GEO Satellite Collision Avoidance Maneuver Strategy Against Inclined GSO Satellite

Byoung-Sun Lee[1] and Yoola Hwang[2]
Electronics and Telecommunications Research Institute (ETRI), Deajeon 305-350, Republic of Korea

Hae-Yeon Kim[3]
National Meteorological Satellite Center (NMSC), Jincheon 365-833, Republic of Korea

and

Bang-Yeop Kim[4]
Korea Aerospace Research Institute (KARI), Deajeon 305-807, Republic of Korea

Orbit maneuver strategy for Geostationary Earth orbit (GEO) satellite is investigated to keep away from inclined geosynchronous orbit (GSO) satellite. Characteristics of inclined GSO with various combinations of eccentricity and argument of perigee are examined first. Then the close approach of inclined GSO SL-12 rocket body to GEO COMS satellite is inspected to develop a maneuver strategy for collision avoidance. Several sizes of delta-velocities are applied to the GEO satellite to check the effect of the maneuvers on separation. It is found that radial separation between the two satellites is the most important factor and the greatest separation can be achieved when the collision avoidance maneuver is executed at 12 hours before the time of closest approach.

I. Introduction

The orbital period of geosynchronous orbit (GSO) is one sidereal day (i.e., about 1436.067 minutes). When the inclination and eccentricity of a GSO satellite are small enough, the satellite is stationary in the sky to the observers on the Earth. This is a special case of the GSO called Geostationary Earth Orbit (GEO). GEO is widely used for telecommunications, broadcasting, Earth observations, tracking and data relay, and space sciences. However, there is a limitation on the number of satellites in GEO because of mutual radio interference and physical collision. In order to reuse the valuable GEO slot, GEO satellite is recommended to increase the altitude more than 200 km above GEO at the end-of-life stage. In 1977, Inter-Agency Space Debris Coordination Committee published a document titled “Reorbit Procedure for GEO Preservation”[1].

When the satellite in GEO is abandoned, the satellite starts to drift along the longitude with latitudinal oscillations in equator. This means that semi-major axis, eccentricity, and inclination of abandoned satellite are gradually changed from the orbital elements of GEO. As time passes by, the satellite orbit will be Inclined Geosynchronous Orbit (IGSO). Approximately 53 years of long-period variation of inclination from 0° to 15° and back with accompanied evolution of the right ascension of ascending node is shown due to the Luni-Solar perturbations[2]. JSpOC cataloged 764 GSO satellites from SYNCOM 2 (SCC#634, 1963-07-26) to YAHSAT 1B (SCC#38245, 2012-04-23) with orbital periods of 1430 – 1450 minutes[3]. There are so many discarded IGSO satellites in the catalog because almost 49 years are passed from the first GSO satellite launch. These kinds of IGSO satellites become hazards to GEO satellites when IGSO satellite passes through equator twice a day. The collision velocity spectrum by IGSO satellite is shifted to higher values up to 4 – 5 km/s compared to the moderate values of down to 0.5 km/s and less in GEO satellite[4].

[1] Principal Researcher, Satellite Systems Research Team, lbs@etri.re.kr.
[2] Senior Researcher, Satellite System Research Team, ylhwang@etri.re.kr, Member AIAA.
[3] Deputy Director, Satellite Planning Division, specialk@korea.kr.
[4] Principal Researcher, Geostationary Satellite Operations Team, kby@kari.re.kr.

Communication, Ocean, and Meteorological Satellite (COMS) was launched on Jun. 26, 2010 and the satellite was positioned at 128.2° E. on Jul. 5, 2010. Since then, the satellite has been controlled within 128.2° E ± 0.05° box. NSSK maneuver is carried out on every Tuesday and EWSK maneuver on every Thursday using a satellite flight dynamics software called COMS FDS[5,6].

There were a series of close approach of Russian Raduga1-7 (SSC#28194) to COMS1 (SSC#36744) in 2011 JAN 14 and FEB 07. When the Raduga 1-7 satellite passed through COMS station-keeping box, close approaches of the two satellites happened two times a day during a few days. A Collision Avoidance Maneuver (CAM) of the COMS satellite was performed on 2011 FEB 07. At that time, the CAM was planned as three times bigger than the normal East-West station-keeping maneuver[7]. There was no dedicated CAM strategy for COMS at that time. JSpOC reported that there were 17 CAMs of GEO satellites in 2011 and 27 CAMs of GEO satellites in 2010[8].

In this paper, GEO satellite CAM strategy against IGSO satellite is investigated. Orbital characteristics of IGSO are examined with various orbital elements. Ground track of the IGSO is used to understand the effect of the eccentricity and argument of perigee. Changes of the orbit radius are inspected for radial separation. Radial and in-track separations between the IGSOs with different argument of perigee are also calculated. A real close approach of IGSO SL-12 R/B (SSC#14195) to COMS satellite is analyzed to develop a CAM strategy. Plus and minus values of delta velocities are applied to explore the effect of the CAM in separation.

II. Characteristics of the Inclined Geosynchronous Orbit

During the past years, IGSO is not actively used for the satellite mission operations. Satellites in IGSO were considered as abandoned former GEO satellites. Nowadays IGSO is actively used for radio broadcasting[9] and satellite navigation[10].

Argument of perigee is changed in IGSO to look into the shape of the ground track. Figure 1 presents ground track of four IGSOs with different argument of perigee as in Table 1. Four different longitude of ascending node are used for easy comparison of IGSOs. Shapes of figure-8 are shown by the combination of the orbital elements such as inclination, eccentricity, and argument of perigee. Crossing point of the ground track is changed with the argument of perigee. In Figure 1, all satellites are at perigee. The equator crossing region is enlarged as in Figure 2. The equator crossing points for IGSO1 (ω=0°) and IGSO3 (ω=180°) are either at perigee or at apogee. Crossing points of figure-8 for IGSO2 (ω=90°) and IGSO4 (ω=270°) are below and above equator, in respectively.

Table 1. Orbital elements of IGSOs (different longitude of ascending node).

Orbital Elements	IGSO1	IGSO2	IGSO3	IGSO4
Argument of Perigee (deg)	0	90	180	270
Lon. of Asc. Node (deg)	110	120	130	140
Period (sec)	86164.091			
Eccentricity	0.001			
Inclination (deg)	15			
True Anomaly (deg)	0			

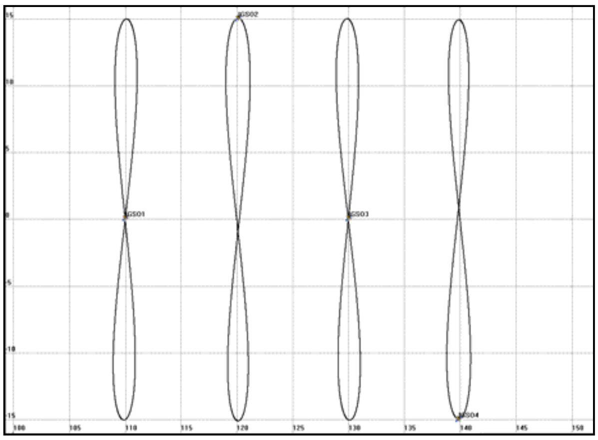

Figure 1. figure-8 shape of the IGSO with different argument of perigee.

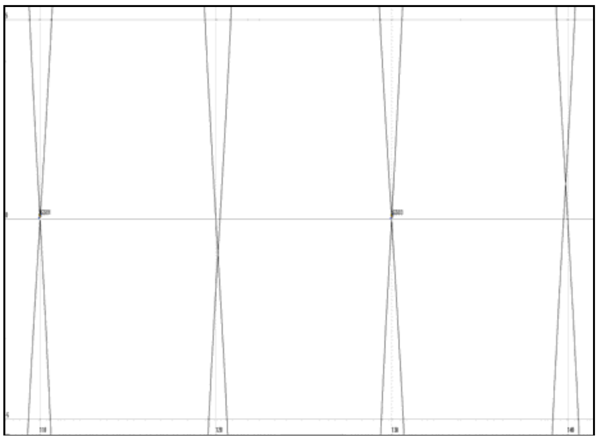
Figure 2. Different crossing points near equator.

The radius of orbit is continuously changed depending on the true anomaly when the eccentricity is not null. The difference of orbit radius is increased with the magnitude of eccentricity. Table 2 summarizes the change of the orbit radius for the eccentricity of 0.001. The orbital elements of IGSO in Table 1 are used. The difference of orbit radius at perigee and apogee is more than 84 km with eccentricity of 0.001, i.e. $\Delta r = 2ae$.
The change of orbit radius is very important for performing collision avoidance maneuver of GEO satellite against IGSO satellite. Due to the argument of perigee, the orbit radius of IGSO satellite near equator crossing point is same, bigger or smaller than the orbit radius of GEO satellite. The argument of perigee of IGSO satellite should be considered in radial separation of GEO from IGSO.

Table 2. Change of the orbit radius with true anomaly.

True anomaly (deg)	Orbit radius (km)	Difference from perigee radius (km)	Comments
0	42122.0055	0	Perigee
45	42134.3340	12.3285	
90	42164.1275	42.1220	
135	42193.9631	71.9576	
180	**42206.3338**	**84.3283**	**Apogee**
225	42193.9631	71.9576	
270	42164.1275	42.1220	
315	42134.3340	12.3285	

The shape of IGSO ground track is not always figure-8. When the eccentricity is increased, the figure-8 shape is gradually distorted with some argument of perigees. Figure 3 shows four shapes of ground track with eccentricity of 0.01. The remaining orbital elements are same as in Table 1. The figure-8 shapes are elongated for ω = 90° and 270° and slanted for ω = 0° and 180°. When the eccentricity of IGSO is 0.025, no more figure-8 shapes are shown for ω = 90° and 270 °.

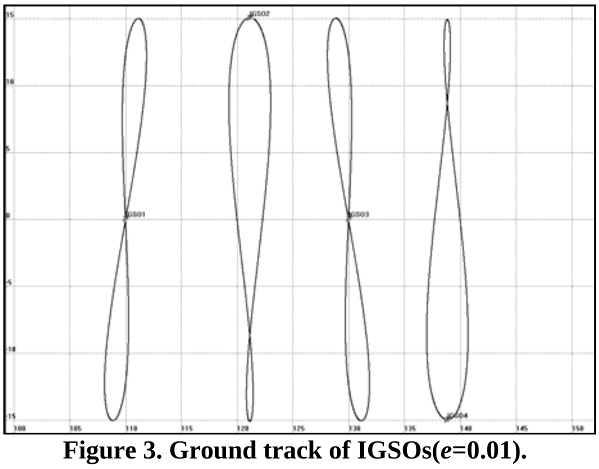

Figure 3. Ground track of IGSOs(*e*=0.01).

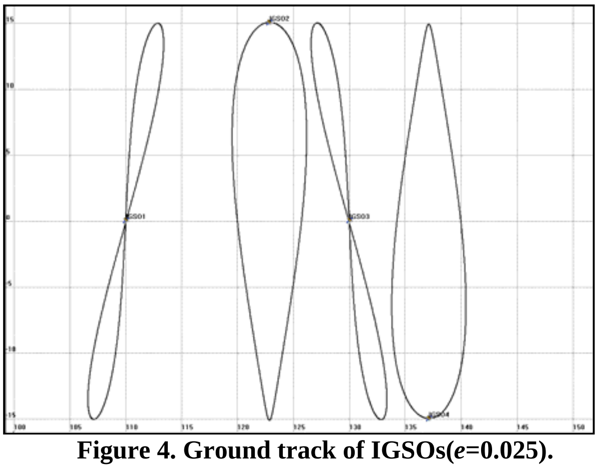

Figure 4. Ground track of IGSOs(*e*=0.025).

The orbital elements of four IGSOs in Table 3 are used to investigate the mutual separation of the IGSOs. The shapes of ground tracks are same as in Figure 1 but coincided with one another. The argument of perigee and true anomaly are adjusted to locate four satellites at the same position.

Table 3. Orbital elements of IGSOs (same longitude of ascending node).

Orbital Elements	S1	S2	S3	S4
Argument of Perigee (deg)	0	90	180	270
True Anomaly (deg)	0	270	180	90
Period (sec)	86164.091			
Eccentricity	0.001			
Inclination (deg)	15			
Lon. Of Asc. Node (deg)	128.2			

Figure 5 presents radial and in-track separation of three satellites from S1. Lissajous oval shapes are shown in Figure 5. Radial separation is the maximum when in-track separation is null for S1 and S3. This happens because the apogee and perigee of S1 and S3 are reversed with each other. For the case of S1-S2 and S1-S4, in-track separation is maintained above 34.3 km when radial separations are null.

Figure 6 shows mutual separation of three satellites from S1. Minimum separations of S1-S3 are 84 km in apogee and perigee point. The radial separation is calculated as $\Delta r = 2ae$ in this case. Cross-track separations are almost nulls for three cases and contribute nothing for the separations.

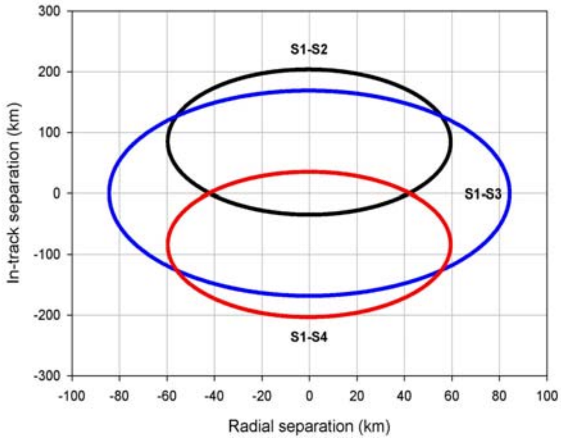

Figure 5. Radial and in-track separation of IGSOs.

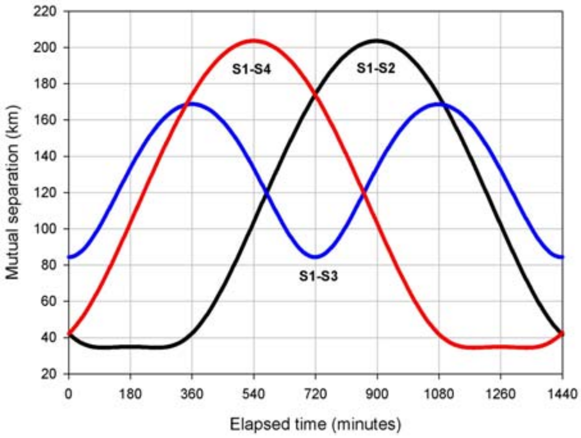

Figure 6. Mutual separation of IGSOs.

III. Close Approach of the IGSO satellite to COMS1

Three different IGSO satellites have been approached to COMS1 during the normal on-station mission operations of COMS1 since 2010 JUL 05. Table 4 summarizes three IGSO satellites and GEO COMS1[11]. There are 65 Russian SL-12 R/Bs in JSpOC catalog[3]. So, the SSC number should be used to find the applicable object.

Table 4. Characteristics of three IGSO satellites and COMS1.

Name	SL-12 R/B(2)	COSMOS 2379	RADUGA 1-7	COMS1
NORAD ID	14195	26892	28194	36744
Int'l Code	1981-102F	2001-037A	2004-010A	2010-032A
Orbit type	IGSO	IGSO	IGSO	GEO
Perigee(km)	35,753.9	35796.2	35,784.6	35783
Apogee(km)	35,880.2	35829.6	35817.2	35791
Inclination(deg)	14.6	7.2	6.3	0.03
Period(min)	1,437.3	1437.1	1,436.5	1436.12
Semi-major Axis(km)	42,188.0	42,183.9	42,171.9	42164.14
Eccentricity	0.0014972	0.0003959	0.0003857	0.0000675
Launch Date	October 9, 1981	August 24, 2001	March 27, 2004	June 26, 2010
Source	CIS	CIS	CIS	Korea
Mission	Rocket Body	Missile Early Warning	Military Communications	Communications, Oceanography, Meteorology
Day of Close Approach to COMS1	2012 APR 06	2011 JUN 19	2011 JAN 14 2011 FEB 07	N/A

On 2012 APR 04, COMS1 satellite operations team received an e-mail from JSpOC about predicted conjunction between COMS1 (SCC# 36744) and SL-12 R/B(2) (SCC#14195). The message indicated that the time of closest approach will occur on 06 APR 2012 at 01:44Z UTC with an overall miss distance of 3.873 Km. Conjunction analysis was performed based on the Conjunction Summary Message (CSM) from JSpOC.

Figure 7 presents ground track of SL-12 R/B and COMS1 for two days from 2012 APR 05 01:44:51.12. Standard figure-8 shape is shown with the combination of e = 0.0016 and ω = 62.5°. Figure 8 depicts two crossing points of the SL-12 R/B. The crossing points are located at southern part of equator because ω = 62.5°. There are other crossing points near equator due to the westward drift of the Sl-12 R/B.

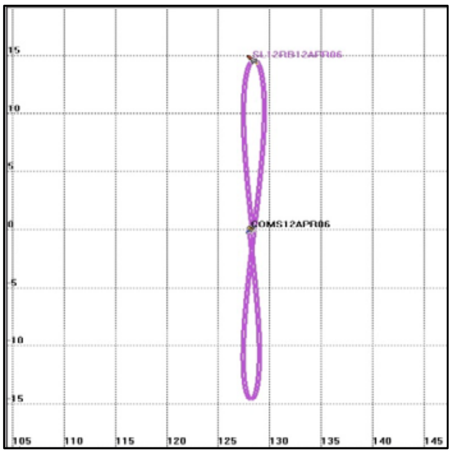

Figure 7. Ground track of satellites (2012 APR 06 14:10:51.12).

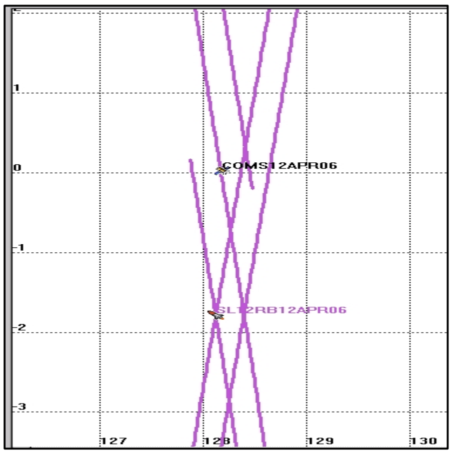

Figure 8. Crossing points of ground track (2012APR05 07:44:51.12).

Figure 9 - Figure 13 present satellite positions on ground track for 24 hours before and after TCA in 12 hours interval, respectively.

In Figure 9, SL-12 R/B at 24 hours before TCA is located in east of COMS1 and moves upward.

In Figure 10, SL-12 R/B at 12 hours before TCA is located in far-east of COMS1 and moves downward. However, SL-12 R/B drifts westward to COMS1 and there is a small westward drift of COMS1.

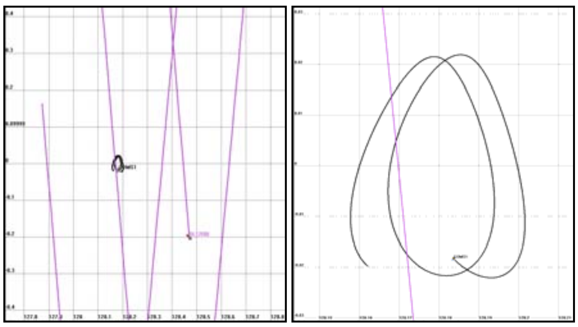

Figure 9. Satellites at 2012APR05 01:44:51.12.

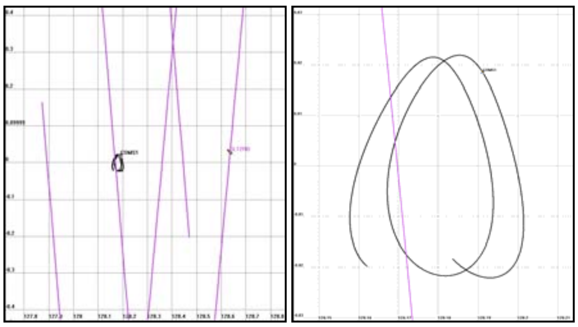

Figure 10. Satellites at 2012APR05 13:44:51.12.

Figure 11 shows positions of the two satellites at TCA. At that time, SL-12 R/B moves upward and COMS1 moves downward. COMS1 is in the east of SL-12 R/B at TCA. The along-track separation is about 1 km.

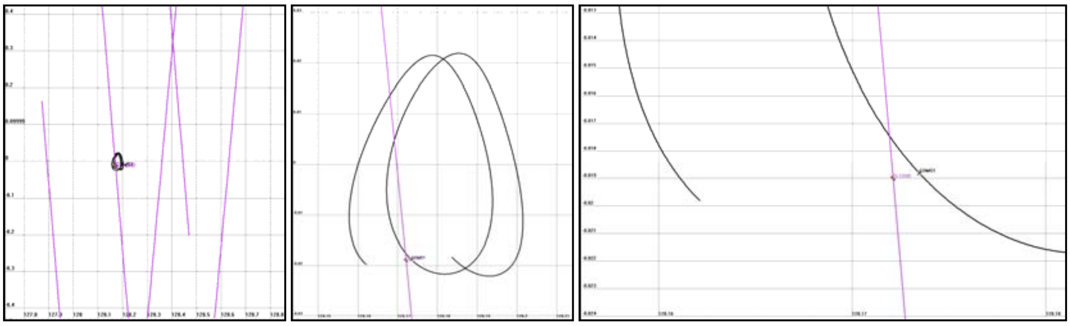

Figure 11. Satellites at 2012APR06 01:44:51.12 (TCA).

In Figure 12, SL-12 R/B at 12 hours after TCA is located in east of COMS1 and moves downward. In Figure 13, SL-12 R/B at 24 hours after TCA is located in west of COMS1 and moves upward.

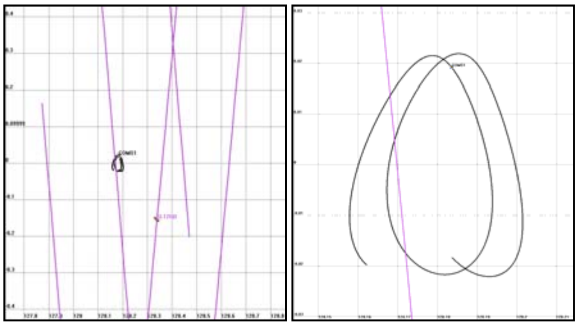

Figure 12. Satellites at 2012APR06 13:44:51.12.

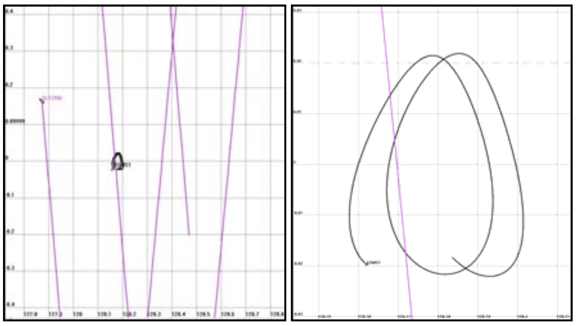

Figure 13. Satellites at 2012APR07 01:44:51.12.

Figure 14 shows 3-dimensional positions of the two satellites near TCA. Time interval between two points is 1 minute. COMS1 moves from left to right and SL-12 R/B goes upward in Figure 14. At TCA, radius of COMS1 is 42160.927 km and that of SL-12 R/B is 42155.934 km. Table 5 presents radial, in-track, and cross-track separation of SL-12 R/B from COMS1.

Table 5. Separation of SL-12 R/B at TCA (km).

Radial	In-track	Cross-track	Separation
-3.739	-0.999	-0.145	3.873

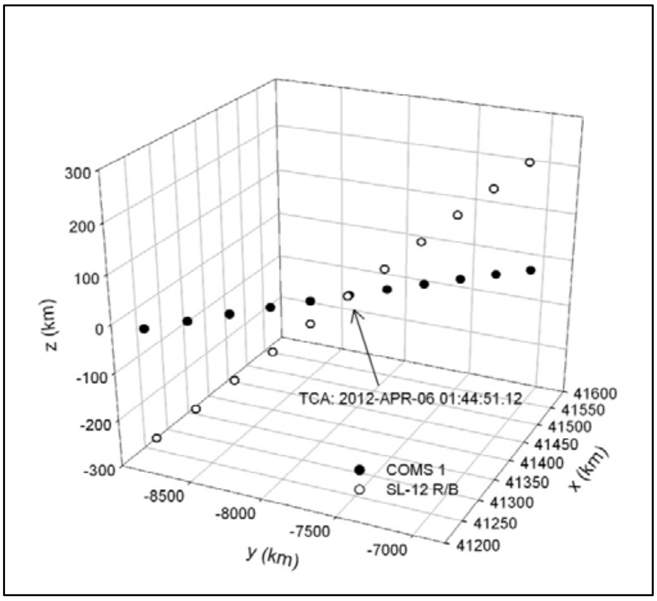

Figure 14. 3-D positions of two satellites near TCA.

IV. Collision Avoidance Maneuver Strategy against IGSO Satellite

Collision avoidance maneuver should be carried out when the mutual separation between the two satellites is within the orbit prediction errors. Satellite on-board thrusters in transverse direction and normal direction are normally used for ΔV operations in GEO environment.

The eccentricity vector $e(e_c, e_s)$ and the inclination vector $W(W_c, W_s)$ are defined by

$$e_c = e\cos(\omega + \Omega) \quad (1a)$$
$$e_s = e\sin(\omega + \Omega) \quad (1b)$$
$$W_c = \sin i \cos\Omega \quad (1a)$$
$$W_s = \sin i \sin\Omega \quad (1b)$$

where, ω is the argument of perigee, Ω specifies the right ascension of ascending node, and i denotes the inclination.

The change of the drift rate (Δd), the change of the semi-major axis (Δa), the eccentricity vector (Δe_c, Δe_s), and the inclination vector (ΔW_c, ΔW_s) by the ΔV in the transverse direction (ΔV_T) and the normal direction (ΔV_N) are expressed in Eq(2)[12].

$$\Delta d = -\frac{3\omega_E}{V_{syn}}\Delta V_T \text{ or } \Delta a = \frac{2a_{syn}}{V_{syn}}\Delta V_T \quad (2a)$$
$$\Delta e_c = \frac{2\Delta V_T}{V_{syn}}\cos\alpha \quad (2b)$$
$$\Delta e_s = \frac{2\Delta V_T}{V_{syn}}\sin\alpha \quad (2c)$$
$$\Delta W_c = \frac{\Delta V_N}{V_{syn}}\cos\alpha \quad (2d)$$
$$\Delta W_s = \frac{\Delta V_N}{V_{syn}}\sin\alpha \quad (2e)$$

Where, ω_E is the Earth's angular velocity, V_{syn} is the synchronous velocity along the geostationary orbit (3.0747 km/s), a_{syn} is the synchronous semi-major axis for the geostationary orbit (42164.1696 km), and α is the right ascension of the satellite.

Radial and in-track separations are important when IGSO satellite approaches to GEO satellite. In order to get the maximum changes of radial and in-track separation, ΔV operations should be performed in the opposite direction from the position of close approach. In GEO case, time for the ΔV operation is about 12 hours before TCA.

Figure 15 shows the change of the orbit shape by ΔV operations. Here, the ΔV operation is in transverse direction. The semi-major axis of the orbit and orbital period is increased when $+\Delta V$ is applied. Equations (2a), (2b), and (2c) are applicable in this case. When the radius of IGSO satellite is smaller than that of GEO satellite at TCA, $+\Delta V$ operation should be performed to get the maximum radial separation. In this case, in-track separation can be also achieved because the drift rate of GEO satellite is decreased. The opposite direction of ΔV, i.e. $-\Delta V$ operation should be performed for bigger orbit radius of IGSO satellite at TCA. The maximum change of orbit radius will be twice of the semi-major axis changes ($\Delta r = 2\Delta a$).

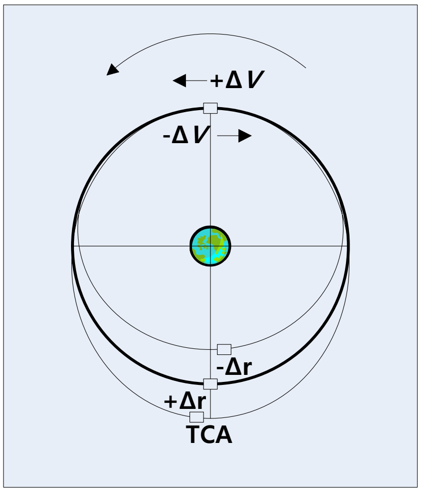

Figure 15. Effect of ΔV operation.

A series of ΔV maneuver operations are performed to investigate the effect of the Collision Avoidance Maneuver (CAM). For the close approach of SL-12 R/B, $+\Delta V$ operation should be performed because orbit radius of COMS1 is bigger than that of SL-12 R/B.

Table 6 presents mutual separation of two satellites when CAM is performed in 12 hours before TCA. Plus and minus ΔVs are applied to investigate the effect of separation. A ΔV of 0.1 m/s increases semi-major axis in 2.74 km and Δr will be 5.48 km. A separation greater than 5 km is enough for collision avoidance in consideration of the orbit determination and prediction errors. As expected, ΔV of 0.1 m/s gives the best results in radial separation. In this case, in-track separation of about 12 km is also ensured due to increasing of the orbital period. For the $-\Delta V$ operations, the radial separations are smaller than those of the no CAM and only in-track separations are increased.

Table 6. Mutual separation of two satellites at TCA (Time of CAM: 12 hours before TCA).

ΔV(m/s)	Radial (km)	In-track (km)	Cross-track (km)	Total (km)	Comments
0	-3.739	-0.999	-0.145	3.873	No CAM
0.1	**-9.244**	**11.979**	**-0.145**	**15.132**	**Max radial**
0.05	-6.501	5.489	-0.145	8.509	
-0.05	-1.016	-7.520	-0.145	7.589	
-0.1	1.725	-14.023	-0.145	14.129	Max in-track

Figure 16 shows the orbit differences of COMS1 for the case of no CAM and ΔV of +0.1 m/s. As time goes by, in-track difference is increased very much due to the change of orbital period. This shows that CAM should be performed earlier from TCA to get the bigger in-track separation. At TCA, the radial difference is at maximum because the orbit of COMS1 with CAM is at apogee.

Figure 17 and Figure 18 present radial vs. in-track and radial vs. cross-track separation near TCA, respectively. Different values of ΔV in Table 6 are applied. In-track and cross-track separations are changed very fast in comparison to radial separation. In any case, radial separation should be maintained when in-track or cross-track separations are nulls. To get the maximum radial separation, the CAM should be performed at 12 hours before TCA.

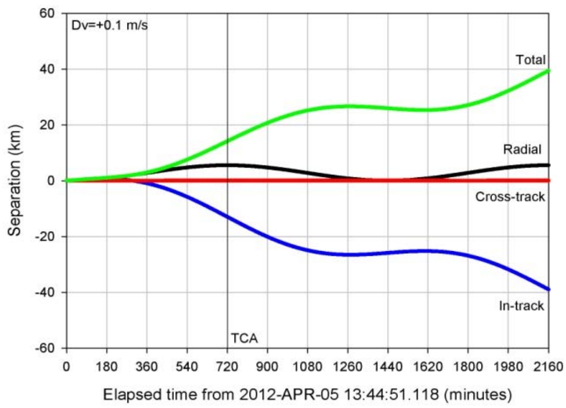

Figure 16. Separation of COMS1 with and without CAM.

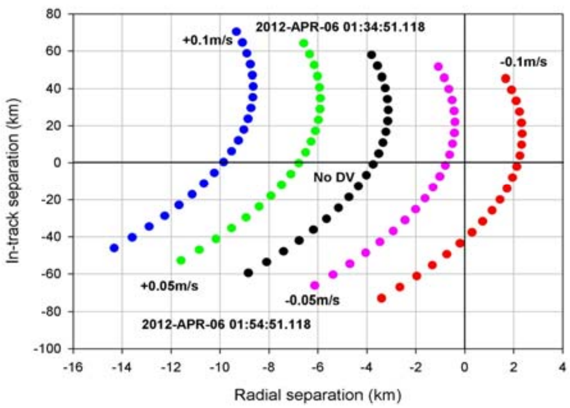

Figure 17. Radial and in-track separation near TCA.

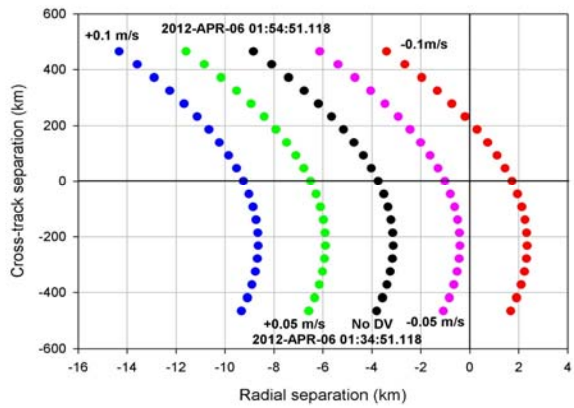

Figure 18. Radial and cross-track separation near TCA.

To investigate the effect of the CAM time, four CAMs in Table 6 are also performed at 6 hours before TCA. Figure 19 presents radial and in-track separations at TCA for CAMs at 12 hours and 6 hours before TCA, respectively. With the same magnitude and directions of ΔVs, four cases of ΔV at TCA-6 hours are not good for collision avoidance. Changes of radial separations are very small because orbit radius at TCA is in between perigee and apogee.

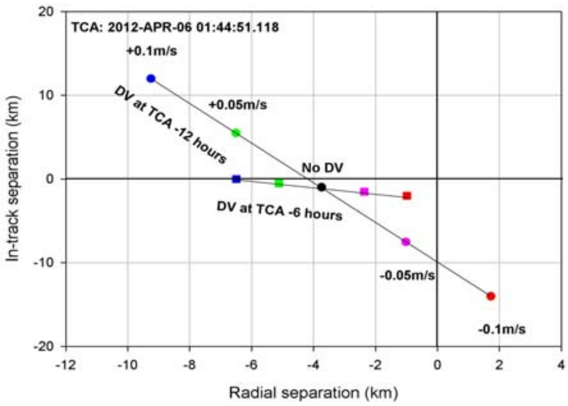

Figure 19. Radial and in-track separation at TCA.

V. Concluding Remarks

Abandoned satellites in GEO region will be inclined GSO satellites librating through the geostationary longitude region. Collision avoidance maneuver (CAM) strategy of GEO satellite from IGSO satellite is important because there are a growing number of abandoned IGSO objects at present. The CAM strategy in this case is treated differently from a close approach between the two active GEO satellites. There is no way to communicate with owner/operator of the abandoned IGSO satellite for coordinated collision avoidance. Active GEO satellite should be prepared for CAM in consideration of the orbital characteristics of the approaching IGSO satellite.

Orbital characteristics of IGSO satellite was examined with different combination of the orbital elements such as eccentricity, inclination, and argument of perigee. Orbit radius of IGSO satellite near equator crossing should be considered. A real close approach situation between the GEO satellite COMS1 and IGSO object SL-12 R/B was inspected for the preparation of CAM strategy. Radial and in-track separation can be achieved with velocity increment in transverse direction. Maximum radial separation was accomplished when the CAM was performed at 12 hours before TCA. Relative orbit radius between the GEO and IGSO satellites should be considered to determine a velocity increment or decrement. Radial separation is important because the separation will be maintained in a few more days. In-track separation will be increased in general with time when the two satellite drifts in opposite direction. However, for the in-track separation case, there can be a collision risk after CAM because of the alternate pattern of equator crossing longitude in IGSO. A few more days of close approach should be considered in CAM planning for in-track separation.

Appendix A
Acronym List

CAM	Collision Avoidance Maneuver
COMS	Communications, Ocean, and Meteorological Satellite
CSM	Conjunction Summary Message
EADS	European Aerospace and Defense System
ETRI	Electronics and Telecommunications Research Institute
EWSK	East-West Station-Keeping
FDS	Flight Dynamics Subsystem
GEO	Geostationary Earth Orbit
GSO	Geosynchronous Orbit
IADC	Inter-Agency Space Debris Coordination Committee

IGSO	Inclined GSO
JSpOC	United States Joint Space Operations Center
KARI	Korea Aerospace Research Institute
NORAD	North American Aerospace Defense Command
NSSK	North-South Station-Keeping
SGCS	Satellite Ground Control System
SSC	NORAD Catalog Number
TCA	Time of Closest Approach

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