of this change in the collocation safety inside the cluster window has been studied and evaluated.

Several collocation scenarios had been studied in order to adjust the location of both satellites inside their cluster to maximize the separation between them and safe the mission.

***Keywords*—**Satellite, GEO, collocation, risk assessment.

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I. Introduction

IN order to increase the satellite lifetime beyond their operational lifetime, the satellite X was put in an inclined orbit (GSO) by stopping the inclination control (N/S maneuver correction) and only performs E/W maneuver corrections to adjust the satellite in the longitudinal window. Using this approach the satellite lifetime could be extended up to more than 2 years in-orbit till a replacement is manufactured and launched in its place.

In this paper, the orbitography effect for a Geo-synchronous orbit and Geo-stationary orbit satellites is analyzed and studied and a modification in the collocation window is proposed to maintain the collocation safety.

II. Space Orbital Parameters

A set of parameters are defined to specify the orbit uniquely [1], [2]. Traditionally used set of orbital elements called the set of Keplerian elements are seen in Fig. 1.

The Keplerian elements are six: Semi-major axis (a), eccentricity of the ellipse (e), inclination angle (i), Right ascension of ascending node (**Ω**), argument of perigee (ω), True anomaly(ϑ).

For geostationary orbit, the inclination angle (i) is nearly equal to zero, so the values of ω and ϑ cannot be given with sufficient accuracy, as the position of the ascending node is not determined accurately. The parameters in the kepelerian set are slightly modified to include implicitly the parameters (i, ω,ϑ), the new sets of modified orbital parameters are given by definition as:

$$\text{Semi-major axis: } a \tag{1}$$

Eccentricity (e) vector in the x, y directions:

$$\bar{e}_x = \bar{e}\cos(\omega+\Omega),\quad \bar{e}_y = \bar{e}\sin(\omega+\Omega) \tag{2}$$

Inclination (i) vector in the x, y directions:

$$i_x = \sin(i)\cos(\Omega),\quad \bar{i}_y = \sin(i)\sin(\Omega) \tag{3}$$

$$\text{Longitude : } l = \omega + \vartheta + \Omega - \text{GAST} \tag{4}$$

where GAST = Greenwich Apparent Sidereal Time.

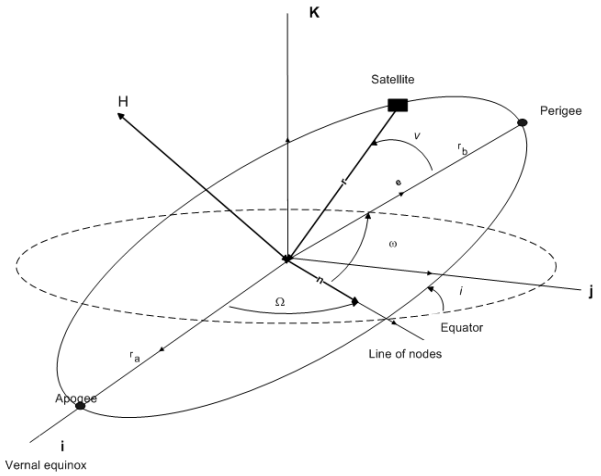


Fig. 1 Orbital angles

III. Station Keeping Maneuver

A satellite in geostationary orbit is continuously perturbed by the forces due to the triaxiality of the Earth, luni-solar gravitational forces, and solar radiation pressure [3]. The semi-major axis of the geostationary satellite tends to increase because of the perturbation from the Earth's tesseral harmonics. The orbital period is increased from the geosynchronous period, so the satellite is drifting west toward a stable point. The perturbations caused by the Sun and Moon are predominantly out-of-plane effects, causing a change in the inclination, and in the right ascension of the ascending node [4]. The eccentricity of a satellite is affected by the Solar radiation pressure.

The East/West Station-Keeping (EWSK) maneuver burn direction is at a tangent to the orbit, and adjusts the drift rate and the eccentricity of the orbit to maintain the satellite within the station-keeping box. The North/South Station-Keeping (NSSK) maneuver burn is normal to the orbit, and adjusts the inclination of the orbit and right ascension of the ascending

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node to control the daily latitudinal excursions of the satellite. NSSK maneuvers normally use over 90% of the fuel loaded on a spacecraft.

The station-keeping maneuver strategy should be designed to minimize the expenditure of spacecraft propellant and the operation of the ground station. The East/West station-keeping box for the GEO satellite was analyzed and allocated with +/- 0.075° band. The same 14-day EWSK cycle is used in this study and the station keeping box allocation is summarized in Table I.

TABLE I
EWSK BAND ALLOCATION FOR 14-DAY CYCLE

Effects	Allocated Values
Guard band for OD and maneuver errors	0.02°
Guard band for luni-solar perturbations	0.014°
Allocation for drift	0.012°
Allocation for eccentricity	0.134°
Mean eccentricity limit	0.0004°

The inclined GSO satellite passes the equator two times in a day. When the inclined GSO satellite passes the equator, there is some possibility of collision with the member GEO satellites. So the satellite orbits should be maintained in a pre-defined manner. The EWSK and NSSK maneuvers for the two satellites should be coordinated to minimize the operational load in satellite control center by avoiding simultaneous maneuvers. A 14-day EWSK and 14-day NSSK maneuver cycles were applied to the collocation strategy. There is no NSSK maneuver for the inclined GSO satellite since the natural drift of the inclination is allowed.

IV. COLLOCATION STRATEGY

Several collocation control schemes are defined in this section as longitude separation, eccentricity separation, inclination separation and finally eccentricity and inclination separation [5], [6].

A. Longitude Separation (LS)

In this scheme, longitude of each satellite is unique to that satellite. Two satellite longitude separation is shown in Fig. 2. This configuration is often referred to as the 'necklace' geometry, and allows each satellite to be considered independently - the only impact on collocation has on nominal operations is a reduction in the allowable EW deadband. The main advantage of this is that co-operation between control centers for different satellites should not be necessary. The main disadvantage is a fuel penalty due to more frequent EW maneuvers.

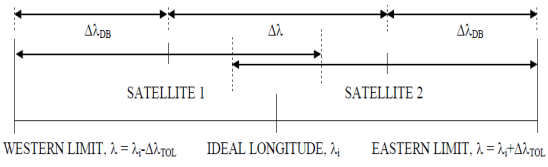


Fig. 2 EW Dead band for longitude Separation Strategy; $2\Delta\lambda_{TOL} = \Delta\lambda + 2\Delta\lambda_{DB}$, $\Delta\lambda$ is the separation between satellites

B. Eccentricity Separation (ES)

An ideal GEO orbit has zero eccentricity, however a non-zero value is acceptable provided the daily libration effect in the longitudinal direction does not cause an EW deadband violation. By separating the eccentricity vectors of two collocated satellites, the relative motion is elliptical.

Maximum separation is obtained by selecting non-overlapping eccentricity control circles on the 'e' plane; however, this also produces the largest eccentricity correction fuel penalty. The 'e' plane and resulting motion is shown in Fig. 3. The inter-satellite distance varies, however two dimensions of the window are utilized making ES more effective for large clusters. The disadvantage is that satellite eclipses can occur, causing possible RF interference problems.

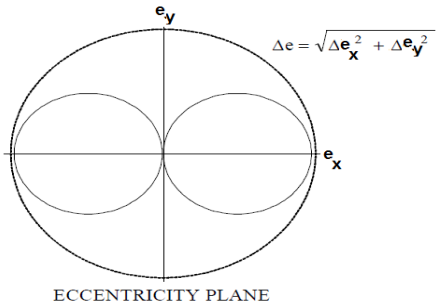


Fig. 3 EW Dead band for Eccentricity Separation Strategy

C. Inclination Separation (IS)

Separating the inclination vectors produce a sinusoidal motion along the 'i' axis, which is shown in Fig. 4.

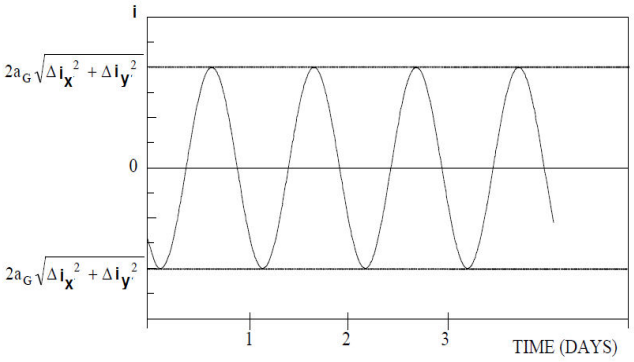


Fig. 4 Motion along the 'i' axis with Inclination Separation Strategy

D. Eccentricity and Inclination Separation (EIS)

Combining eccentricity and inclination separation strategies results in eccentricity-inclination separation. Although there is no requirement for a specific relationship between the eccentricity and inclination vectors in EIS one specific case is of interest; namely parallel EIS.

The semi-major and semi-minor axes of the relative ellipse are then;

$$\text{Semi-major axis:} \quad 2a_G\sqrt{(\Delta i^2 + \Delta e^2)} \qquad (5)$$

$$\text{Semi-minor axes} \quad a_G\Delta e \qquad (6)$$

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Thus, the semi-*major* axis has been increased above the value obtained from pure ES. Theoretically, EIS perpendicular is superior to parallel in that the minimum separation distance is increased and, as seen from the Earth, satellite eclipses do not occur. In practice however parallel is 'better' at maintaining separation distances when manoeuvre errors are considered.

Table II provides a comparison summary for longitude separation, eccentricity, and inclination separation methods. And, thus due to the ability to utilize all the available window and keep high safety with respect to the reliability issues as indicated in Table II, the inclination and eccentricity separation strategy is used.

TABLE II
COMPARISON OF DIFFERENT COLLOCATION STRATEGIES

	Longitude synchronization	Inclination and Eccentricity Separation
Separation axis	1 axis separation	3 axis adjustable separation
Cluster Window	Non-optimum use of the orbital window	Use of all the available window
Reliability	Low Reliability(risk of collision)	High safety
Maneuver timing	Need to be performed at the same time	No risk for maneuver delay

V. INCLINED ORBIT CONTROL

Geosynchronous orbit inclination constitutes a primary cause of daily continuous satellite yaw variation as depicted in Fig. 5 [7]. As a matter of fact, the non-zero inclination causes the sub-satellite point to move along a figure-of-eight, see Fig. 6, whereby,

1. When the satellite is at orbit nodes (T0+6 and T0+18 hrs in the Fig. 5), the sub-satellite point is above the Equator and the satellite has a yaw error equal to the inclination;
2. When the satellite is 90° away from the orbit nodes, (T0 and T0+12 hrs), the sub-satellite point is at the top (or bottom) of the eight and the yaw error is zero.

From the ground station perspective, the satellite is seen as moving in the sky along a similar figure-of-eight around its nominal station. The satellite reaches northerly and southerly latitudes (declinations) equal in value to the inclination of the orbital plane with respect to the equatorial plane. The inclination changes on a yearly basis by 0.75° - 0.95°, owing to the luni-solar perturbation and depending upon the orientation of the Moon orbital plane.

The suppression of North/South station keeping maneuvers on satellite X had been decided 6 months before the expected end of life date of this satellite in order to increase S/C lifetime approximately 2 additional years with the ability to re-allocate it in another orbital position if required.

VI. CASE STUDY

The satellite X was placed in inclined orbit since the 1st of March 2015, were the inclination control maneuvers had been stopped and only longitude and eccentricity maneuver corrections in the East and West direction were performed since this date. In addition, since this date it was seen a repetitive violation for the "**Normal_vs_Radial separation**" circle during our routine flight dynamic computations, as seen in Fig. 7.

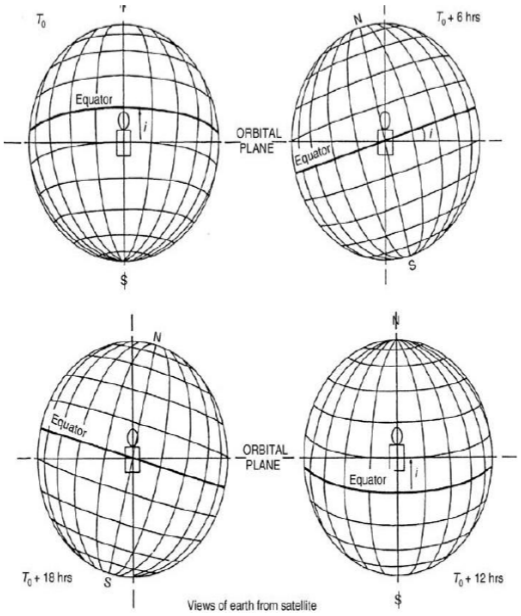


Fig. 5 Satellite inclination-induced Yaw Variation along the orbit

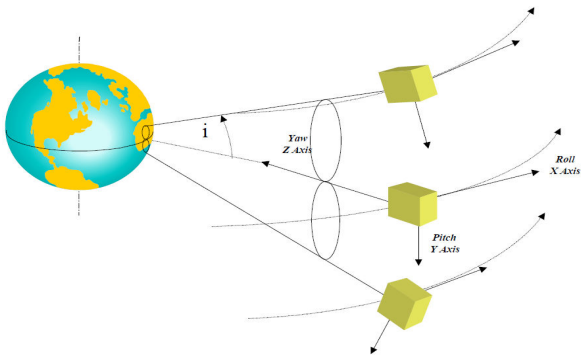


Fig. 6 Satellite pointing in inclined orbit configuration

Checking the current eccentricity and inclination evolutions circles for both X and Y satellites, it was as shown in Figs. 8 (a) and (b). Therefore, it could be shown that the eccentricity circles have become very close to each other (Fig. 8 (a)), leading to the repetitive collocation safety violations.

Several solutions which will be presented in the next subsections had been implemented in order to reach at the end to a final stable collocation solution.

A. Maneuver Durations and Timing Adjustments

The violation of the "Normal_vs_Radial separation" circle was seen in consecutive orbit determination computation as seen in Fig. 9. Moreover, the problem was solved by either decreasing the maneuver duration as done in a North maneuver performed on satellite Y or changing the date of the Satellite X East/West maneuvers to be performed earlier on Monday instead of the Thursday, as seen in Fig. 10.

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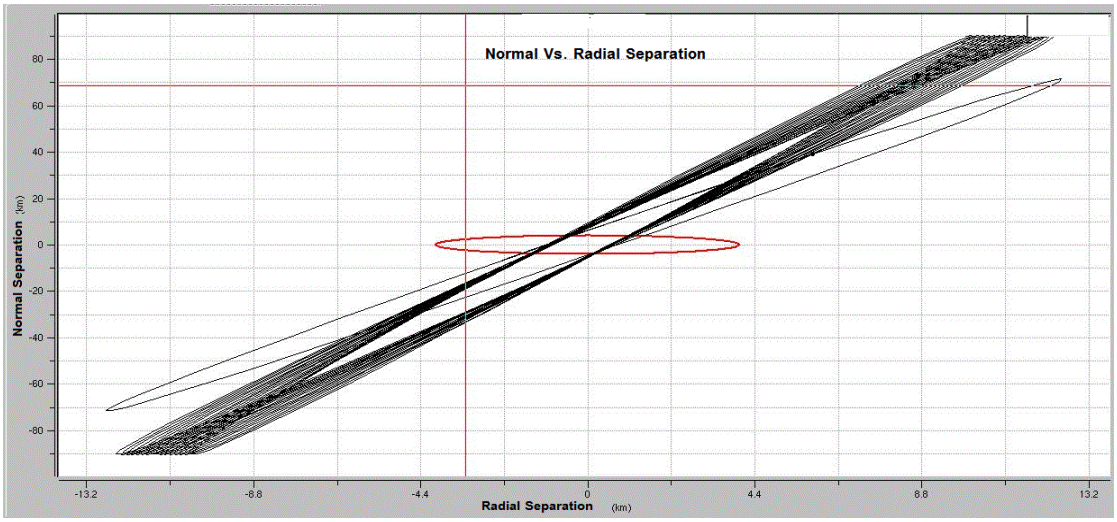
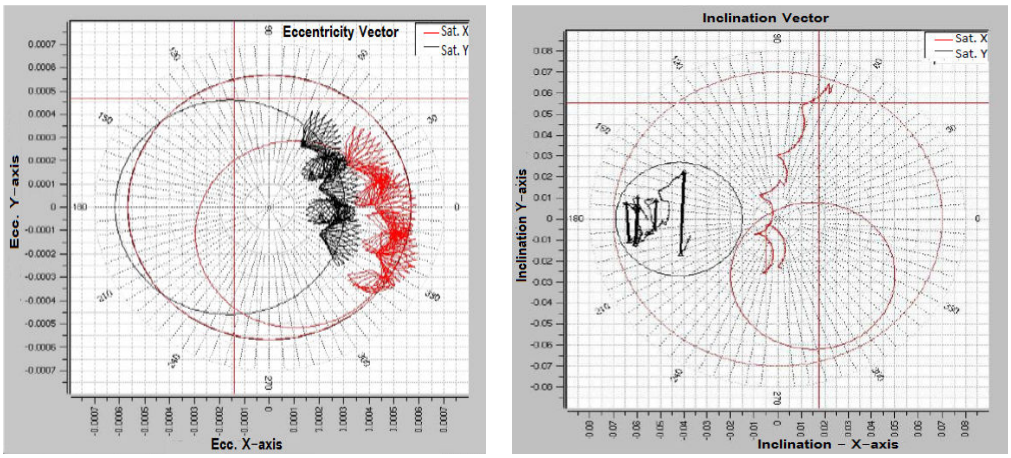


Fig. 7 Violation of the "Normal_vs_Radial separation" circle



(a) (b)

Fig. 8 (a) Satellite X, Y eccentricity evolution for 3 months (b) Satellite X, Y inclination evolution for 3 months

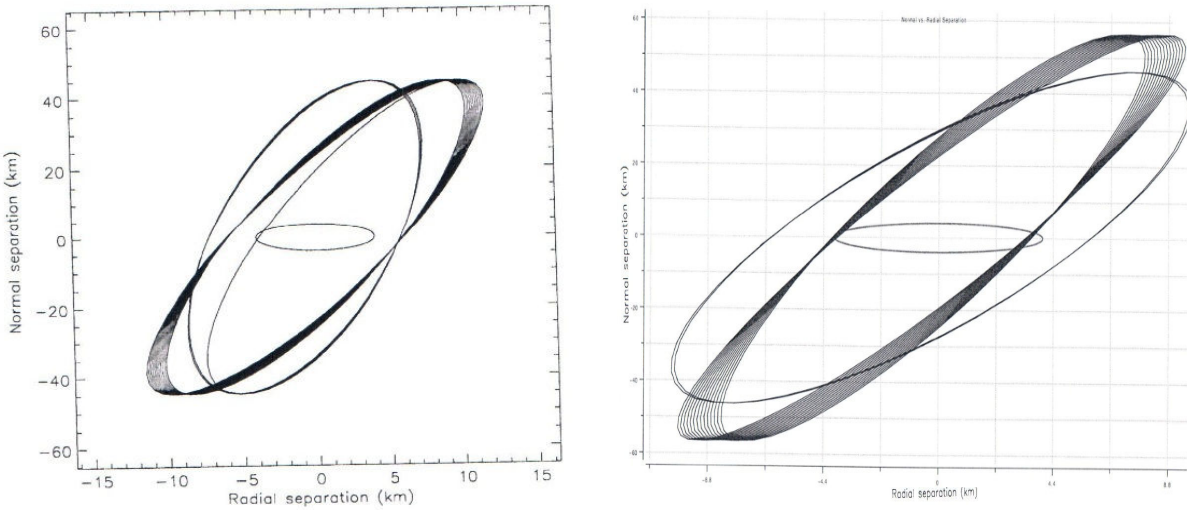


Fig. 9 Two Cases of circle violation for Satellite X, Y

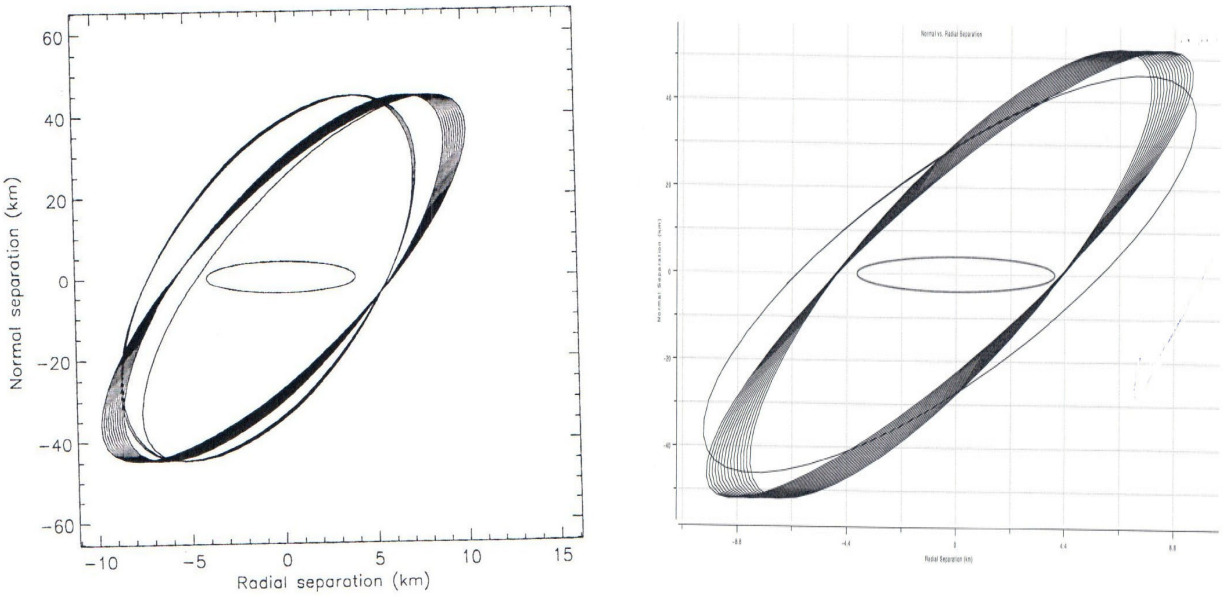


Fig. 10 Two Cases of circle violation corrections for Satellite X, Y

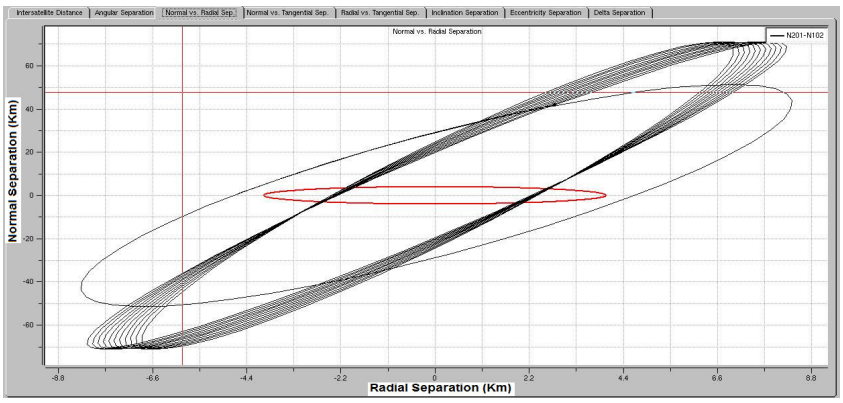


Fig. 11 Case of circle violation for Satellite X, Y

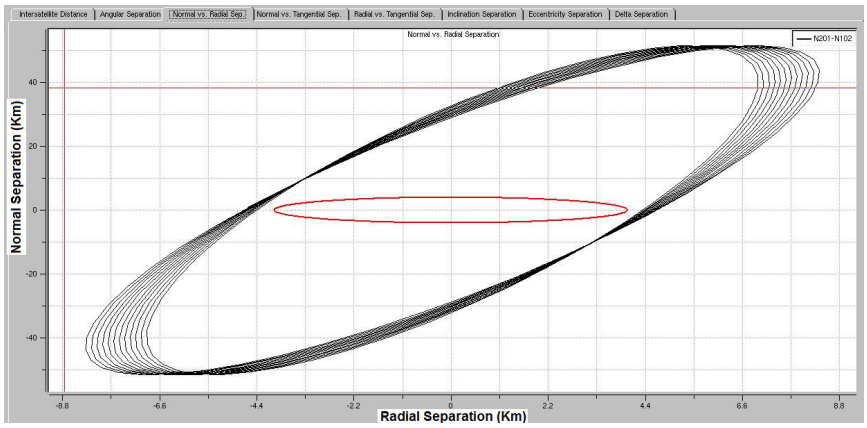


Fig. 12 Normal_vs_radial separation" circle with NO maneuver

B. Ignoring the "Normal_vs_Radial Separation" Criteria

During the orbitography computations for satellite Y, the results produced a NORTH with DVn = 2.030344m/s has generated a violation for the "normal_vs_radial separation" circle as seen in Fig. 11. Trying to correct this violation through decreasing the DVn or postpone the time of the maneuver, the operator was not able to avoid the **violation** in the "**normal_vs_radial separation**" circle. The only way we were able to avoid this transgression was by not performing the North maneuver correction (Fig. 12).

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As an alternative way, we look for the safety of the collocation through another parameter: **"inter-satellite min distance"**, were it could be shown in Fig. 13 that the Min inter-satellite distance was **above** the min value (4 Km) and was not a problem. And, it worth mentioning that the flight dynamic tool accept the results once the min inter-satellite distance check is passed, but if this value is less than the accepted criteria then the ground tool stops and provide a warning message indicating the need to perform a "maneuver avoidance" correction, which was not the case in this point. Therefore, as we consider the "normal_vs_radial separation" circle is a too restrictive criteria with X satellite in inclined orbit, we could accept to have a good **inter-satellite min distance** separation, which is the case, there is no risk of collision. And thus the maneuver has been performed.

CO-LOCATION ANALYSIS REPORT

Satellite Y and Satellite X

Minimum intersatellite distance: 6.5305 (Km) at 2015/05/04-13:00:00

Maximum angular separation from Station CAI_0 is: 0.1148 (Deg) at 2015/05/14-06:00:00

Fig. 13 Print-out of the Co-location analysis report

We faced a **violation** in the two main criteria **"normal_vs_radial separation"** circle and **"min inter-satellite distance"**, which means that from our point of view this time, is a real problem as seen in Fig. 14. By using the first solution by tuned the maneuver date and time to avoid this situation, we **succeeded** to respect the **"min inter-satellite distance"** criteria by shifting the maneuver date by one day and adjusting the maneuver time by around 1 hour.

C. Re-Adjusting the Eccentricity Control Circle

As the violation problem was repetitively appearing, so to go to the safer collocation strategy and to respect both "normal_vs_radial separation" circle and **"min inter-satellite distance"** separation, several collocation window scenarios had been performed by modifying X-satellite eccentricity circle (shift_ex, shift_ey and radius) and compute the East/West maneuver correction and then perform orbit prediction to see the collocation effect with respect the "min inter satellite distance" parameter and the "normal_vs_radial separation" circle to prove the collocation strategy is secured. From these analyses had shown the need to move the eccentricity circle of satellite X to secure the collocation with satellite Y.

VII. Conclusion

As Satellite X has started drifting in inclination after the stop of South maneuvers, a new setting of the collocation parameters is required for satellite X and Y so as to optimize their relative movement and ensure secured inter-distance. These setting are summarized in Table III. So, the eccentricity window was modified as seen in the Fig. 16. By this new setting the eccentricity separation had increased and we regain Δi//Δe vector directions as seen in Fig. 17.

GENERATING CO-LOCATION INFORMATION
Minimum intersatellite distance: 3.1047 (Km) at 2015/05/16-00:30:00
Maximum angular separation from Station CAI_0 is: 0.1235 (Deg) at 2015/05/19-18:00:00

********** WARNING **********
** Threshold distance violated at epoch:2015/05/16-00:30:00 **
** Intersatellite distance limit (Km) : 4.00000 **
****
** Collision Avoidance Manoeuvre might be required **
****
WARNING: Eccentricity prediction after manoeuvres exceeds maximum eccentricity
WARNING: Eccentricity prediction after manoeuvres exceeds maximum eccentricity

Manoeuvre on satellite:
EAST THRUST MID-POINT ON 2015/05/15 AT 04:00:32 SIZE = 0.2217 M/S

WEST THRUST MID-POINT ON 2015/05/15 AT 15:58:34 SIZE = -0.2217 M/S

Minimum longitude : -7.05263 (Deg) at 2015/05/17-03:30:00
Maximum longitude : -7.00434 (Deg) at 2015/05/15-03:30:00

Limits of longitude window (Deg): Min: -7.09000/ Max: -6.91000

** The new minimum intersatellite distance is: 35.10057344 (Km) AT 2015/05/15-12:00:00
** The new maximum angular separation from Station CAI_0 is: 0.1434 (Deg) at 2015/05/16-18:30:00

*** END OF PROGRAM

Fig. 14 Print-out of the Co-location analysis report

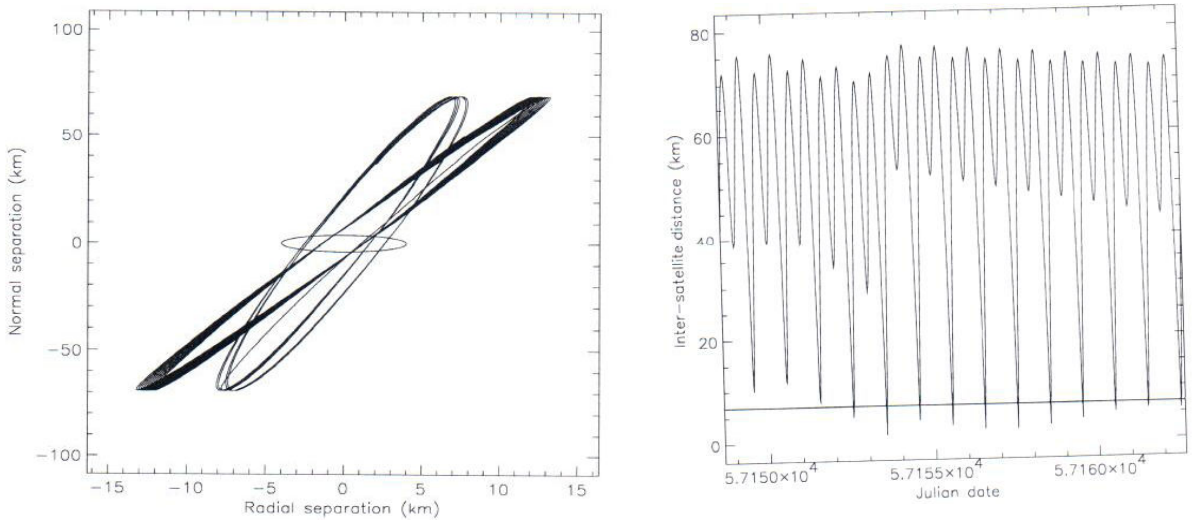


Fig. 15 (a) Scenario 1 – No Change

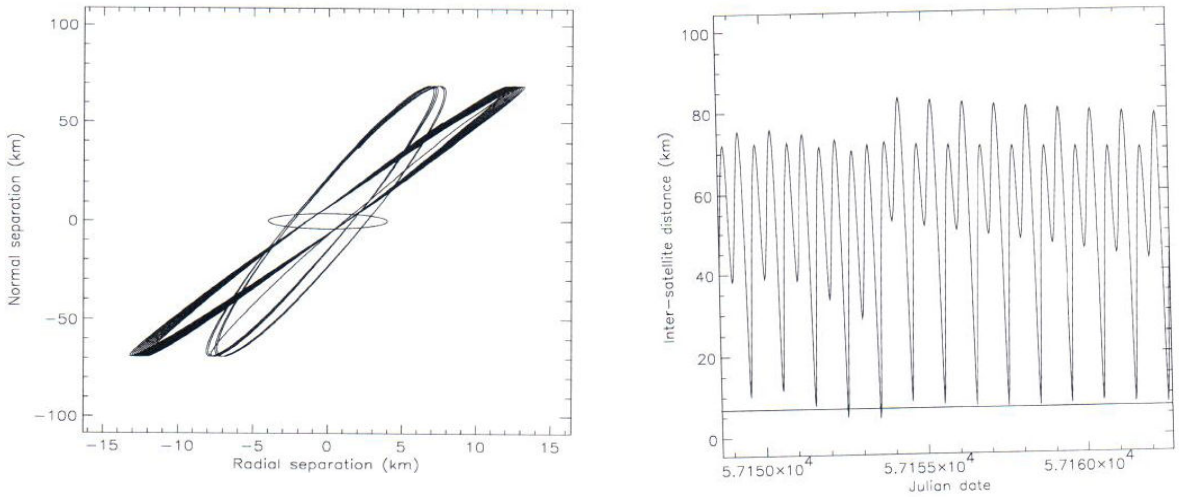


Fig. 15 (b) Scenario 2 – Change ex, ey with required E/W

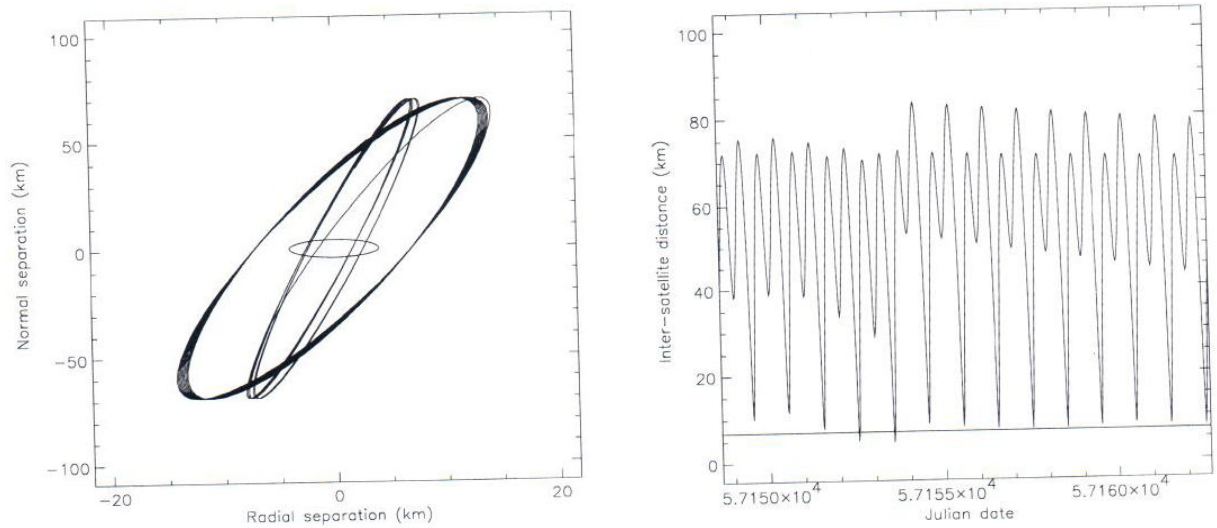


Fig. 15 (c) Scenario 3 – Change ex and ey and ecc radius

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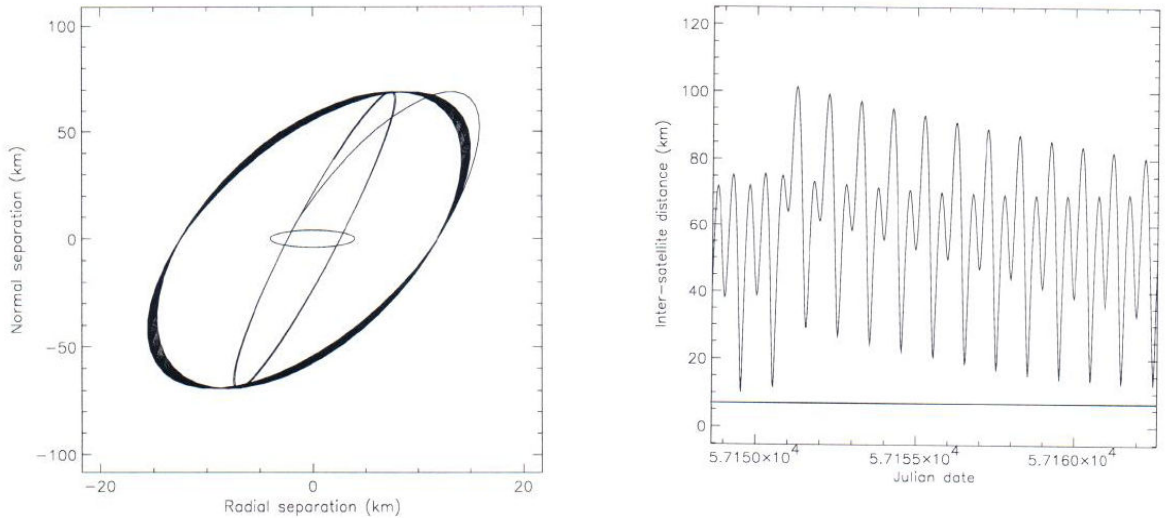


Fig. 15 (d) Scenario 4 – Change e_x and e_y and date of correction

TABLE III
CURRENT AND NEW ECCENTRICITY CIRCLE SETTINGS

Parameters	Satellite X		Satellite Y	
	Current Value	New Value	Current Value	New Value
Shift_ex	0.000105	0.0	-0.000156	0.0
Shift_ey	-0.000115	-0.000129	0	0.000156
Control eccentricity	0.0004	0.000487	0.00046	0.00046

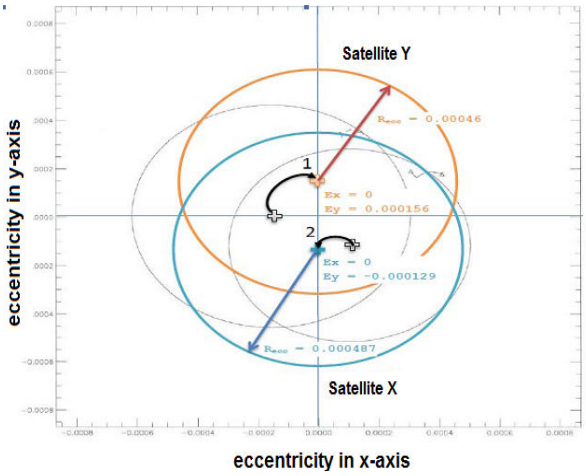


Fig. 16 New control circle adjustment

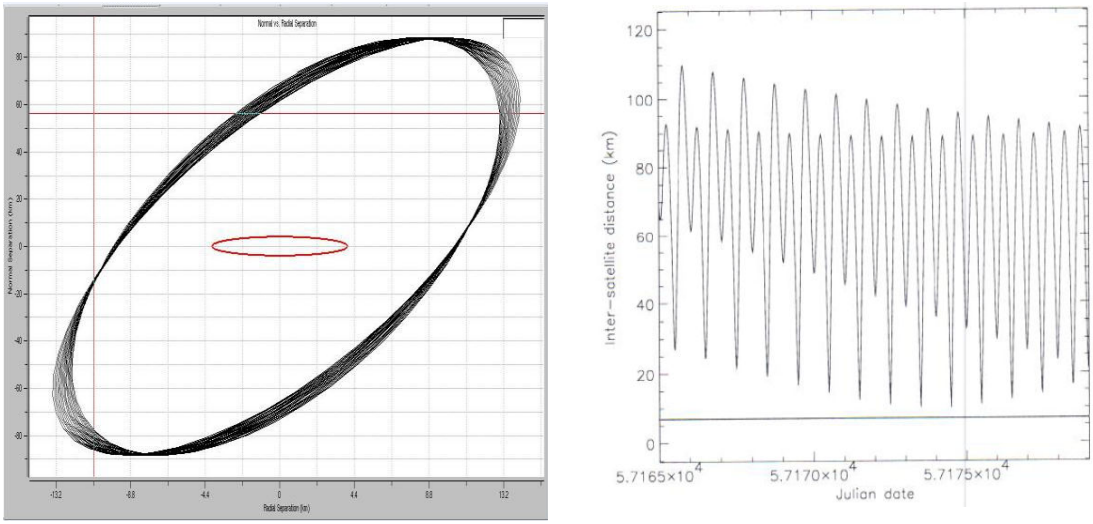


Fig. 17 Adjustment of the "normal_vs_radial separation" circle and min inter-satellite distance

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