COLLISION RISK ASSESSMENT AND MITIGATION STRATEGY FOR THE GSOC GEO SATELLITES

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Abstract: The collision avoidance strategy for geostationary satellites is discussed in the paper. The possible encountering objects were first analyzed from the past events and also from the object population in the geostationary ring. Compared with the conjunctions in LEO, an in-track maneuver for the collision avoidance has to be planned more carefully, because the satellites have to be kept inside the control box. To mitigate the high collision risk while keeping the satellites inside the box, different maneuver strategies were analyzed. Depending on the avoidance maneuver size as well as the drift time, an appropriate E/W maneuver strategy had to be applied. Another strategy using the N/S maneuver allows performing larger thrusting without violating the control box; however the achieved separation varied according to the orbital plane angle and the close approach epoch. The strategies were finally applied to high risk conjunctions in the past. For all cases, the conjunctions could be mitigated and the control requirements were satisfied.

Keywords: *Collision avoidance, Geostationary satellite, Station keeping*

1. Introduction

The ever increasing number of objects in the near Earth region has been causing growing concerns about the space environment and accordingly about the safety of future space missions. Since most of orbital debris stay in the orbit for years, even a single collision between space objects could seriously increase the debris population, making further collisions more likely. The sun-synchronous obit is heavily used by spacecraft, and the altitude region in 750-850 km is most densely populated in the near Earth region, leading to the first satellite collision of Cosmos 2251 and Iridium 33 in 2009. In the higher altitude, the Geosynchronous Earth Orbit (GEO) is a useful and valuable region, where satellites share the same orbital path. The critical population could be reached quickly, because the objects remain in the same altitude range for a long period. The monitoring and mitigation of the space debris is therefore highly important.

The German Space Operations Center (GSOC) has been performing collision avoidance for the operational satellites, currently 6 in LEO and 2 in GEO. Contrary to locally operated satellites, high accurate orbital parameters are not available for the bulk of other space objects. The Conjunction Data Message (CDM, formerly CSM, Conjunction Summary Message) provided by the Joint Space Operations Center (JSpOC) is currently the main source for an assessment of the collision risk against space objects due to the quality and timeliness of the available information. When a CDM is received, the close approach to the corresponding space object is carefully analyzed, and then an avoidance maneuver possibility is investigated, if a critical conjunction is confirmed. A proper mitigation strategy is required in advance to handle the critical situation correctly and promptly.

The typical collision avoidance maneuver, which has been already applied to the operational LEO satellites, is to increase the radial separation by an in-track thrusting half an orbit before the closest approach [1]. A certain separation can be achieved in a short period and also with a relatively small maneuver in this way. Additionally, the satellite can easily come back to the nominal orbit shortly after the closest approach. When possible, an avoidance maneuver is combined with an orbit maintenance maneuver to reduce fuel consumption as well as the mission cost. For the geostationary satellites, an additional constraint needs to be considered because the satellites have to be kept inside the control box. An in-track thrusting for the radial separation causes a drift in the longitude direction, which could lead to a violation of the permitted region. For such cases, the possibility of the out-of-plane separation was also investigated. Another consideration is the orbit accuracy of geosynchronous objects. Compared with the LEO case, the estimated covariance available for the space object is mostly larger, while its growth dependent on the propagation is smaller because of the absent atmospheric influence. Therefore, the mitigation scenario needs to be planned carefully based on the possible separation requirements and maneuver options as well as the suitable timeline.

In this paper, the operational collision avoidance experience is shown, followed by the typical conjunction characteristics in the GEO case. The mitigation strategy for the geostationary satellites is then discussed, and the performance is evaluated using some conjunction examples in the past.

2. Operational Process

2.1. GEO Satellite Operation

Two geostationary satellites COMSATBw-1 (SB1) and COMSATBw-2 (SB2) are currently operated at GSOC, providing communication capability to the German Armed Forces. The satellites are controlled inside the control window of ± ~0.1° around 63.0° East for SB1, and 13.21° East for SB2.

Due to various perturbations caused by the Sun, the Moon and the Earth itself an initially geostationary orbit will gradually build up a small eccentricity and inclination and drift away from its nominal position. In order to counteract these perturbations and to limit the satellite motion to a prescribed tolerance window around the nominal position, both East/West and North/South maneuvers have to be performed on a semi-regular basis. For operational reasons (regular maneuver schedule) it is convenient to introduce a fixed station keeping cycle, at the end of which certain prescribed target elements have to be achieved. This cycle repeats every three weeks for the current nominal operation and includes a longitude and eccentricity correction near the start of the cycle (2nd day) and an inclination correction near the end of the cycle (21st day). An example of the satellite motion during a station keeping cycle is shown in Figure 1.

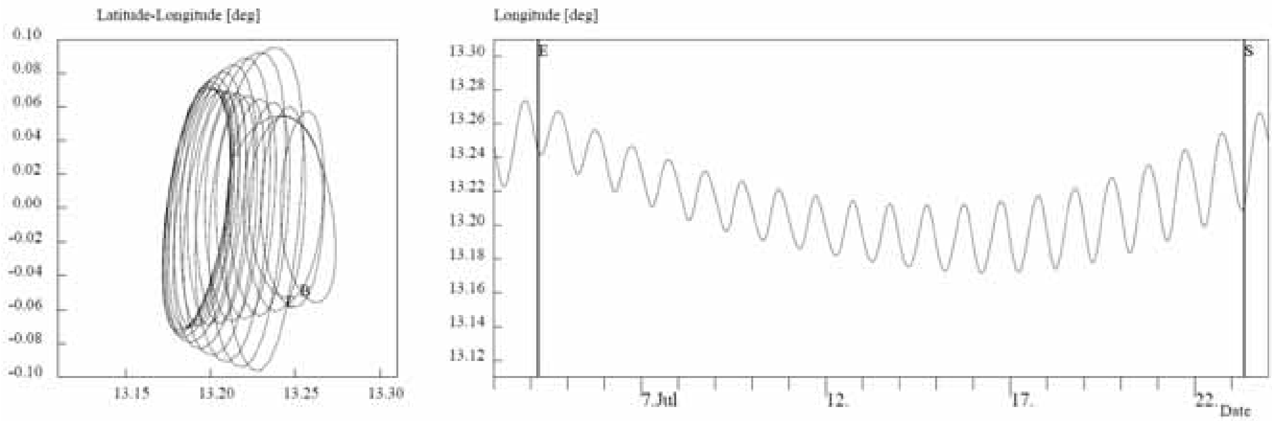

Figure 1 Satellite Motion during A Station Keeping Cycle (SB2)

2.2. Collision Avoidance Operation

GSOC has been performing collision avoidance operation for the locally controlled satellites since 2009. Currently 6 satellites in LEO and 2 in GEO are supported 24/7 by the Flight Dynamics personnel.

The collision avoidance process consists of mainly three steps: detection of the possible conjunction, risk analysis and mitigation. The main source for the conjunction detection is the CDM provided by JSpOC, because the catalog with sufficient orbital information is not available for other space objects. When any conjunction is detected by the JSpOC screening process within certain thresholds, each conjunction event is reported to the Flight Dynamics personnel through the CDM. The conjunction with the corresponding space object is carefully analyzed using orbit information of the satellite and an avoidance maneuver possibility is investigated, if a critical conjunction is confirmed.

3. Conjunction Case Analysis

3.1. Population of Geosynchronous Objects

Table 1 shows the population of the objects near the geostationary ring as of the end of 2012 [2]. The geosynchronous region is defined here as orbits with a mean motion between 0.9 and 1.1 revolutions per day, an eccentricity smaller than 0.2 and an inclination below 70 deg. The main orbit source is the Two-Lime Elements catalog provided by US Strategic Command (USSTRATCOM). Additionally, objects observed by ground based telescopes are also included. The object size is larger than about 1 m so that they can be tracked regularly from ground. The orbit type of the objects is categorized as follows:

- C1: objects under longitude and inclination control
- C2: objects under longitude control
- D: objects in a drift orbit
- L1: objects in a libration orbit around the Eastern stable point (longitude 75° East)
- L2: objects in a libration orbit around the Western stable point (longitude 105° West)
- L3: objects in a libration orbit around both stable points [3]

Almost half of the total objects are in the drift orbit, whereas not all of them cross the geostationary ring. On the other hand, the uncontrolled objects remaining in the libration orbit could also become a potential conjunction risk for the satellites, because the objects remain at the geostationary altitude during the whole orbital period.

The longitude distribution of the objects in the libration orbit (L1 and L2) is shown in Figure 2. The value at each longitude indicates the number of the objects which pass through the corresponding longitude during the libration around the stable point. Therefore, the number increases closer to the stable point, and only a small number of objects with a larger libration magnitude are counted at the edge of the distribution. Figure 2 shows that the region of the L1-type orbit is more populated and the number becomes higher near the Eastern stable point.

Table 1 Number of Geosynchronous Objects

Orbit type	C1	C2	D	L1	L2	L3	Others	Total
Number (%)	289 (21)	133 (9)	662 (48)	114 (8)	46 (3)	18 (1)	107	1369

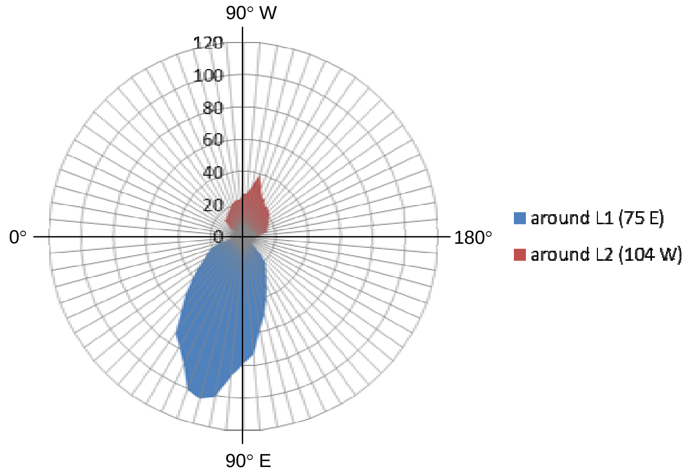

Figure 2 Objects in Libration Orbit

3.2. Historical Events

Table 2 shows the number of the encountering objects for the two operational geostationary satellites COMSATBw-1 (SB1, 63.0° East) and COMSATBw-2 (SB2, 13.21° East) in the past years. Each object is classified according to the orbit type in 3.1. The number of the controlled satellites which are operated inside the neighboring window is not counted. The conjunctions were detected and alarmed by JSpOC with the thresholds of the relative / radial distance of 50.0/50.0 km. Among all the events, one avoidance maneuver was performed so far in 2012, which was a close approach of a non-operational satellite.

Table 2 Number of Encountering Objects

Satellite	SB1 (63° East)			SB2 (13° East)		
Orbit type	C1/C2	D	L1	C1/C2	D	L1
2011	0	2	3	0	1	0
2012	1	0	6	0	0	0
2013	0	0	6	1	0	1
Total	1	2	15	1	1	1

The most encountering objects are uncontrolled satellites and rocket bodies. A few cases are related to controlled satellites, which could have been during the station acquisition phase, in-orbit testing or the longitude shifts. It should be also mentioned that the maneuver information for the controlled satellites are not considered in the JSpOC prediction. In the case of SB2, the encountering objects of each orbit type are comparable in the number, whereas the frequency of the L1-type objects is distinctively high for SB1. It can be explained by the longitude distribution of the objects in a libration orbit as shown in Figure 2. The results also indicate a strong need of the end-of-life re-orbit for the operated satellites to the disposal orbit.

The orbital inclination of objects near the geostationary ring grows up to ~15 deg due to the perturbation caused by the gravitational attraction of the Sun and the Moon. Assumed that the orbit is nearly circular, it corresponds to a relative velocity of up to ~800 m/s, when an object encounters a geostationary satellite.

4. Avoidance Maneuver Strategy for GEO satellites

The typical collision avoidance maneuver, which has been already applied to the operational LEO satellites, is to increase the radial separation by an in-track thrusting half an orbit before the closest approach. For the geostationary satellites, an in-track maneuver has to be planned more carefully, because the satellites have to be kept inside the control box. An in-track thrusting for a radial separation causes a drift in the longitude direction, which could lead to a violation of the permitted region. Another maneuver possibility is an out-of-plane thrusting, which is regularly performed in the station keeping for the inclination control. Since date and the size of a N/S maneuver can be changed more flexibly compared to the E/W maneuver, it could be applied to the collision avoidance. Radial thrusting was not considered, because it is not applicable during routine operations.

The software package *GeoControl* was used for the orbit prediction as well as the maneuver planning. The software was developed at GSOC to enhance the operational station keeping of geostationary satellites and to meet the requirement for safe colocation of multiple satellites at a common location. The package consists of the following tools:

- Orbit determination and maneuver estimation (ORBIT)
- Maneuver planning (MAPLA)
- Ephemeris and event prediction (EVENT) and
- Relative motion monitoring of collocated satellites (COLO)

In MAPLA, an initial orbit obtained from a previous orbit determination is compared with a prescribed target orbit at a given epoch to compute the required E/W and N/S maneuvers in a consistent way. This approach allows for a consideration of deterministic cross-coupling effects to improve the maneuver computation and to reduce the total fuel consumption. The target elements may either be provided by the user or generated by MAPLA according to a predefined strategy.

4.1. Maneuver for Station Keeping

Changes in the orbital elements related to impulsive maneuvers are formulated by the following equations [4]:

$$\Delta D = -\frac{3n}{V}\Delta V_T \tag{1}$$

$$\Delta l = -\frac{2}{V}\Delta V_R + \tau\Delta D \tag{2}$$

$$\Delta e_x = \frac{1}{V}\left(+\Delta V_R \sin\alpha + 2V_T \cos\alpha\right) \tag{3}$$

$$\Delta e_y = \frac{1}{V}\left(-\Delta V_R \cos\alpha + 2V_T \sin\alpha\right) \tag{4}$$

$$\Delta i_x = \frac{1}{V}V_N \cos\alpha \tag{5}$$

$$\Delta i_y = \frac{1}{V}V_N \sin\alpha \tag{6}$$

where ΔD and Δl is the drift rate and mean off-station longitude, respectively. The angle α stands for the right ascension of the satellite during the maneuver and τ for the time passed since the maneuver.

The longitude and eccentricity control is performed by the E/W maneuver. The typical size of an E/W maneuver is in the order of several cm/s. At the 13° East location, the acceleration caused by the triaxiality of the Earth is ~1.5×10^{-2} deg/s^2. An East maneuver of ~8 cm/s is required to counteract the East drift in the 21-days cycle. On the other hand, the minimum size of a maneuver is limited to ~1 cm/s, because a maneuver consists of several pulses. A smaller thrusting is not possible, or could lead to a growth of the performance error. In order to reduce the oscillations in longitude, the eccentricity has to be decreased, which requires regular E/W maneuvers. An eccentricity control circle of appropriate size is therefore introduced and the target eccentricity is chosen such that the e-vector stays near this control circle with the perigee pointing towards the Sun. The control circle for SB2 is set to $\sim 1.5\times10^{-4}$ for nominal operations.

The inclination is controlled by N/S maneuvers to counteract the natural drift caused by the gravitational attraction of the Sun and the Moon. During nominal operations, a maneuver of ~2.4 m/s is regularly performed during a cycle, which amounts to an inclination change of ~0.045°. Additionally the inclination vector is kept inside a control circle of 0.1°. To achieve a change in the desired direction, a North pulse must be performed, when the right ascension of the satellite is close to 270°. Alternatively a South pulse may be used 12 hours later.

4.2. ΔV Estimation for Collision Avoidance

The main purpose of a collision avoidance maneuver is to reduce the collision risk, which can be evaluated by the collision probability. When two objects encounter in a short period, the collision probably *P* can be defined in the B-plane, which is perpendicular to the relative velocity vector and is calculated as follows. [5]

$$P = \frac{HR^2}{\exp(1)\sqrt{\det(C_B)}\cdot \Delta\hat{r}_B{}^T C_B{}^{-1}\Delta\hat{r}_B} \tag{7}$$

HR is the combined object radius (hitradius), $\Delta\hat{r}_B$ is the position offset from the primary object in the B-plane, and C_B is the combined covariance matrix projected on the B-plane. $\Delta\hat{r}_B$ and C_B are calculated at the time of the closest approach (TCA). Taking the coordinate axes of the B-plane ($X_{B\text{-plane}}$ and $Y_{B\text{-plane}}$) aligned with the minor/major axis of the covariance ellipsoid with the standard deviations of σ_x and σ_y, the contour line with respect to the probability can be shown as in Figure 3, which corresponds to the scaled covariance ellipsoid in the B-plane. The minor axis X_0 of the ellipsoid for the probability P_0 can be expressed by the following equation:

$$X_0{}^2 = \frac{HR^2}{\exp(1)\cdot AR\cdot P_0} \tag{8}$$

where *AR* is the ratio of the standard deviations σ_y / σ_x.
Assuming that the encountering objects have a circular orbit (*e* ~0.0), the radial direction of two objects are aligned and lies in the B-plane at the closest approach. The radial direction is furthermore close to the $X_{B\text{-plane}}$ axis for the typical conjunction case, using the standard deviation of SB1 and SB2 as shown in Table 3. To estimate the standard deviation, the covariance matrix was numerically calculated from orbit determination and orbit propagation results [6].

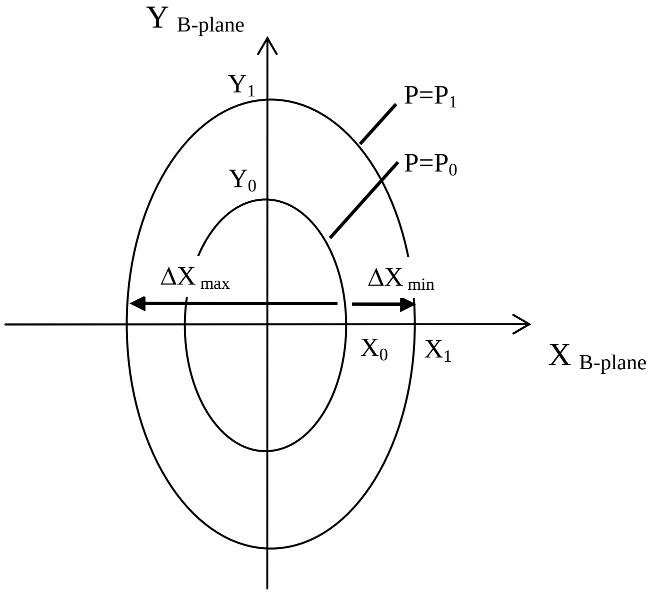

Figure 3 Probability Plot in B-plane

The required radial separation ΔX to achieve P_1=10^{-5} from P_0=10^{-4} was estimated for a different hitradius and a ratio of the standard deviations as shown in Table 4. The collision probability of 10^{-4} was regarded as the indication of the highly critical conjunction. Two separation possibilities ΔX_{max} and ΔX_{min} were considered for the maneuver direction of East and West (see also Figure 3). Considering a SB1/SB2 radius of 8.6 m, the hitradius (*HR*) is assumed to be 10-15 m for most of the conjunction cases, when the secondary object is smaller than the satellite or in the same size. The value of the ratio (*AR*) varies depending on the covariance matrices of the two encountering objects and the hit angle. It was estimated as ~5-10 from the historical events. In case of a geostationary satellite, the change of the semi-major axis due to a tangential burn of 1 cm amounts to ~270 m. A change of the radial distance by ~540 m can be accordingly achieved, if the satellite position during the maneuver is separated from the position at the closest approach by half an orbit. Therefore an in-track maneuver of up to 2-3 cm is sufficient to achieve the required radial separation in most of the conjunctions.

Table 3 Standard Deviation of OD/OP Results, [m]

	R			T			N		
Prop.days	0	3	7	0	3	7	0	3	7
SB1	41.86	41.87	41.94	86.8	97.4	119.8	351.7	351.7	351.6
SB2	36.62	36.60	36.60	149.1	173.1	207.2	290.4	290.5	290.6

Table 4 Radial Separation to Lower Probability from 10^{-4} to10^{-5}, [m]

	ΔX_{max}				ΔX_{min}			
[m]	*AR*=1	*AR*=5	*AR*=10	*AR*=15	*AR*=1	*AR*=5	*AR*=10	*AR*=15
HR= 5	1262	565	399	326	656	293	207	169
HR=10	2525	1129	798	652	1311	587	415	339
HR=15	3787	1694	1197	978	1967	880	622	508
HR=20	5049	2258	1597	1304	2623	1173	829	677

4.3. 1 EW Maneuver

The satellite motion after the E/W collision avoidance maneuver was simulated using orbital elements of SB2 during a cycle period from January 15 to February 5 in 2014. The objective is to keep the satellite inside its control box of ± 0.1°. For operational reasons, the regular maneuver cycle needs to be unchanged: the E/W maneuver is performed on the 2nd day of the 21 days period and the N/S maneuver on the last day. However, the maneuver size and epoch can be adjusted. Based on the orbital elements after the collision avoidance maneuver performed during a cycle (here named as first cycle), the station keeping maneuvers for the next cycle (second cycle) were calculated using the MAPLA tool. To counteract the irregular longitude drift due to the collision avoidance, the nominal East maneuver for the second cycle needs to be adjusted. For the collision avoidance, different maneuver options in size, direction and epoch were applied. A maneuver size of 1 cm/s and 2 cm/s in both of the E/W directions was used, based on the estimation in 4.2. Since the longitude drift increases according to the time as shown by Equation 2, different maneuver epochs of 6, 12, 18 days from the beginning of the cycle were considered.

The E/W maneuver planned for the second cycle is shown in Table 5. The East maneuver without collision avoidance is also listed for a comparison. For some cases, the satellite was out of the control box, which are marked with a *. The planned East maneuver can be reduced in the case of an East collision avoidance maneuver, because it can replace a part of the longitude drift correction. When the maneuver size for the collision avoidance is 1.0 cm/s, the satellite could be kept inside the control box for each maneuver epoch and direction. However, larger size of the maneuver and longer drift time lead to a violation of the control box, therefore another strategy is required. The satellite motion in longitude and latitude during the two cycles is shown in Figure 4. For each case, the first thrusting (indicated by a vertical line in the longitude/time plot) is the collision avoidance maneuver before TCA.

The selection of the collision avoidance maneuver in size, direction and epoch depends on several parameters at TCA, such as the relative position, the object size and the covariance information of two objects. The maneuver direction needs to be selected carefully, considering the effect on the E/W maneuver correction for the following cycle. In addition, the maneuver epoch affects the eccentricity vector as well as the longitude drift. The size of Δe caused by a 1 cm/s burn amounts to 6.5×10^{-6}. Table 6 shows that the planned maneuver size remains almost unchanged, while the epoch is slightly modified to adjust the eccentricity vector.

Table 5 E/W Maneuver for Second Cycle [m/s]

Avoidance maneuver epoch [UTC]	2014/01/21 06:00	2014/01/27 06:00	2014/02/02 06:00
Day in the 1st cycle	6	12	18
dV= 2.0 cm/s (East)	0.046 *	0.053 *	0.059
dV= 1.0 cm/s (East)	0.064	0.068	0.071
No maneuver	0.083	0.083	0.083
dV= -1.0 cm/s (West)	0.101	0.098	0.095
dV= -2.0 cm/s (West)	0.119 *	0.113	0.107

*: Out of the control box

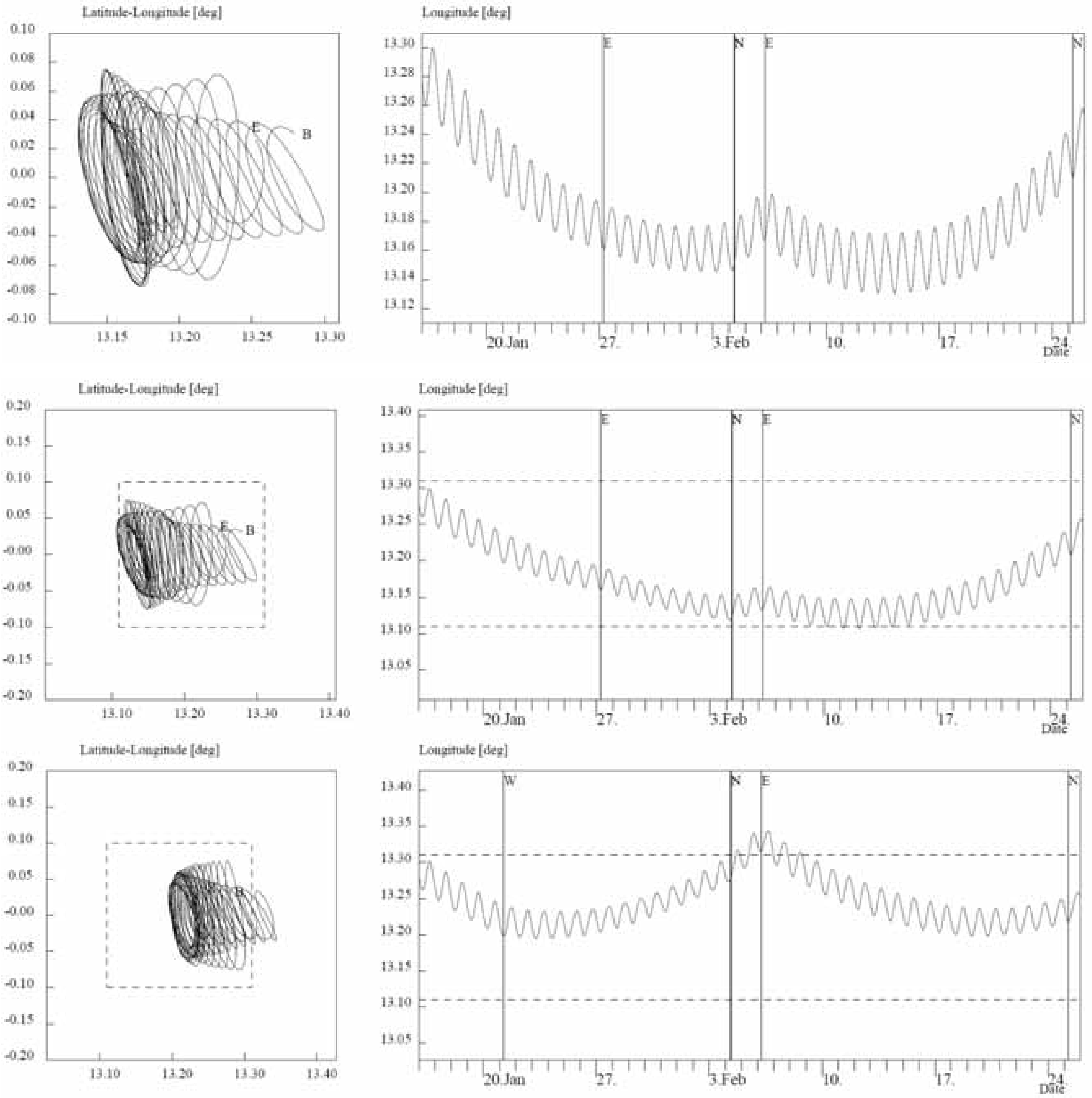

Figure 4 Satellite Motion during Two Cycles

Top: *dV*= 1.0 cm/s (East), 2014/01/27 06:00 [UTC]
Middle: *dV*= 2.0 cm/s (East), 2014/01/27 06:00 [UTC]
Bottom: *dV*= -2.0 cm/s (West), 2014/01/21 06:00 [UTC]

Table 6 E/W Maneuver for Different Avoidance Maneuver Epoch

Avoidance maneuver		E/W maneuver for the second cycle	
Size and direction	Epoch [UTC]	Size [m/s]	Epoch [UTC]
dV= 1.0 cm/s (East)	2014/01/21 06:00	0.0645	2014/02/06 05:48
	2014/01/21 14:00	0.0646	2014/02/06 05:30
dV= -1.0 cm/s (West)	2014/01/21 06:00	0.1009	2014/02/06 05:46
	2014/01/21 14:00	0.1008	2014/02/06 06:05

4.4. 2 EW Maneuver

When the size of the maneuver is larger and the drift time is longer, another E/W maneuver needs to be performed to keep the satellite inside the control box. For such situations, the rest of the cycle after the collision avoidance maneuver was considered as another cycle, and the station keeping maneuvers in the E/W and N/S directions were planned using the MAPLA tool. Since the end of the cycle is not changed, the regular N/S maneuver can be still applied. After the first cycle, the station keeping maneuvers were planned as during nominal operations, and the satellite motion during the whole period was simulated. Four cases of a collision avoidance maneuver were considered, which are different in direction and epoch. The first E/W maneuver needs to be placed after the closest approach, which is approximately 12 hours after the avoidance maneuver, and the date can be changed. Therefore, a maneuver date of 1 day and 3 days after the avoidance maneuver were selected.

The resulting two E/W maneuvers after the collision avoidance are shown in Table 7. The E/W maneuvers for the first cycle were planned to counteract the avoidance maneuver into the reverse direction, while maneuver sizes were not the same due to the epoch difference. Since the longitude drift increases according to the time, the maneuver needs to be placed soon after the close approach to compensate the drift with a smaller size of the maneuver. The maneuver for the second cycle was slightly affected by the collision avoidance maneuver; however the satellite motion in longitude and latitude during the whole cycle was controlled as during nominal operations (refer also to Figure 5). For all cases, the satellites could be controlled inside the box.

Table 7 E/W Maneuver for First/Second Cycle

Avoidance maneuver epoch [UTC]	2014/01/21 06:00			2014/01/27 06:00		
Cycle	1st		2nd	1st		2nd
	Epoch [UTC]	Size [m/s]	Size [m/s]	Epoch [UTC]	Size [m/s]	Size [m/s]
dV= 2.0 cm/s (East)	2014/01/22 08:30	-0.026	0.090	2014/01/28 13:19	-0.027	0.090
	2014/01/24 09:02	-0.029	0.092	2014/01/30 13:20	-0.036	0.099
dV= -2.0 cm/s (West)	2014/01/22 04:20	0.017	0.086	2014/01/28 05:14	0.019	0.083
	2014/01/24 04:39	0.021	0.082	2014/01/30 05:16	0.027	0.074

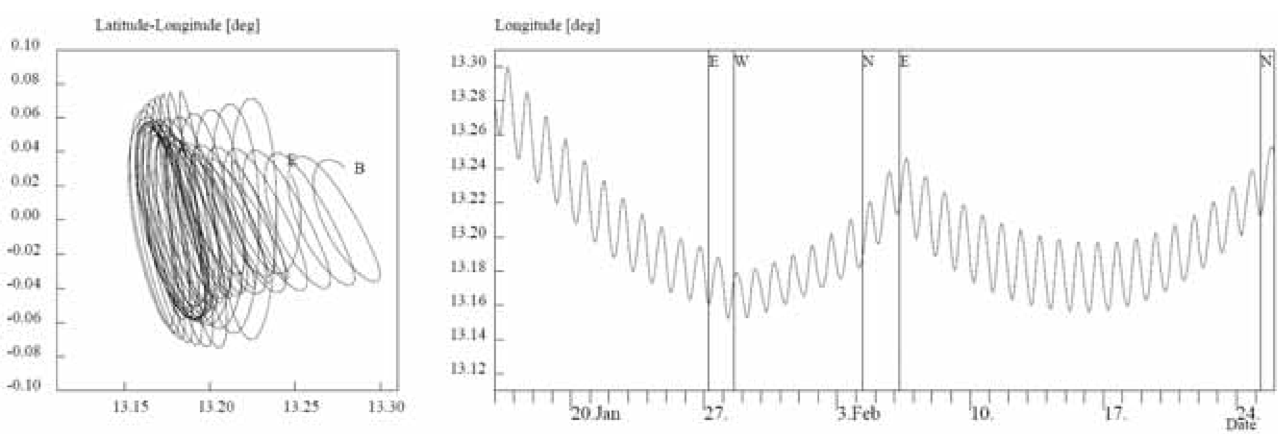

Figure 5 Satellite Motion during Two Cycles

dV= 2.0 cm/s (East), 2014/01/27 06:00 [UTC]
E/W maneuver during the 1st cycle: 2014/01/28

4.5. NS Maneuver

When a N/S avoidance maneuver is planned for a geostationary satellite, the maneuver time during a day as well as the direction are constrained to the inclination control: a North pulse is performed when the right ascension of the satellite is close to 270°, and alternatively a South pulse 12 hours later. Size and date of the maneuver can be adjusted so that the conjunction is mitigated and the inclination vector is controlled inside the control circle of 0.1°.

An orbit change in the out-of-plane direction ΔN at the close approach depends on the difference of the satellite's right ascension at the maneuver and at TCA $\Delta\alpha$, in other words the epoch difference between the maneuver and TCA. The close approach geometry is accordingly changed, because the orbital node between two objects shifts, which is shown in Figure 6. The orbital node is defined here as a point where the orbit of one object intersects the orbital plane of the other object. In Figure 6, the lines Lp and Ls are the orbital paths of each object, which intersect at the node Q with the angle Δi being the angle between the two orbital planes. The closest approach occurs near the node, where the primary position P, the secondary position S and the corresponding node Q at TCA form a triangle, when two objects are moving toward each other in circular orbits at the same altitude [7] (Equation 9).

$$\overline{PQ} \approx \overline{SQ} = l \qquad (9)$$

The shift of the orbital path by ΔN changes the scale of the triangle, where

$$\Delta l = \frac{\Delta N}{2\tan(\Delta i)} \cdot \left(\frac{1}{\cos(\Delta i)} - 1\right) \qquad (10)$$

The line of the relative position $\overline{PS}$ lies on the B-plane at TCA. Additionally the line is perpendicular to the radial direction on the assumption that both objects are in circular orbits. Therefore the change of $\overline{PS}$ corresponds to the change of the relative position in the $Y_{B\text{-plane}}$ direction defined in Figure 3, when the radial direction is nearly aligned with the $X_{B\text{-plane}}$ axis as estimated in 4.2. The resulting separation ΔY due to the N/S maneuver can be expressed as follows:

$$\Delta Y = 2\Delta l \cdot \cos\left(\frac{\Delta i}{2}\right) \qquad (11)$$

Table 8 shows the size of ΔY achieved by a 1 m/s North pulse for the inclination control. Depending on the required ΔY to decrease the collision risk, the N/S maneuver size needs to be selected for the corresponding $\Delta\alpha$ and Δi. However, this strategy is not effective for all conjunctions, but only when the values of $\Delta\alpha$ and Δi are higher.

Table 8 ΔY Achieved by a 1 m/s North Maneuver [km]

$\Delta\alpha$	ΔN	Orbital plane angle Δi [deg]			
[deg]	[km]	1	5	10	15
0	0.0	0.000	0.000	0.000	0.000
30	6.9	0.060	0.299	0.598	0.895
60	11.9	0.104	0.518	1.035	1.551
90	13.7	0.120	0.598	1.195	1.790

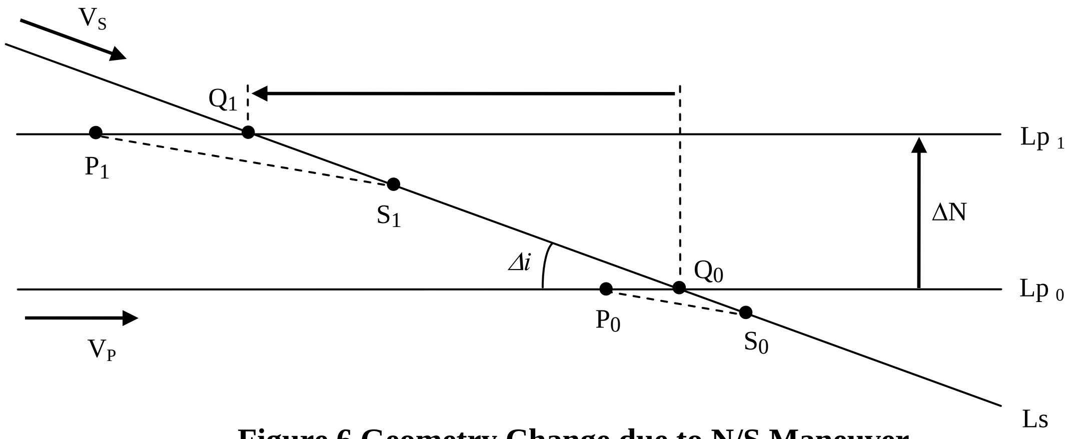

Figure 6 Geometry Change due to N/S Maneuver

5. Examples

The maneuver strategies discussed in the previous sections were applied to the conjunctions in the past years. The CDMs concerning the following objects were used:

- Case 1: SB1, object ID: 24435 (2014/01/20)
- Case 2: SB1, object ID: 22981 (2012/03/20)
- Case 3: SB2, object ID: 04376 (2013/07/07)

Since the critical case occurred only a few times (case 2), the high risk conjunctions for case 1 and case 3 were simulated from the CDM by changing the orbital elements of the secondary objects. The parameters at the closest approach are listed in Table 9 for each case. The strategies using the E/W maneuver and the N/S maneuver were both tested to reduce the collision risk and to keep the satellite inside the control box. An avoidance maneuver was selected so that the collision probability expressed by Equation 7 becomes lower than 10^{-5} by less fuel consumption.

Table 9 Close Approach Parameters

	TCA [UTC]	Probability [-]	Miss distance [km]	Relative distance (in RTN) [km]	Relative velocity [km/s]	Orbit Angle [deg]
Case 1	2014/01/20 02:16	1.05×10^{-3}	0.281	0.057; 0.274; -0.031	0.690	12.9
Case 2	2012/03/20 10:26	7.13×10^{-5}	0.298	0.250; -0.161; -0.017	0.679	12.7
Case 3	2013/07/07 00:47	5.12×10^{-4}	0.121	-0.085; 0.085; 0.007	0.434	8.1

The results of the E/W maneuver strategy are shown in Table 10 and the close approach parameters after the collision avoidance maneuver in
Table 11. To reduce the fuel consumption as well as the operational cost, a 1EW strategy was first applied. The 2EW strategy was then used, when additional maneuvers were necessary to keep the satellite inside the box. The satellite motion during two cycles is shown in
Figure 7. Using two types of the E/W maneuver strategy, all conjunctions were mitigated.

The results of the N/S maneuver strategy are shown in Table 12 and Table 13. Depending on the orbital angle and the difference between maneuver epoch and TCA, a wide range of the maneuver size was applied to achieve the required separation. However, the larger size of the maneuver has to be planned carefully during the operation due to the expected cross-coupling errors. It should be also mentioned that the applicable N/S maneuver is limited to 4.2 m/s for SB1 and SB2. A larger size of thrusting needs to be separately performed.

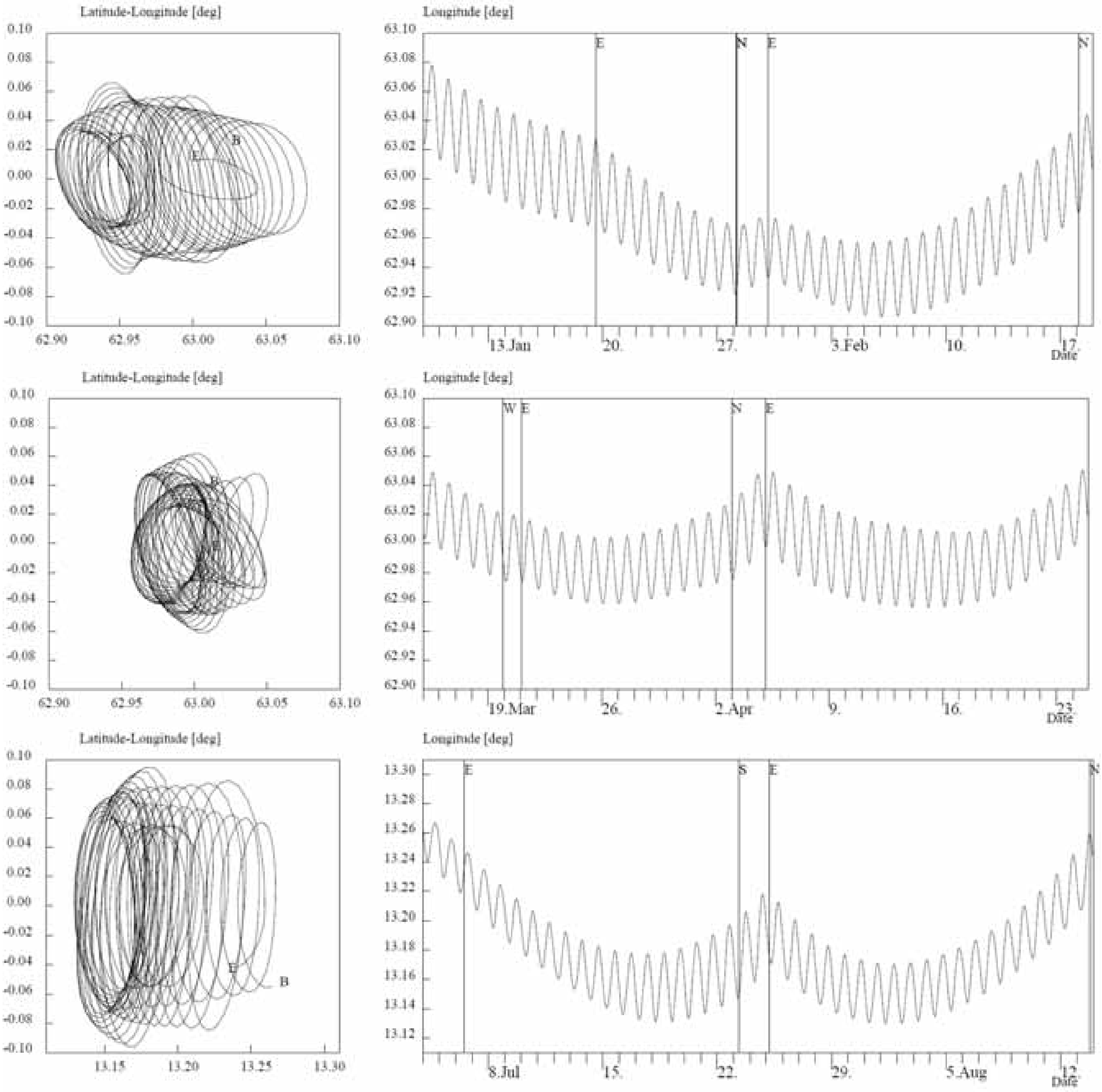

Figure 7 Satellite Motion for E/W Maneuver Strategy

Top: Case 1, Middle: Case 2, Bottom: Case 3

Table 10 Avoidance Maneuver and E/W Maneuver for First/Second Cycle

	Avoidance maneuver		Strategy	1st cycle		2nd cycle
	Epoch [UTC]	Size [cm/s]		Epoch [UTC]	Size [m/s]	Size [m/s]
Case 1	2014/01/19 14:16	2.0 (E)	1EW	Not performed		0.031 (0.061)
Case 2	2012/03/19 22:26	-1.0 (W)	2EW	2012/03/21 01:22	0.016	0.064 (0.066)
Case 3	2013/07/06 12:47	1.0 (E)	1EW	Not performed		0.070 (0.089)

( ): Nominal station keeping maneuver without collision avoidance

Table 11 Close Approach Parameters after E/W Avoidance Maneuvers

	TCA [UTC]	Probability [-]	Miss distance [km]	Relative distance (in RTN) [km]
Case 1	2014/01/20 02:16	9.65×10^{-6}	3.044	-1.041; 2.842; -0.318
Case 2	2012/03/20 10:26	4.89×10^{-6}	1.660	0.798; -1.447; -0.159
Case 3	2013/07/07 00:47	8.84×10^{-6}	1.521	-0.634; 1.379; 0.099

Table 12 North Maneuver for Collision Avoidance

	Epoch [UTC]	Size [m/s]	Strategy
Case 1	2014/01/19 05:10	4.1	NS
Case 2	2012/03/19 01:34	2.3	NS
Case 3	2013/07/06 21:08	8.4	NS

Table 13 Close Approach Parameters after N/S Avoidance Maneuver

	TCA [UTC]	Probability [-]	Miss distance [km]	Relative distance (in RTN) [km]
Case 1	2014/01/20 02:17	9.83×10^{-6}	3.044	-1.041; 2.842; -0.318
Case 2	2012/03/20 10:27	9.52×10^{-6}	2.683	0.232; -2.657; -0.293
Case 3	2013/07/07 00:51	9.83×10^{-6}	6.651	-0.160; -6.632; -0.469

6. Conclusion

The collision avoidance strategy for geostationary satellites was discussed. The event history showed that the most encounters occurred due to uncontrolled objects. Additionally, the number of encounters caused by objects in a libration orbit indicated an object distribution around L1. To mitigate the high collision risk while keeping the satellites inside the control box, different maneuver strategies 1EW, 2EW and 1NS were analyzed. Depending on the avoidance maneuver size as well as the drift time, either of the 1EW or 2EW strategy could be applied. Another strategy using the N/S maneuver allows performing larger thrusting without violating the control box; however the achieved separation varied according to the orbital plane angle and the close approach epoch. Finally, the strategies were applied to high risk conjunctions in the past. For all cases, the conjunction could be mitigated and the control requirements for the satellites could be satisfied.

7. Reference

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