

Optical Monitoring Strategy for Avoiding Collisions of GEO Satellites with Close Approaching IGSO Objects

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Several optical monitoring strategies by a ground-based telescope to protect a Geostationary Earth Orbit (GEO) satellite from collisions with close approaching objects were investigated. Geostationary Transfer Orbit (GTO) objects, Inclined GeoSynchronous Orbit (IGSO) objects, and drifted GEO objects forced by natural perturbations are hazardous to operational GEO satellites regarding issues related to close approaches. The status of these objects was analyzed on the basis of their orbital characteristics in Two-Line Element (TLE) data from the Joint Space Operation Center (JSpOC). We confirmed the conjunction probability with all catalogued objects for the domestic operational GEO satellite, Communication, Ocean and Meteorological Satellite (COMS) using the Conjunction Analysis Tools by Analytical Graphics, Inc (AGI). The longitudinal drift rates of GeoSynchronous Orbit (GSO) objects were calculated, with an analytic method and they were confirmed using the Systems Tool Kit by AGI. The required monitoring area was determined from the expected drift duration and inclination of the simulated target. The optical monitoring strategy for the target area was analyzed through the orbit determination accuracy. For this purpose, the close approach of Russian satellite Raduga 1-7 to Korean COMS in 2011 was selected.

Keywords: GEO, GTO, IGSO, optical monitoring observation, collision avoidance, analytic solution

1. INTRODUCTION

With the increasing amount of space objects, the Geostationary Earth Orbit (GEO) region has become congested with operational and nonoperational satellites as well as space debris. GEO is a special case of the GeoSynchronous Orbit (GSO) with non-inclined orbital plane. The International Telecommunication Union (ITU) assigns a sector for each GEO satellite, and operational GEO satellites are maneuvered frequently for station keeping in the assigned sector. After a mission, GEO satellites not re-orbited to the graveyard remain adrift near the GEO region as space debris (Vallado 2004). The Inter-Agency Debris Committee (IADC) has determined a protected area for the GEO known as

Region B at GEO altitude of ± 200 km and equatorial latitude of $\pm 15^\circ$ of the arc (IADC 2014).

GSO objects stay in orbit without re-entry to the ground and can be hazardous to operational GEO satellites. Oscillation of space objects in the GSO region around geopotentially stable points increases the possibility of collisions with the maneuvering of satellites (Soop 1994). The collision velocity of Inclined GSO (IGSO) objects with GEO satellites may reach 4–5 km/s (Westerkamp et al. 1997). The Joint Space Operation Center (JSpOC) provides collision alert to owners and operators of satellites. Also, an automatic process of providing information for close conjunctions is available in the form of Satellite Orbital

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Conjunction Reports Assessing Threatening Encounters in Space (SOCRATES) in CelesTrak (Kelso et al. 2005). Although Conjunction Data Messages (CDMs) for collision alert have been provided by the JSpOC with the Two-Line Elements (TLEs) for all possible space objects, dedicated GEO monitoring system is still needed. It is required not only to survey for finding hazardous space objects but also to increase an accuracy of orbit estimation of them. Also other disturbing events including radio interference could be detected with the GEO monitoring system.

The Communication, Ocean, and Meteorological Satellite (COMS) is positioned at 128.2°E within a $\pm 0.05^\circ$ station-keeping box. Russian satellite Raduga 1-7 has approached close to COMS several times during January and February 2011. As the orbit of Raduga 1-7 was inclined, they approached close to each other two times a day before a collision avoidance maneuver of COMS (Lee et al. 2011) was performed. Although the COMS has been operational safely up to date, possible close approaching candidates can be confirmed by monitoring observations in the vicinity (Flury et al. 2000; Lee et al. 2012). A series of intensive observations of candidates can provide data for estimating its precise orbit. For such a purpose, a dedicated optical telescope is needed.

GSO objects are mainly perturbed by the geopotential of the Earth, solar radiation pressure, and luni-solar gravity. They drift in the longitudinal direction and oscillate in the latitudinal direction once a day. Allan (1963) analyzed the motion of a GEO satellite induced by the tesseral harmonics along the longitude. Shrivastava (1978) described GEO satellite perturbation in detail. Agneni et al. (1986) investigated long-term evolution of GSO objects. Choi et al. (1986, 1987) established maneuvering strategies with an analytical solution for Koreasat-1. This solution was also applied to a COMS case by Kim et al. (2006). Lee et al. (1997) and Lee (2001) developed a new analytical ephemeris solution for GEO satellites with equinoctial elements and compared it with a numerical solution. The equinoctial elements are useful to describe the GEO motion without singularity of orbital elements. Also Lee et al. (2012) analyzed orbital types of the IGSO objects and maneuver strategy for COMS. In general, the analytical solution was more suitable for long-term prediction of orbits than the numerical solution (Choi 1997).

Schildknecht et al. (1997) analyzed the optical observation of space debris with a strategy considering the motion of GSO objects. A network observation with multi-telescope sites was also analyzed using a similar strategy (Olmedo et al. 2011). Choi et al. (2015b) analyzed an optical GSO survey observation to maintain a catalogue and estimate the orbits of objects detected from the Korean peninsula. Longitudinal

variations in the drift of satellites could be used to analyze the efficiency of the monitoring observation. Determination of the horizontal width using the inclinational evolution was also needed to define the survey area.

In this study, we analyzed the orbit of an operational GEO satellite with orbital characteristics and a conjunction analysis using the Conjunction Analysis Tool (CAT; Analytical Graphics, Inc). The longitudinal drift rate of IGSO objects was used to determine the required observation area for the optical tracking system. From the determined area and specifications of the optical tracking system, a GEO monitoring strategy was analyzed for domestic GEO satellite case.

2. HAZARDOUS ORBIT FOR THE OPERATIONAL GEO SATELLITE

Operational GEO satellites are stationed within assigned sectors in the GEO. Although there are various types of orbits from the LEO to GEO, three types of hazardous orbits for GEO satellites regarding collision can be distinguished. Being hazardous orbits for GEO satellites depends on the evolution of the original orbits. Fig. 1 shows possible cases of GEO satellite collisions. The IGSO evolved from GEO and drifted to geopotentially stable points along the longitudinal direction. In the same manner, GEO satellites without station-keeping maneuvers may drift and become hazardous to other GEO satellites. Objects in the Geostationary Transfer Orbit (GTO) are more complicated because they are not usually on the same orbital plane with GEO satellites, and can intersect with the GEO; in many cases, the GTO is inclined. In addition, as GTO is perturbed by the atmospheric drag near its perigee, objects in this orbit can go slowly downward to the Earth's surface and away from the GSO region.

The orbital distribution of all catalogued space objects was analyzed using TLE data from the JSpOC. Fig. 2 shows the distribution of space objects on a plot of semi-major axis versus eccentricity. The semi-major axes of GSO objects are near 42,164 km from the center of the Earth and their eccentricities are very small. In case of the GTO region, two

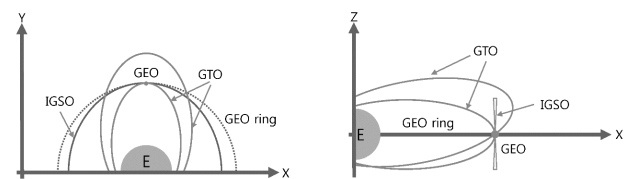


Fig. 1. 2-dimensional illustrations of hazardous orbits for GEO satellites.

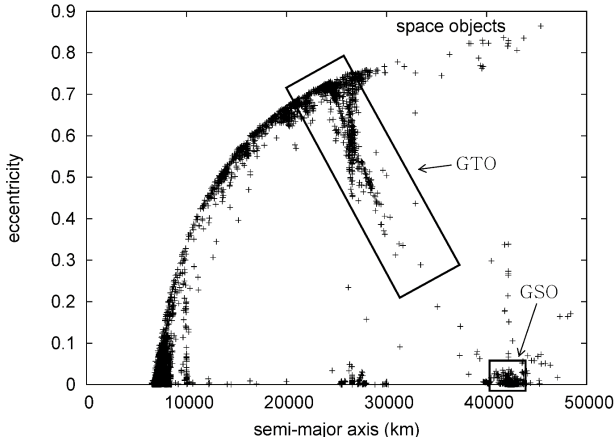


Fig. 2. Distribution of space objects on a plot of semi-major axis versus eccentricity.

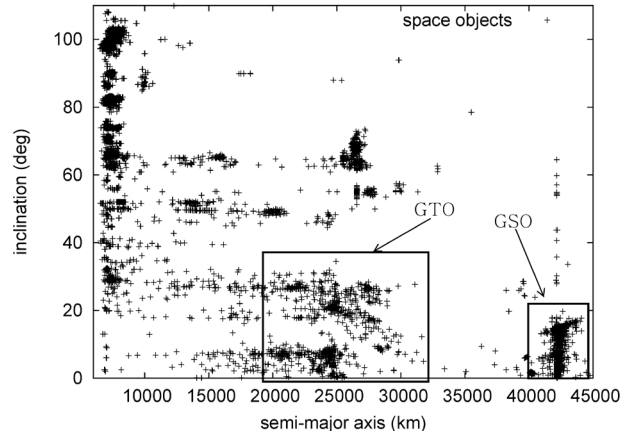


Fig. 3. Distribution of space objects on a plot of semi-major axis versus inclination.

types of orbits are distinguished. The semi-major axes of GTO objects are widely distributed near 27,000 km and their rotation periods are shorter or longer than those of the GSO.

A plot of semi-major axis versus inclination (Fig. 3) shows differences between the characteristics of the GSO and GTO. Under natural perturbation, the inclinations of GSO objects oscillate at 15° with a 53 year period variation (Schildknecht et al. 2001). Regular station-keeping maneuvers with ±0.05° inclination are performed for operational GEO satellites. However, the semi-major axes and inclinations of GTO objects are distributed sparsely on wide range. Several GTO objects have inclinations similar to GEO objects. Among 2,464 space objects investigated (apogee altitude over 33,786 km), 825 are in the GTO with only 15 having an inclination within 1°; these are BLOCK DM-SL Rocket bodies.

The CAT is an application module of Systems Tool Kit (STK) for predicting conjunction events using TLE data by the JSpOC. The analysis period was from October 3, 2013 to October 4, 2015. Boundary conditions for alerting a close approach event was set to 20, 10, and 5 km for in-track, radial, and cross-track, respectively. The boundary conditions for alerts when the close approach or intersect events happened, were determined by considering the uncertainty of TLE and empirical optical observation accuracy (Flohrer et al. 2009). Over the period of 2 years, 55 conjunction events occurred with 15 space objects. Furthermore, there were 13 “intersect” cases where the minimum range between two objects was less than 10 km. A minimum range was 3.28 km from the COMS to the approaching object. The positions of all approaching objects oscillated between 0° E and 140° E longitude during the target period except the one that started from 300° E longitude. All the events involved nonoperational IGSO objects including 4 rocket bodies. In this study, we focused only on IGSO objects to analyze the monitoring observation

strategy for COMS.

3. LONGITUDINAL DRIFT OF IGSO OBJECTS

Each orbital element could be analyzed by separating short- and long-term variations from secular variation. Short-term variations can be neglected in the analysis of long-term variations (Kim 2005). Long-term variations are mainly caused by luni-solar perturbations with a period of 6 months and amplitude variation of ±0.019°. Secular variations are calculated from drift rate and acceleration by tesseral harmonics of the Earth and the gravity of the Sun. Mean longitude at time t can be calculated by the sum of mean longitude (\bar{L}), acceleration component (\ddot{L}), drift rate (\dot{L}), short-term and long-term variations ($(\Delta L)_{sp} + (\Delta L)_{lp}$) in Eq. (1) (Lee et al. 1997; Kim 2005).

$$L_{mean} = \bar{L} + \dot{L} \cdot t + \frac{1}{2} \ddot{L} \cdot t^2 + (\Delta L)_{sp} + (\Delta L)_{lp} \quad (1)$$

Longitudinal variations of GSO objects are close to the variations of their semi-major axes. In case of their semi-major axes, the frequency of a long-term variation is 800 days and changes over 50 km per year (Choi et al. 1987; Pocha 1987). It makes the oscillational motion of the orbit of GEO objects between stable and unstable points. The stable points exist at longitudes of 75.1° and 254.7° and the unstable points also exists at longitudes of 161° and 348° (Gedeon 1969). The domestic GEO satellites (COMS: 128° E, KOREASAT 5: 113° E and KOREASAT 6: 116° E) drift to the stable point at 75.1°, and GSO objects between 161° and 75.1° longitudes drift to stable points at 75.1°. Here, we focused on the longitudinal area between 113° and 161°.

The longitudinal evolution of IGSO objects between 113°

and 161° longitudes was analyzed using secular variation and validated using the STK. Eight simulations with different longitudinal origins were defined and the longitudinal variation was calculated. The Simplified General Perturbation 4 (SGP4) propagator was used and periodic variations of the longitude were checked between 2011 and 2015. Every orbital parameter in the eight simulations was identical except for the right ascensions of ascending nodes, which were set from -5° to 30° for different longitudinal origins. Fig. 4 shows the longitudinal variation of the eight simulated objects and the three domestic GEO satellites. We attempted to describe the end of life situation without re-orbiting the objects to the graveyard. Eight objects drifted to the stable point at 75.1°. Objects beyond 161° longitude drifted to another stable point at 254.7° in the opposite direction. We also analyzed the effects of the inclination variation from 0° to 15° and found that it was insignificant on longitudinal variation.

The time taken for each of the eight objects to reach the domestic GEO satellite was investigated. The longitude drift, which is described in the quadratic form in Eq. (1), showed that each case had a similar variation. However, as time elapsed from the epoch increased, the acceleration term became more dominant and longitude drift showed a sharp change. Table 1 describes the duration in days from each longitudinal origin. In case of CMOS, the object departing from 160° longitude was predicted to reach near 128° after 390 days. In contrast, if the object started from 135° longitude, the predicted duration was only over 2 months.

Fig. 5 shows the longitude rate of the eight cases analyzed for 450 days. As the objects neared the unstable point, the longitude rate showed a smooth increase or decrease. Even after each object passed the duration for drift from the origin to each domestic GEO satellite, the speed kept increasing. In case of CMOS, Case 5 showed the fastest longitude rate of -0.266°/day after passing 128°. The objects

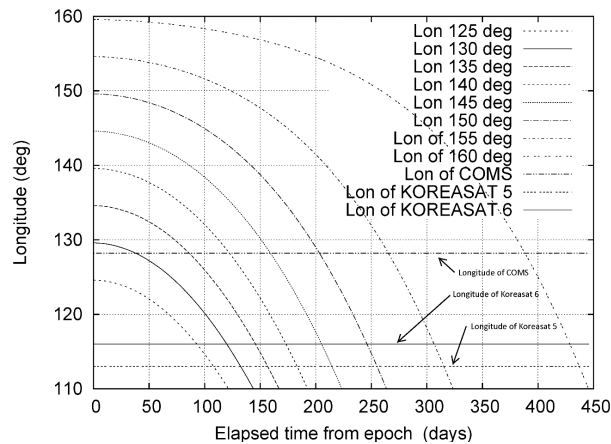


Fig. 4. Longitudinal evolution of GSO objects with various origins.

Table 1. Duration of the longitude drift from the different origins near domestic GEO satellites

Case	1	2	3	4	5	6	7	8
Longitude (degree)	125	130	135	140	145	150	155	160
KOREASAT 5	108	133	156	183	214	254	315	437
KOREASAT 6	93	121	145	173	205	246	307	429
COMS	-	-	88	124	161	205	267	390

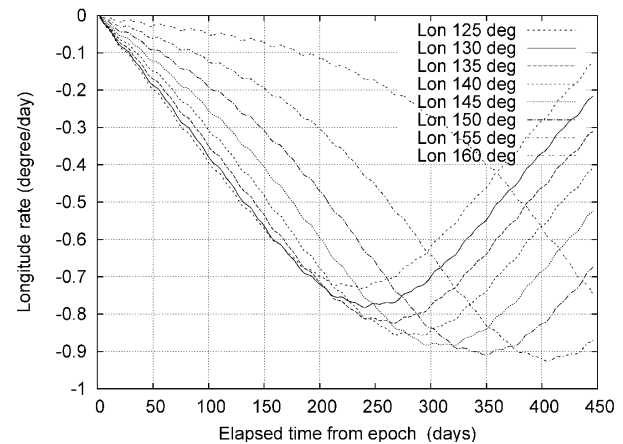


Fig. 5. Longitude rate of GSO objects with various origins.

that departed from 125, 130, 135, 140, 145, and 155° turned to the opposite direction after 220–400 days. The longitude rates of each case at 128° longitude were -0.149, -0.22, -0.225, -0.245, -0.266, and -0.263°/day. The longitudinal velocity of GSO object against GEO object could be higher than these latitudinal drift rates for inclination.

The inclination of naturally perturbed objects in the GSO changed at a rate of 0.75–0.95°/year. The inclination may change to a maximum of 15° within a 53 year period. IGSO objects have a 1 day period longitudinal variation for its inclined orbital plane. Its horizontal width can be calculated using a simple relation with a small inclination, Eq. (2) (Choi 1997). In case of an object with an inclination of 15°, the maximum horizontal width was about 2°. In Eq. (2), ΔL is the horizontal width from the center and *i* is the inclination of the object.

$$\Delta L \cong i^2/230 \quad (i \leq 5^\circ) \tag{2}$$

4. SIMULATION OF OPTICAL MONITORING FOR COMS

The optical monitoring strategy for protect operational GEO satellites was analyzed considering that longitudinal drift rate, horizontal width, and latitudinal variation were affected by inclination. Forty-eight years have passed since the launch of the first GEO satellite and during

this period, latitudinal change occurred twice due to natural perturbations. In this study, we set the latitudinal observation range at $\pm 15^\circ$. Table 2 shows the longitudinal range for objects reaching domestic GEO satellites from various position during 30, 60, and 90 days. It was calculated using the duration for reaching domestic GEO satellites in Table 1. In case of departure from 160° , the longitudinal range was wider than for other cases for all 3 durations, implying that the longitudinal monitoring range must be set based on case 6. Considering that the horizontal width of the object in the orbit inclined 15° , the required monitoring area was determined to be 554° for the 90 day case.

In this study, we assumed that all GSO objects are continuously reflecting light without any interruption like the shielding by Earth’s shadow. Schildknecht (2007) showed a distribution of GSO objects’ brightness. Even if we limited the observation targets to large size objects, the observation system should detect the light from the object as ~ 17 mag. We considered the Optical Wide-field patrol Network (OWL-Net) developed by Korea Astronomy and Space Science Institute (KASI) for this study (Park et al. 2013). According to this study, OWL-Net is useable to detect large size GSO objects for about only 55% above total observable GSO objects except non-observable small size space debris. Also, the observation system needs to determine the astrometric position of detected objects in 5 arc seconds considering TLE uncertainty (Flohner et al. 2009). If the tracking Field of View (FOV) was set to 1° and the observation time span was 10 s, the required monitoring time was 92 min. In case of 30 days, the monitoring area was 245° and the required monitoring time was 41 min for COMS case.

The monitoring observation strategy for multi-targets was analyzed with the orbit improvement observation. Choi et al. (2015a) showed orbit estimation accuracy with TLE data for COMS satellite. An astrometric uncertainty needed for proper orbit estimation was found as 3 arc seconds by the time and position accuracy. In the 2 day observation case, one exposure was needed every 1 hr during 6 hr for each day to acquire appropriate orbit estimation accuracy. Five satellites could be observed in 6 hr for the same period and the monitoring of each satellite could also be observed.

In 2010, there was a close approach event between Raduga

1-7 satellite and COMS. Raduga 1-7 had been maneuvered from 85° longitude to the position of COMS. It was moved opposite in direction to the natural longitude drift, which could be achieved by reducing the semi-major axis. During the drift period, Raduga 1-7 was not hazardous owing to its smaller semi-major axis than that of COMS. After Raduga 1-7 neared the position of COMS, it was maneuvered again and the longitude position was maintained for 9 months (Lee et al. 2011). During this period, its inclination was increased by up to 5° by natural perturbations. This was not a natural drift case. However, if an area of $\pm 7.18^\circ$ at the position of the COMS was monitored, we could detect the movement of Raduga 1-7 30 days before collision.

5. SUMMARY AND DISCUSSION

The monitoring observation strategies were analyzed considering the longitudinal variation of IGSO objects to protect operational domestic GEO satellites. For GEO satellites, station-keeping maneuvers are repeatedly performed to maintain their longitudinal position. However, GSO and GTO objects are forced by perturbations and drift towards the longitudinal direction. Although the JSpOC is sending conjunction alert messages to the owners and operators, a domestic stand-alone monitoring system is required for more effective protection of the GEO satellite. The optical tracking system proposed in this paper can be a suitable monitoring tool for the GSO region.

In various types of orbits, the GTO, IGSO, and drifted GEO can be hazardous orbits for GEO objects. In this study, we analyzed their orbital characteristics. In case of the IGSO and drifted GEO, the semi-major axes are distributed with small margins and the inclinations do not exceed 15° under natural drift. In contrast, GTO objects have various semi-major axes, inclinations, and eccentricity values. CAT was used to analyze the possibility of conjunction for COMS. During the 2 years from 2013, there were 55 possible conjunction events within 50 km, and all the corresponding objects lie in the IGSO. Therefore, we focused the IGSO and GEO to develop a monitoring strategy for the protection of the operational GEO satellite, COMS.

In the GSO region, space objects drift in the longitudinal direction under the geopotential, solar radiation pressure, and luni-solar gravity. Under the geopotential, there are two stable and two unstable points. The inclination also changed within a 53 year period. The longitude drift of GSO objects was analyzed using the analytic method. We simulated eight cases from 125° to 160° for every 5° longitude. These objects drifted to the stable point at 75.1° . The duration of each

Table 2. Longitudinal range for objects reaching 128° during given times

Longitude (degree)	135	140	145	150	155	160
Duration (days)	Longitudinal range (degree)					
30	3.74	5.04	5.90	6.52	6.96	7.18
60	5.91	8.58	10.34	11.59	12.48	12.91
90	-	10.74	13.49	15.43	16.76	17.47

object to reach the position of the COMS was analyzed. For the case of departure at 160°, the object neared the position of the COMS after 390 days. In this case, 30 days before the object reached the position of COMS, it drifted 7.18° towards the longitudinal direction. This implies that we could detect close IGSO objects 30 days before collision by monitoring the longitudinal range at 7.18°. From the evolution of the inclination, not only the latitudinal range was increased but the horizontal width was also changed, increasing to approximately 2°.

We analyzed the monitoring strategy considering the motion of the IGSO and observation system in the longitudinal and latitudinal directions. If the monitoring observation is planned to be repeated every month, the required monitoring area is 245(°)² and the monitoring observation can take 41 min. After identifying the monitoring observation, intensive observation is needed to precisely estimate the orbit of the target object. For maintaining accuracy in the estimation of the orbit, in case of 2 day simultaneous observations, sparse observations for every hour during 6 hr must be carried out for each days (Choi et al. 2015a). In this manner, we could make the monitoring observation to detect close approaching objects and perform a follow-up observations to maintain the accuracy of target satellites' orbit by turns.

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