Operational Results of
Conjunction Assessment and Mitigation at German Space Operations Center

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Results of the collision avoidance operation at the German Space Operations Center (GSOC) are presented in this paper. Currently, five operational satellites in the LEO region are supported in the monitoring system. In addition to the daily prediction using Two-Line Elements (TLEs) as source of orbital elements for space objects, possible critical approaches are also detected by the proximity search performed by Joint Space Operations Center (JSpOC). An automated alarming system is available for both screening results, and the detailed risk evaluation is performed by the Flight Dynamics team in case of a remaining high risk. After the introduction of the operational collision avoidance procedure, the risk assessment process for critical close approaches as well as the maneuver planning strategy are further discussed in this paper. For the two operational satellites TerraSAR-X and TanDEM-X (TerraSAR-X add-on for Digital Elevation Measurement), which are controlled against a reference orbit inside a control tube with a diameter of 500 m and in a very close formation (min. distance of about 400 m), a dedicated mitigation strategy has to be applied to minimize the violation of strict mission requirements. Two cases of the recent critical approach are presented for these satellites, which lead to the execution of a collision avoidance maneuver after a careful risk assessment, followed by the operational experiences and feedbacks.

Key Words: Collision avoidance, Conjunction Summary Message

1. Introduction

The increasing number of space objects in the near Earth region has been causing growing concerns for control centers as well as for satellite owners about the safety of their missions. Even a single collision in the space could deteriorate the debris population dramatically, causing another collision more likely.

Close approaches of the operational LEO satellites have been monitored at GSOC, whereas TerraSAR-X and TanDEM-X are operated in a very close formation since December 2010, with a minimum distance of about 400 m. A daily proximity prediction using TLEs has been operationally running, for which the preliminary analysis of the TLE propagation accuracy as well as the numerical propagation accuracy was performed to derive the conjunction assessment criteria [1-3)]. Additionally, the conjunction summary message (CSM) from JSpOC is available since mid of 2010. For a possible critical event, a careful risk assessment and an effective maneuver planning under mission constraints are required. Any unnecessary avoidance maneuver would increase the mission cost in terms of fuel consumption, operational lifetime, man power, and science data losses. Therefore orbit refinement of the jeopardizing object is foreseen by using a radar tracking campaign. A test campaign was already performed to assess the achievable orbit accuracy [1)]. In the past collision avoidance operation for nearly one and a half years, a few conjunction events were mitigated by executing the collision avoidance maneuver.

In this paper, the operational collision avoidance procedure at GSOC is presented, followed by the detailed discussion of the risk assessment and the maneuver strategy. A dedicated event handling process is discussed for TerraSAR-X and TanDEM-X, which require the highly strict control requirement. Operational experience and feedbacks are then presented, together with the examples of the mitigation operation performed for TerraSAR-X and TanDEM-X.

2. Operational Collision Avoidance Procedure

The GSOC collision avoidance system is available since 2009, where a monitoring based on the TLE catalogue has been running operationally. Moreover, the warning message from JSpOC is an additional source for the analysis of a close approach. The monitoring and mitigation process of a proximity event is explained in this chapter.

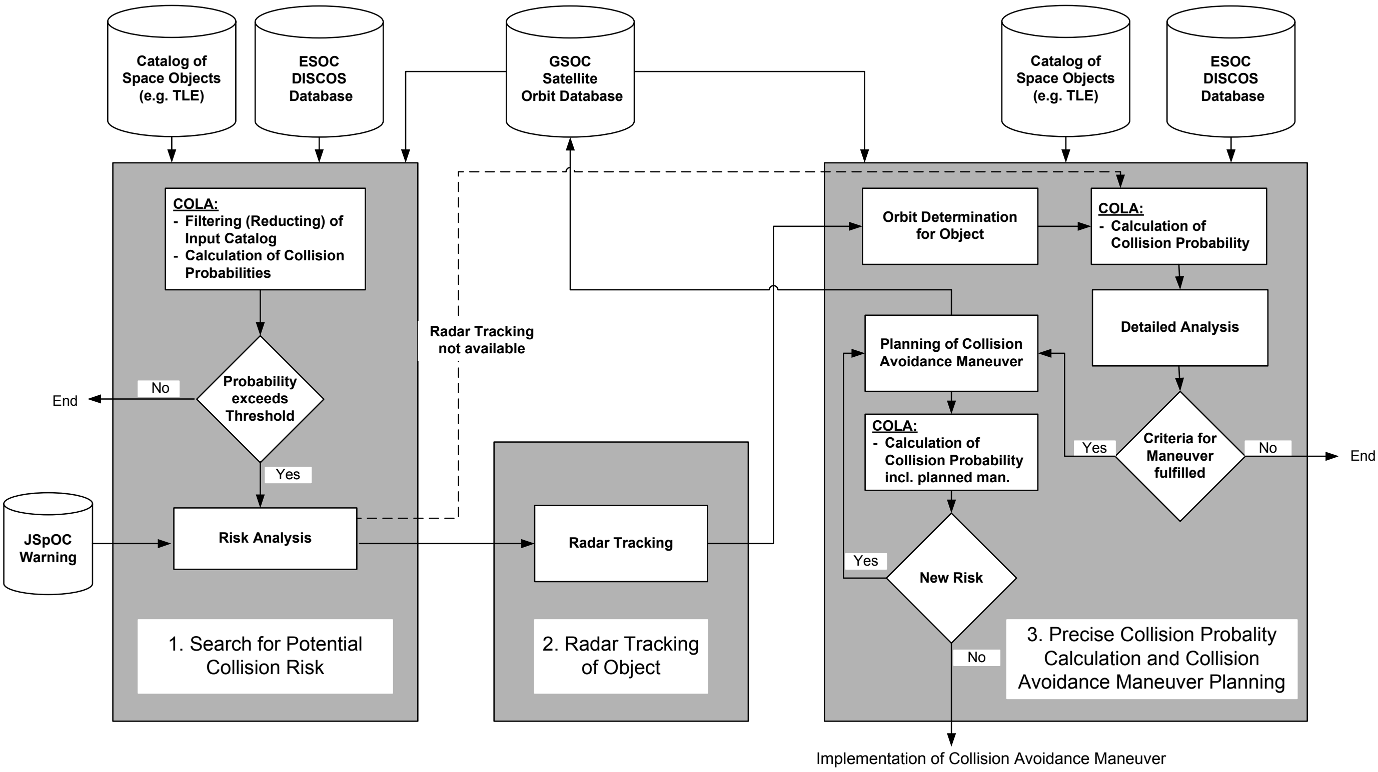

Fig. 1. GSOC collision avoidance procedure overview.

2.1. Process Overview

Currently, five operational LEO satellites are monitored in the collision avoidance system at GSOC. In addition to TerraSAR-X (514 km), TanDEM-X (514 km), and GRACE-1&2 (460 km), two PRISMA satellites (MANGO and TANGO, 750 km) have been handled since March 2011. The overview of the GSOC collision avoidance procedure is shown in Fig. 1. The procedure comprises mainly three steps;

1. Search for potential collision risk
2. Orbit refinement by radar tracking
3. Precise collision risk assessment and planning of possible avoidance maneuver

In the first step, the potential close approach is detected and the risk assessment is performed in case of a high risk. The daily screening is performed twice a day using the latest TLE catalog as an orbit source for space objects. Detected conjunction events in the upcoming seven days are listed in a report file, if a distance to a jeopardizing object violates the pre-defined two distance thresholds, a minimum distance < 10 km and a radial distance < 3 km. These thresholds were derived from the past TLE accuracy assessment [1] The collision probability is also calculated for each event, based on the estimated orbit uncertainties obtained from the previous TLE propagation error statistics [2,3]. The resulting report files for the upcoming close approaches are sent by email to the Flight Dynamics staff and are also uploaded on the internal Flight Dynamics website, so that the GSOC staff can share the information about the upcoming close approach. This screening and reporting process is running in an automated process since 2009. An automated alarming system is also available when critical events with small distance (radial distance < 0.3 km) and high probability ($>10^{-4}$) is detected. An alarming email is sent to the Flight Dynamics staff, which includes the latest prediction, past prediction histories if available, initial analysis results such as close approach geometry and statistics of the past TLEs. In the case of an alarm, the collision risk is further analyzed.

In addition to the daily TLE-based prediction, the warning message CSM provided by JSpOC has been another source for the critical proximity detection. When a CSM is received, the prediction is updated based on the latest orbit data of the operational satellite as well as those of the jeopardizing object derived from the CSM.

The orbit refinement of the jeopardizing object using a radar tracking is planned as the second step, if a high collision risk is expected in the previous step. The accuracy of such a radar tracking was already investigated using the TIRA (Tracking and Imaging Radar) facility of FHR [1]. The results of the test campaign performed for TerraSAR-X and CHAMP (~330 km) showed an enormous reduction of the orbit uncertainty especially compared to TLEs. Even for the JSpOC warning, which provides a relatively accurate orbit information, its given orbit accuracy could be not enough for a proper decision of taking a collision avoidance maneuver for non-operational satellites or small debris. Therefore, radar tracking is an important process to get the latest and the more precise orbit information.

At the final step, the prediction is updated based on the latest orbit information. The criticality of the conjunction is assessed again in terms of the proximity geometry as well as the collision probability, and a collision avoidance maneuver is planned in case of a remaining high risk. The decision of taking maneuvers is done by the Flight Dynamics team between a half day and one day prior to time of the closest approach (TCA), involving the whole mission operations team.

After the whole process, a report is generated for the analyzed critical close approach as a record and also as a summary of lessons learned from the event.

2.2. Interface to JSpOC Warning

Since the JSpOC warning is operationally available, this information has been getting more important for the detection of the critical close approach. Contrary to the TLE catalogue, CSM includes detailed information regarding the orbit quality, such as covariance and number of observations used for orbit determination. Additionally, more accurate orbit information is often available compared to the estimated TLE uncertainties. In case of LEO satellites, the notification by the CSM is currently provided, when the minimum distance is < 1 km, the radial distance < 200 m and the time to the closest approach < 72 hours [4)].

An automated processing of the JSpOC warning has been developed at GSOC. When a CSM is received, the prediction is updated using precise orbital elements of the operational satellite. Some warnings can be cancelled at this process, due to the recent or planned maneuvers, which are not yet available at JSpOC. An alarm is then sent to the Flight Dynamics staff per e-mail, which includes the summary of CSM, updated prediction results, and initial analysis results. Further analysis is preformed in case of a remaining high risk.

3. Collision Risk Assessment

When a possible close approach is detected, the event is first assessed carefully based on the prediction results. The important parameters listed in the report file are:

- Time of the closest approach
- Orbit propagation time
- Geometry parameters:
  - Minimum distance
  - Relative velocity
  - Relative position
    (in radial/along-track/out-of-plane)
  - Radial distance between two orbital arcs
  - Angle between two orbital planes
- Collision probability
- 1σ orbit uncertainties
  (in radial/along-track/out-of-plane)

For the geometry analysis, the radial distance is the important parameter along with the total distance, since the orbit accuracy is generally better in the radial direction. In addition, the radial distance is less affected by the timing of the close approach compared with the other components. The orbital arc distance is also an important parameter, which expresses the possible minimum distance of the two objects. The orbit uncertainties are calculated for the corresponding propagation length, altitude, and solar flux, based on the preliminary analysis of the orbit propagation error [2,3)]. In this analysis, orbit prediction errors were estimated for the SGP4 propagation as well as the numerical propagation, using precise orbits of the operational satellites as reference orbits. When CSM orbit data is used for the calculation, 1σ orbit uncertainties is derived from CSM.

After the first analysis, the criticality of the event is further assessed especially in terms of the geometry and collision probability. Some tools for the risk assessment have been developed, such as the geometry quick view and the three-dimensional visualization. Such tools are helpful for the better understanding of the proximity geometry and accordingly for the implementation of collision avoidance maneuvers. The propagation error statistics of the past TLEs is also available, to assess the consistency of the TLE for the corresponding object.

When an alarm from JSpOC is received, the prediction is first updated using precise orbital elements of the operational satellite. Since maneuvers performed for the operational satellites are not reflected in the JSpOC information, the warning could be cancelled by re-calculating the risk using the past or planned regular maneuvers. When necessary, precise orbit ephemerides are also sent to JSpOC in the CCSDS OEM format (Orbit Ephemeris Message) for a screening update.

For two operational satellites TerraSAR-X and TanDEM-X, which are controlled against a reference orbit inside a control tube of 500 m diameter and also flying in a close formation with the relative distance of about 400 m, the collision avoidance process has to be handled very carefully. The highly accurate orbit control requirement has to be achieved for both satellites to obtain high-resolution Synthetic Aperture Radar (SAR) data. Since the close formation was established in December 2010, risk assessment is done for both satellites, when one of two satellites has a proximity alarm. In addition, the JSpOC warning has to be checked with caution due to the very close orbits of two satellites and also due to the frequent maneuvers: roughly once per week with both satellites and two formation control maneuvers per day with TanDEM-X.

4. Planning of Collision Avoidance Maneuver

A collision avoidance maneuver is planned under the mission constraints, so that the collision probability is reduced or the relative distance (or at least one of its components) of the target satellite is brought outside the orbit uncertainty region. Of course fuel consumption as well as mission interruption due to the mitigation has to be minimized. The maneuver strategy taken for the operational LEO satellites are presented in this chapter, followed by the dedicated strategy applied for TerraSAR-X and TanDEM-X.

4.1. Maneuver Strategy

In case an avoidance maneuver is planned, either of the following strategies is normally considered: a change of the execution epoch or the size of an upcoming regular maneuver or the implementation of a collision avoidance maneuver to reduce the collision probability. The former is more preferable with regard to fuel consumption and operational aspects, but its availability depends on the timing of the existing maneuver. If any change of the regular maneuver is not possible, the latter strategy is applied to increase the relative distance mostly in the radial direction, considering the mission constraints of the satellite. A change of the radial distance is mostly chosen, because such a separation is achieved in a shorter period and with a smaller maneuver compared to the out-of-plane direction. Additionally, an orbit prediction is generally more accurate in the radial direction. After a collision avoidance maneuver, another maneuver is often required to come back to the nominal orbit like TerraSAR-X and TanDEM-X, which have to be kept in a certain control tube and with a certain formation.

After the possible avoidance maneuver is calculated, the new orbit data is screened against all objects, so that any additional collision risk does not detected. When necessary, new orbit ephemerides are sent to JSpOC for the re-screening.

4.2. Maneuver Strategy for TerraSAR-X and TanDEM-X

Due to the high orbit control requirements of TerraSAR-X and TanDEM-X as mentioned in section 3, a dedicated maneuver strategy has to be considered to handle the close approach. When a significant risk remains, the following collision avoidance scenarios have to be considered:

A. Change execution time and size of a regular maneuver to take place before (or after) the event, the other satellite replicates the maneuver as usual, or

B. One satellite performs two maneuvers: collision avoidance and re-acquisition of reference orbit, and

B.1 The other satellite replicates the maneuvers (fuel-expensive), or

B.2 The other satellite remains passive and the formation has to be re-acquired afterwards (time-consuming).

Of course, the risk assessment is to be repeated for every maneuver planned for TerraSAR-X and/or TanDEM-X before command upload. Due to such a complexity operation, the maneuver planning process has to be performed manually to minimize the violation of the mission requirements. For more details about the maneuver strategy, please refer to [5].

5. Operational Results of Critical Events

Operational results of the GSOC collision avoidance in the past one and a half years are presented in this chapter. Two recent close approaches are also mentioned, which were handled for TanDEM-X and TerraSAR-X and lead to avoidance maneuvers.

5.1. TanDEM-X Close Approach to a CZ-4 Debris

The close approach of TanDEM-X to CZ-4 Debris (~15 cm diameter from the radar cross section) at 2011/03/25 15:08:11 UTC was the first critical close approach and consequently lead to the first collision avoidance maneuver, since the close formation of TerraSAR-X and TanDEM-X was achieved.

A half day before TCA, JSpOC warnings were received for both satellites with the total/radial distance of 84/83 m (TanDEM-X) and 245/165 m (TerraSAR-X). The prediction was updated using precise orbital elements of the satellites and orbit data of the debris provided by JSpOC. In the daily prediction using TLE, the corresponding event was below the critical thresholds.

The updated results as shown in Table 1 also showed a critical proximity of the debris to both satellites, passing through their close formation (260 m radial separation) as shown in Fig. 2. Compared with the estimated orbit uncertainties (radial 1σ of 6 m for TanDEM-X, and 20 m for the debris), the small total/radial distance for TanDEM-X 88/87 m were nearly in the 3σ region and considered as critical. In addition, radar measurement for debris orbit refinement was not available. Therefore seven hours before TCA a collision avoidance maneuver was decided for TanDEM-X. An additional radial separation of 40 m was planned to bring TanDEM-X to 50 % outside the 3σ uncertainty region. After the collision avoidance maneuver, the minimum distance of 136 m and the radial distance (radial/along-track/out-of-plane) of (-125, 38, 38) m was achieved. Two maneuvers were performed in total; one was for the collision avoidance a half orbit before TCA and the other for the formation re-acquisition half an orbit after TCA.

Fig. 3 shows the TanDEM-X – TerraSAR-X relative motion (blue curve) in the plane perpendicular to the flight direction. The pink error bars show the 20 m (1σ) radial and normal control requirement. Because of the avoidance maneuvers, TanDEM-X was slightly outside the 1σ control band (upper blue curve). The maximum cross-track error was only 37 m with regard to the target formation parameters and therefore it can be concluded that the SAR instrument operation was not affected.

Table 1 Prediction results before maneuver planning.

		TanDEM-X	TerraSAR-X
Primary		TanDEM-X precise (GPS)	TerraSAR-X precise (GPS)
Secondary		JSpOC	JSpOC
TCA	[UTC]	2011/03/25 15:08:11	
Orbital plane angle	[deg]	90	
Rel.velocicty	[km/s]	10.8	
Probability	[-]	2.8E-05	6.8E-06
Min.distance	[m]	88	186
Rel.position, R	[m]	-87	173
Rel.position, T	[m]	-9	-5
Rel.position, N	[m]	-9	-5
1σ (RTN), satellite	[m]	(6,191,5)	(2,69,1)
1σ (RTN), debris	[m]	(20,876,11)	(20,876,11)

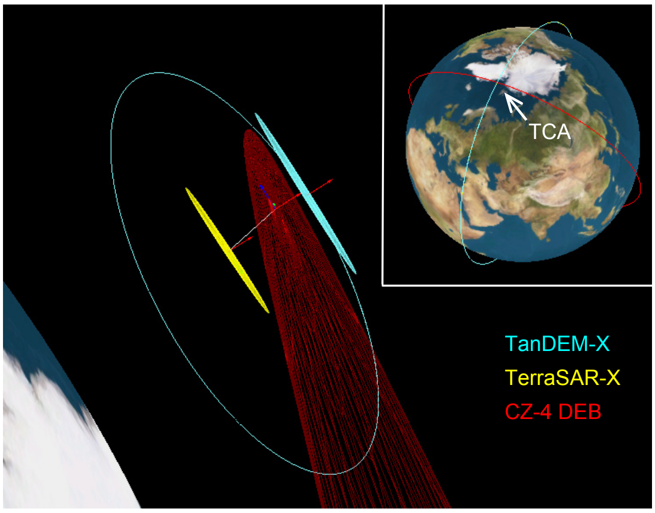

Fig. 2. Close approach geometry at TCA: Two satellites TerraSAR-X and TanDEM-X in a close formation and the CZ-4 debris are depicted with their 3σ covariance ellipsoids. A relative motion of TanDEM-X to TerraSAR-X is also shown with the radial/out-of-plane separation of ~300/400 m.

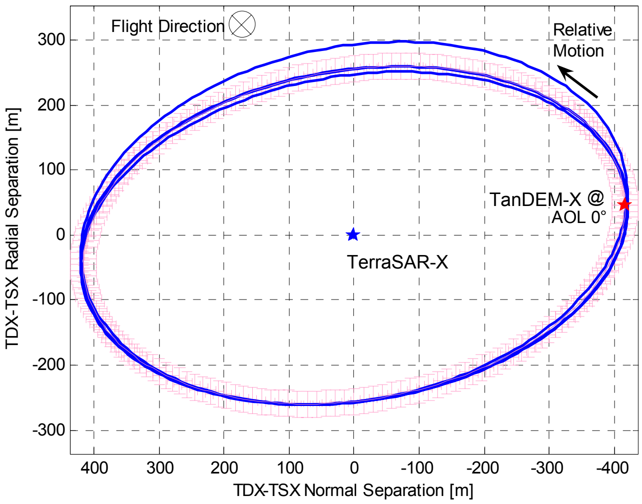

Fig. 3. TanDEM-X – TerraSAR-X relative motion: Due to the planned maneuvers, TanDEM-X was slightly outside the 1σ control band (pink bars, +/- 20 m in the radial and normal directions).

5.2. TerraSAR-X Close Approach to a Pegasus Debris

Another recent critical case was the Pegasus debris (~10 cm diameter from the radar cross section) close approach to TerraSAR-X at 2010/08/07 13:19:35 UTC. Flight Dynamics staff received a conjunction warning for TerraSAR-X from JSpOC one and a half days before TCA, with the total/radial distance of 90/69 m. The close formation with TanDEM-X was not yet achieved at this time. Due to the expected high risk, a radar tracking was performed around one and two days before TCA to get better orbit information of the debris. Based on the most recent and precise orbit information available, collision avoidance maneuvers were decided.

Table 2 shows the prediction results based on different orbit sources for the debris. In the daily prediction based on TLEs, the event had been constantly detected since the earliest prediction of seven days before TCA, with a maximum probability of ~10^{-4}. Table 2-(A) shows the results using a TLE (TCA-2.7 days) generated one day before TCA. The relative distance was not as critical as (B) and (C), whereas the estimated orbit uncertainties of the debris were also very large. Table 2-(B) is an update of the JSpOC warning using precise orbital elements of TerraSAR-X. Since a even higher risk was predicted based on the better orbit information, a debris orbit refinement using the TIRA system was decided. The radar tracking was planned covering four passes around one and two days before TCA, among which the last two passes could be used for the orbit determination. The precise orbit of the debris was determined using the resulting tracking arc of nearly 10 hours and the prediction was updated as shown in Table 2-(C).

Although the latest and the most precise prediction at the time showed a larger relative distance compared with the prediction before, the close radial distance of 19 m and the orbital arc distance of 13 m, which is the possible minimum distance of two orbital arcs of TerraSAR-X and the debris, were considered as critical. Therefore a collision avoidance maneuver was finally decided. Two maneuvers were performed half an orbit before and after TCA to separate the radial distance by ~150 m, and then to come back to the nominal orbit. After the maneuver planning, the updated prediction showed the minimum distance of 337 m, the relative position of (165, -46, -291) m, and the collision probability of 1.8E-05. For these maneuvers, ca. 64g hydrazine was used in total.

In the radar tracking campaign, the tracking data from the second half of a pass (TCA-1.5 days, 2010/08/06 05:00 UTC) and a whole pass (TCA-1.0 day, 2010/08/06 15:30 UTC) could be used for the orbit determination. The orbit of the debris was thus obtained using the 10 hours data arc of these one and a half passes with the estimated RMS as shown in Table 2-(C). The RMS at TCA was obtained by numerically propagating the initial value over a one day period from the epoch of the last measurement. Even with this short data arc, the orbit accuracy in the radial and the along-track direction could be improved compared to those given by JSpOC. Compared with the reference TLE accuracy, the accuracy improvement is enormous.

The reason for the relatively poor accuracy in the out-of plane component can be explained by the positional constraints of the used passes. For each pass used for the orbit determination, the maximum elevation was 89 and 84 degrees, which means that the observation plane was almost identical to the orbital plane of the debris. Accordingly, the lack of tracking information in the out-of-plane direction lead to a reduction of the orbit determination accuracy.

Table 2 Prediction Results before maneuver planning.

		(A) Daily prediction	(B) JSpOC warning	(C) Radar Tracking
Primary		TerraSAR-X precise	TerraSAR-X precise	TerraSAR-X precise
Secondary		TLE	JSpOC	Radar data
TCA	[UC]	2010/08/07 13:19:35		
Orbital plane angle	[deg]	160		
Rel.velocicty	[km/s]	15.1		
Probability	[-]	1.4E-05	3.4E-04	1.1E-03
Min.distance	[m]	1064	81	216
Rel.position, R	[m]	166	71	-19
Rel.position, T	[m]	184	5	-31
Rel.position, N	[m]	1035	39	-213
1σ (RTN), satellite	[m]	(3,272,2)	(3,272,2)	(3,272,2)
1σ (RTN), debris	[m]	(302,2101, 448)	(12,135,18)	(3,16,29)

5.3. Number of Critical Events

Since the start of the collision avoidance operation at GSOC in 2009, close approaches of operational LEO satellites TerraSAR-X, TanDEM-X (since June 2010), GRACE-1&2, PRISMA (since March 2011) and CHAMP (until September 2010) have been monitored and handled. Some critical cases were alarmed from daily prediction using TLEs, or more recently, from JSpOC warning.

The yearly event number of the five LEO satellites is summarized in Table 3. So far collision avoidance maneuvers were performed three times for TerraSAR-X and twice for TanDEM-X, among them two cases were decided based only on TLE information. Since the JSpOC warning is operationally available in mid 2010, the decision for a collision maneuver is preferably based more on JSpOC orbit information, or when available, measurement data of radar tracking. TLE is the widely available orbit information, but the uncertainty is not publicly provided and the estimated orbit uncertainty is often too large for the risk assessment compared to the orbit information provided by JSpOC, as shown in Table 2.

The number of events is estimated to increase in the next years, as the following satellite missions such as PRISMA are operated in a higher altitude of 750 km, which is one of the most populated regions in the space.

Table 3 Critical events for operational LEO satellites.

	Analyzed	JSpOC warning	Man.planned
2009 (August-)	3	2	2
2010	12	5	2
2011 (-March)	9	5	1

6. Conclusion

Close approach of the operational LEO satellites are monitored based on the daily prediction using TLE as well as the JSpOC warning. An automated alarm process is available for a possible high risk and the detailed assessment and planning of the avoidance maneuvers are performed manually by the Flight Dynamics team. In the past one and a half years, a few critical conjunctions were mitigated by collision avoidance maneuvers for TerraSAR-X and TanDEM-X.

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