COLLISION AVOIDANCE ASSESSMENT AND MITIGATION MEASURES FOR CONTROLLED GEO/GSO SPACECRAFTS WITH ORBITAL DEBRIS

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ABSTRACT

Indian Space Research Organisation (ISRO), India, has been operating several communication, meteorological and navigational spacecrafts in Geostationary (GEO) and Geosynchronous (GSO) orbital regime. Master Control Facility (MCF), India, is the prime center for spacecraft operations during launch, orbit raising, in orbit testing, on orbit and end of life phases of GEO/GSO missions. MCF is also responsible for the orbit determination, orbit maintenance, orbit control and colocation of spacecrafts. MCF regularly monitors the close approach of objects in GEO/GSO based on publicly available two line elements (TLE) for debris objects and orbit determined (OD) using radio ranging for operational spacecrafts.

Whenever, any uncontrolled object approach close-in distance to any of the operational spacecrafts the risk of collision exists. Collision avoidance involves detection of close approach, risk assessment and mitigation measures, to be executed for smooth and safe space operations. In this paper, strategy followed at MCF, while a close approach to an operational spacecraft by orbital debris is encountered, is discussed. The long term orbital profile of the threat object, based on historical TLE, provide the correctness of latest TLE update and close approach situational awareness. Since, more than one spacecraft is positioned and maintained at a given orbital slot, the impact of close approach and collision avoidance maneuver on other colocated spacecrafts also has to be envisaged and analysed. Moreover, the uncertainties present in the TLE and OD impose a major hindrance in planning the collision avoidance mitigation measures. A list of close approaches encountered with the operational Indian geostationary satellites in recent past is presented. A catalogue of such close approach events would help in safe mission planning activities.

1 INTRODUCTION

Spacecraft technology is one of the emerging and revolutionary technologies which have evolved to a great extent in the last six decades. Spacecrafts have become indispensable tool for day to day life, because of its wide spectrum of applications such as remote sensing, weather forecasting, navigation, military, tele-communication and space exploration. This has motivated the space faring nations to launch more spacecrafts to the space for its better utilization. In the present scenario, the number of satellites orbiting around the Earth is in increasing fashion, even though some of them re-enters to Earth's atmosphere and burns. Recent debris catalogue [1], as on October 2016, shows that there are 17,817 objects are present in the Earth bound space in which only 4,257 (24 %) are the operating spacecrafts. The remaining objects existing are the orbital debris formed due to the end of life, fragmentation, collision, launch/spacecraft anomalies and things left by astronauts during extra-vehicular activity. In case of GSO region, there are 1,438 objects out of which, 454 (31.5 %) are controlled in their longitude slot, as reported in [2] during end of the year 2014.

Ever increasing orbital debris has become a major concern for the space faring and spacecraft operating nations; since it possesses a potential threat to the operating satellite. A collision or explosion in space would increase the number of catalogued objects catastrophically; also such an event could paralyse or permanently damage an operating spacecraft, resulting in technological as well as economical loss. The scenario of orbital debris in Low Earth Orbit (LEO) and Medium Earth Orbit (MEO) compared to Geosynchronous Orbit (GSO) are different, with respect to population flux density and overall collision probability. However, the collision risk between two objects in GEO/GSO regime is not fully negligible.

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As on January 2017, Indian Space Research Organisation (ISRO), the Indian space agency is operating 23 spacecrafts in Geosynchronous orbit (GSO) for the purpose of communication, meteorology and navigation. Among them, 15 spacecrafts are maintained in geostationary orbit, colocated at four orbital slots. Master Control Facility (MCF), India, is responsible for the spacecraft operations such as telemetry acquisition, commanding, ranging, and station keeping of GEO/GSO spacecrafts throughout its mission lifetime. Flight Dynamics and Systems of MCF is involved in orbit determination, using ranging data acquired using C-band tone ranging, planning of station keeping maneuvers for orbit control and colocation of spacecrafts. As a part of FDS operations, using the publicly available two line elements (TLE) published in www.space-track.org by United States Strategic Command (USSTRATCOM), close approach encounters between the ISRO spacecrafts and other objects are checked regularly.

In this paper, strategy followed at MCF during a close approach event and the collision avoidance planning as a mitigation measure is discussed. Analysis carried out for COSMOS-2440 with 74 deg E colocated spacecrafts namely, GSAT-14 and INSAT-4CR close approach event during July 2015 is explained in detail. A list of close approach events occurred in during the year 2015 and 2016 is also presented.

2 CLOSE APPROACH ANALYSIS METHODS

Though, different terminologies, spacecraft conjunction, spacecraft proximity and spacecraft close approach are used widely, all these terms deal with the phenomenon of two man made space objects reach a relative distance, which is equal or lesser to the estimated or predicted position accuracy of the involved objects. There are several methods of close approach analysis; most of them rely on the TLE data available in public domain. Byoung Sun Lee, et, al, [3] explained the strategy followed for collision avoidance using Conjunction Summary Messages (CSM) from Joint Space Operations Command (JSpOC) and choosing the optimal delta-velocity for collision avoidance maneuver. Sang Cherl Lee and Hae Dong Kim [4] proposed a mathematical method using Genetic Algorithm for collision avoidance maneuver planning to decrease the collision probability with minimal delta-velocity for maneuver. Satellite Orbital Conjunction Reports Assessing Threatening Encounters Space (SOCRATES) also publishes the close encounters based on minimum range and maximum probability of collision by analysing all the catalog objects [5]. Independent orbit determination of the close approaching object reduces the risk involved and help in obtaining better state covariance [6], but it is possible for the spacecraft operator facilitated with radar and/or optical network data, so that the orbit of inactive spacecrafts can be determined.

2.1 GEO/GSO TLE Accuracy

Extraction of covariance information from TLE to generate covariance look up table for GEO shown that averaged uncertainties in the along-track and radial are better than 0.5 km and in out of plane better than 0.1 km using 878 GEO objects [7]. Ref. [8] emphasizes that the covariance obtained from TLE ephemeris will not accurately represent the covariance of the observation; it would interpret the uncertainty present in the TLE. Space surveillance networks rely on optical methods to track and catalog objects in GEO/GSO regime. Investigations on the accuracy of TLE by comparing with optical observations [9] reported the differences of 25 km in along-track and 10 km in the cross-track direction. Also, the catalog accuracy is in the order of angular spacing between clustered/collocated GEO spacecrafts. TLE accuracy can be enhanced by integrating with optical observations to determine true collision probability [10]. In addition to the strange TLE events mentioned in [11], cross-tagging or mis-identification of clustered GEO spacecrafts leads to wrong TLE updates. Ref [12] explains the use of a proprietary algorithm to increase the accuracy of TLE propagation, compared to the standard model and automations involved in close approach analysis. We analysed the TLE position accuracy, for MCF operational spacecrafts during maneuver-free period, by comparing the orbit estimated using single station C-band tone ranging and multi-station CDMA ranging for GEO and GSO respectively, and observed that the position difference can be up to 12 km.

2.2 Methodology

Close approach analysis is initiated on weekly basis, by using TLE obtained from www.space-track.org. Firstly, coarse analysis with TLE of operational spacecraft and other objects will be carried out, then the state vector from operational ephemeris is converted to TLE and COLA (Collision Analysis) program will be executed. COLA program provides the time of close approach, minimum distance and TLE age. Details on COLA program can be found in Ref [13]. If any close approach, less than 10 km is encountered, long term orbital nature of the close approaching object is studied, using historical TLE updates, followed by consistency check of the latest TLE update by propagating few of the previous TLEs. Then, a detailed analysis using COLMON (Colocation Monitoring) program with finer step size, by including the inactive object (debris) as one of the participating spacecraft in colocation, will be carried out. The parameters such as relative eccentricity-inclination vector separation, radial distance, along-track and out of plane separation are checked. These steps are repeated with the subsequent TLE updates until the day of close approach. In the meantime, tracking data collection for the operational spacecraft will be sought from the ground station network for orbit determination. Collision avoidance maneuver will be planned for the operational spacecraft based on the minimal delta-velocity at an optimal time, required to achieve a safe distance. Impact on the existing colocation due to collision avoidance maneuver on orbit maintenance and control also will be analysed. Once the maneuver planning is finalised, details will be intimated to the Spacecraft Operations Team for further actions.

Collision Analysis (COLA) program was developed by Applied Mathematics Division, Vikram Sarabhai Space Centre, ISRO, India. Colocation Monitoring (COLMON) program was developed by Flight Dynamics Division, ISRO Satellite Centre, ISRO, India

3 COSMOS-2440 : GSAT-14 & INSAT-4CR CLOSE APPROACH

In this section, the details of close approach of COSMOS-2440 with the operational collocated spacecrafts at 74 deg East longitude and the actions carried out are discussed. During the year 2015, at 74 deg East longitude five spacecrafts, INSAT-3C, INSAT-4CR, GSAT-14, GSAT-7 and KALPANA-1 (METSAT-1) were controlled, as per mission specifications. COLA analysis carried out on 23 July 2015 shown that COSMOS-2440 was approaching 74 deg East longitude and minimum distance less than 10 km was predicted. It required further analysis as per the operational guidelines. COSMOS-2440 is an uncontrolled librating object around L1 (75.1 deg E stable point). Long-term longitude profile of COSMOS-2440 is shown in the Figure 1.

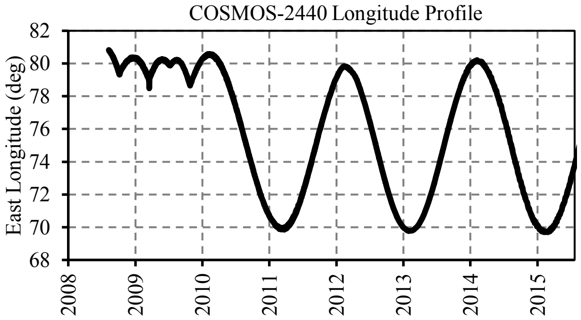

Figure 1. Longitude profile of COSMOS-2440, librating around 75.1 deg East stable point with an amplitude of 5 deg and period 2 years

The TLE update characteristics of COSMOS-2440 were studied using 273 TLEs between Jan 2014 and Jul 2015. Figure 2. shows the histogram plot of time gap between consecutive TLE updates. A peak at 48 hours shows that almost every 2 days an orbital update is expected.

The absolute difference between right ascension of ascending node (RAAN) and right ascension (RA) of the spacecraft can be used as a measure to analyse whether the TLE epoch is closer to ascending node. If the absolute difference is close to 0 deg then the epoch chosen is closer to ascending node and if it is close to 180 deg then the epoch chosen is close to descending node. This epoch need not to be the observation start or end epoch. In general, the estimated orbit is propagated to the previous ascending node crossing time and it is fixed as TLE epoch [8]. Figure 3, shows the histogram plot of absolute difference between RAAN and RA, interprets that most of the time, the TLE epoch is set closer to the ascending node of COSMOS-2440.

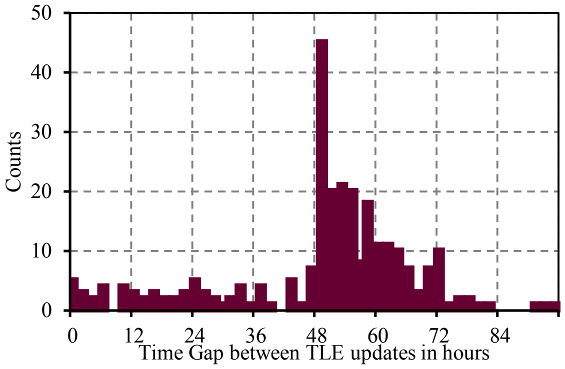

Figure 2. Histogram plot of time gap between COSMOS-2440 TLE updates during Jan 2014-Jul 2015, showing a peak at 48 hours (Bin Size = 2 hours)

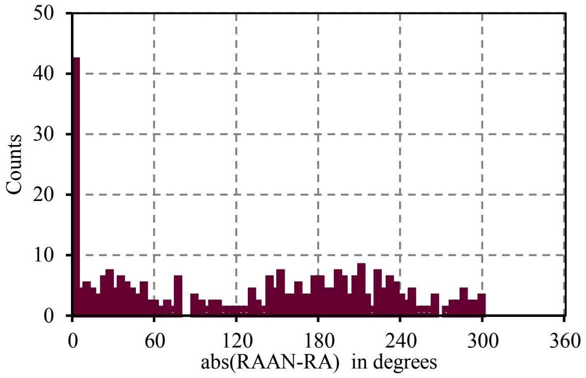

Figure 3. Histogram plot of absolute difference between RAAN and RA of COSMOS-2440 (Bin Size = 4 deg)

It is observed that, jumps in the order of 1 km were present in semi major axis (SMA) of COSMOS-2440 which is shown in the Figure 4. During this SMA jump, there was more than one TLE update on the same day. Also, the value of first derivative of mean motion is latched to zero (Figure 5.). In addition to that, the B* value is set to 10^{-4} instead of zero, which has no computational importance in GEO/GSO regime. Such jumps are observed in other catalogued objects also. Though, the first derivative of mean motion and B* value is not used in TLE propagation, the jumps in SMA can result an inconsistent TLE update with position difference in order of kms at the TLE epoch.

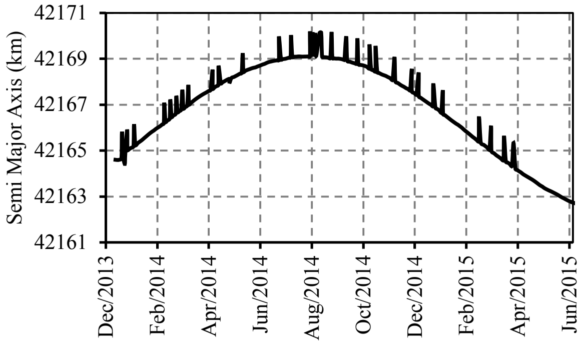

Figure 4. Jumps observed in Semi Major Axis of COSMOS-2440 TLE updates

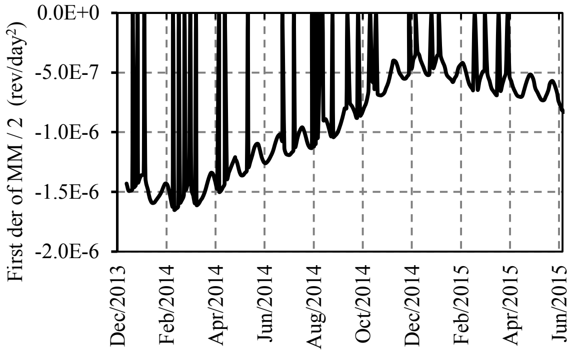

Figure 5. Plot showing the First derivative of mean motion value being latched to zero, when SMA jumps are observed

Consistency of 26 July 2015 TLE update was checked using previous TLEs and the position difference was found to be within the accepted range. During this time SMA jumps were not observed. Table 1. shows the osculating orbital elements obtained from TLE with an epoch of 26 July 2015 22:20 UT. COSMOS-2440 was drifting towards East Longitude with a drift rate of 0.033 deg/rev. Detailed analysis carried out based on 26 July 2015 TLE update with COLMON predicted relative distance of 7.5 km with GSAT-14 on 30 Jul 2015 14:39 UT and 4.2 km with INSAT-4CR on 31 Jul 2015 02:27 UT. The time of close approach is the ascending and descending nodal crossing time of COSMOS-2440 respectively.

For the other three colocated spacecrafts, the relative distance with COSMOS-2440 was found to be better than 15 km. The subsatellite profile of COSMOS-2440, GSAT-14 and INSAT-4CR is shown in the Figures 6 and 7.

Table 1.Osculating Orbital Elements of COSMOS-2440 based on TLE

PARAMETER	VALUE
Epoch (UT)	26 July 2015 22:20:42.9
Semi Major Axis (km)	42162.273
Eccentricity	0.000397
Inclination (deg)	3.462
Right Ascension of Ascending Node (deg)	58.807
Argument of Perigee (deg)	110.133
Mean Anomaly (deg)	184.414

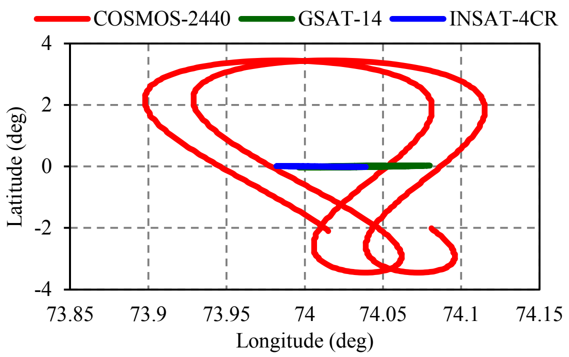

Figure 6. Sub-satellite profile of the spacecrafts COSMOS-2440, GSAT-14 and INSAT-4CR during 30 Jul 2015 to 31Jul 2015.

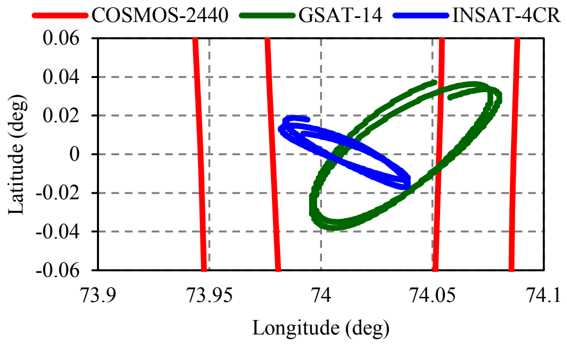

Figure 7. Zoomed portion of Sub-satellite profile of the spacecrafts COSMOS-2440, GSAT-14 and INSAT-4CR during 30 Jul 2015 to 31Jul 2015

The in-plane separation, in terms of radial and along- track are the only relative separation involved with respect to COSMOS-2440 at the time of its equatorial crossing. Figures 8 and 9 shows the in-plane separation of COSMOS-2440 with GSAT-14 on 30 Jul 2015 and COSMOS-2440 with INSAT-4CR on 31 Jul 2015, respectively.

Table 2. List of close encounters to the operational GEO/GSO spacecrafts during the year 2015 and 2016. Spacecrafts marked with an asterisk ('') are librating around both the stable points and all other are librating around 75.1 deg E stable point. Close encounter events marked with 'o' and '+' had undergone along track and out of plane orbital corrections as per routine operations respectively. Events marked with '#' had shown relative distance better than 10 km when operational ephemeris is used for COLA analysis*

Date of Analysis	Epoch of Close Approach (UT)	Long. (deg E)	Controlled Spacecraft	Approaching Object	Distance (km)	Comments
04 Mar 2015	04 Mar 2015 19:17	93.5	INSAT-3A	INSAT-1C	3.1	+
10 Apr 2015	11 Apr 2015 06:33	93.5	INSAT-4B	EXPRESS-2	3.2	+
16 Apr 2015	17 Apr 2015 05:09	74	GSAT-7	COSMOS-1738*	2.6	#
07 May 2015	16 May 2015 16:39	74	GSAT-7	COSMOS-2133	4.9	o
14 May 2015	15 May 2015 15:55	74	INSAT-4CR	COSMOS-1961	3.7	o
14 May 2015	20 May 2015 03:35	74	GSAT-7	COSMOS-1961	4.1	#
11 Jun 2015	25 Jun 2015 11:17	83	GSAT-12	RADUGA-12	4.7	+
25 Jun 2015	30 Jun 2015 14:29	74	INSAT-4CR	INSAT-1D	4.4	#
21 Oct 2015	23 Oct 2015 03:55	74	GSAT-14	RADUGA-12	2.4	#
21 Oct 2015	26 Oct 2015 05:43	74	INSAT-3C	STTW-2	3.7	#
28 Jan 2016	01 Feb 2016 23:46	83	GSAT-6	KUPON	4	#
18 Feb 2016	24 Feb 2016 22:58	74	INSAT-3C	LUCH-1	2.6	+
03 Mar 2016	04 Mar 2016 05:54	74	INSAT-4CR	RADUGA-4	3.3	#
09 Jun 2016	14 Jun 2016 14:53	74	INSAT-3C	RADUGA 1-3	3.5	#
14 Jul 2016	14 Jul 2016 23:50	129.5	IRNSS-1G	INTELSAT-804*	4.3	#
14 Jul 2016	19 Jul 2016 11:17	74	INSAT-3C	COSMOS-1961	3.6	#
14 Jul 2016	19 Jul 2016 23:17	74	GSAT-14	COSMOS-1961	4.6	+
18 Aug 2016	21 Aug 2016 22:08	74	KALPANA-1	COSMOS-2371	4.7	#
18 Aug 2016	24 Aug 2016 19:47	74	INSAT-4CR	ESIAFI-1	4.8	o
19 Aug 2016	21 Aug 2016 22:08	74	KALPANA-1	COSMOS-2371	1.9	#
19 Aug 2016	23 Aug 2016 07:54	74	INSAT-4CR	ESIAFI-1	3.5	o
19 Aug 2016	24 Aug 2016 11:16	74	GSAT-14	COSMOS-2371	5	#
19 Aug 2016	25 Aug 2016 07:46	74	GSAT-14	ESIAFI-1	2.9	#
19 Aug 2016	25 Aug 2016 23:10	74	GSAT-14	COSMOS-2371	2.6	#
08 Sep 2016	10 Sep 2016 07:03	93.5	INSAT-3A	RADUGA-26	4	+
08 Sep 2016	12 Sep 2016 23:26	74	GSAT-7	COSMOS-2440	3.5	o
15 Sep 2016	21 Sep 2016 17:17	83	GSAT-12	RADUGA-14	2.3	#
22 Sep 2016	26 Sep 2016 07:11	74	GSAT-7	GORIZONT-20	4.5	#
06 Oct 2016	11 Oct 2016 16:21	74	INSAT-4CR	RADUGA-12	2.9	+
24 Nov 2016	28 Nov 2016 03:31	74	GSAT-14	EKRAN-20	2.8	+
01 Dec 2016	02 Dec 2016 23:45	83	GSAT-12	RADUGA-10	5	o
01 Dec 2016	03 Dec 2016 11:43	83	GSAT-12	RADUGA-10	4.2	o
15 Dec 2016	16 Dec 2016 00:15	74	GSAT-7	COSMOS-1546	4.3	o

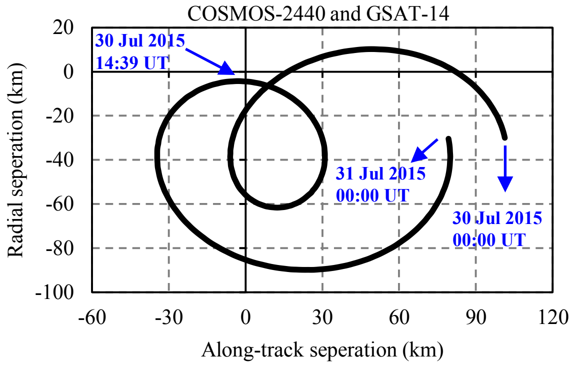

Figure 8. COSMOS-2440 and GSAT-14 on 30 Jul 2015 along-track and radial separation. (minimum relative distance = 7.5 km)

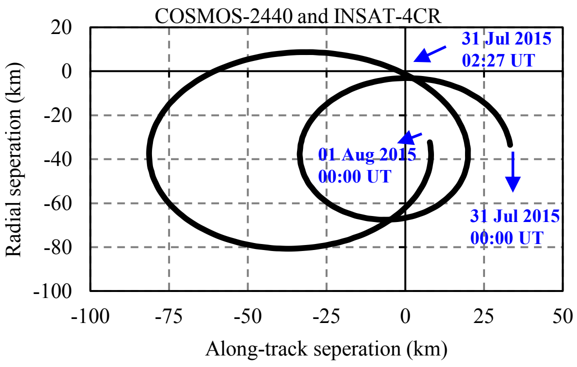

Figure 9. COSMOS-2440 and INSAT-4CR on 31 Jul 2015 along-track and radial separation. (minimum relative distance = 4.2 km)

3.1 Mitigation and Orbit Maintenance

The relative distances involved in the COSMOS-2440 with GSAT-14 and INSAT-4CR explained in the previous section, essentially didn't require a collision avoidance maneuver. As part of orbital maintenance strategy, along track maneuver with low thrust pulses which was already planned to be carried out was preponed and executed. In turn, it helped in improving the minimum close approach distance also. For GSAT-14, tangential delta velocity of 0.016 m/s was imparted on 28 Jul 2015 15:30 UT, and 29 Jul 2015 03:30 UT. In case of INSAT-4CR, at 29 Jul 2015 04:00 UT, tangential delta velocity of 0.027 m/s was imparted.

4 CLOSE APPRAOCH EVENT LIST

Since, 74 deg East longitude being close to the East Stable point in GEO ring, several librating inactive objects pass closer to this slot frequently. A database of such events and the TLE update nature would help in analysing and planning actions, during a next close encounter. Table 2. lists the close approaches encountered during the year 2015 and 2016. Initial analysis based on TLE vs TLE COLA with minimum relative distance less than 5 km is tabulated. Mostly, the close distance was observed to be better than 10 km when an operational ephemeris is used for active spacecraft. Sometimes, the recently carried out orbital correction is not reflected in TLE update of controlled spacecraft. In some cases, the close approach is due to an old TLE update and later updates have shown better results.

5 CONCLUSIONS

Vulnerabilities due to orbital debris close approach with active GEO/GSO spacecrafts are emphasized. Close approach analysis methods are reviewed. Orbital accuracy issues involved in using TLE are discussed. Characteristic study of long term TLE update nature and orbital profile is very much essential to ascertain the trueness of the TLE update involved in close approach analysis. Strategy followed by MCF during a close approach encounter is briefly described. The case of COSMOS-2440 close encounter with GSAT-14 and INSAT-4CR is illustrated.

6 ACKNOWLEDGEMENTS

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