COLLISION RISK ASSESSMENT AND OPERATIONAL EXPERIENCES FOR LEO SATELLITES AT GSOC

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Abstract: *The German Space Operations Center (GSOC) is monitoring close approaches of the operational satellites against the tracked space objects. Contrary to the controlled satellites, precise orbit information is not available for a massive space objects. Currently, the TLE (Two-Line Elements) catalogue maintained by the USSTRATCOM (US Strategic Command) constitutes the only publicly available and reasonably comprehensive orbit information, which has been used for such a monitoring. In addition to TLEs, warnings from the Joint Space Operations Center (JSpOC) can be recently used as another source for the proximity prediction. Although JSpOC provides orbit information including covariance information with a relatively higher accuracy, its availability is limited and the accuracy is still not enough for a maneuver decision and also for a proper planning of an avoidance maneuver. An orbit refinement using a radar tracking is therefore foreseen in case of a critical close approach.*

This paper describes the operational collision avoidance system, followed by the discussion of the orbit prediction accuracy of the TLE propagation as well as the numerical propagation from the operational point of view. The radar tracking accuracy is additionally presented for a comparison. A recent close approach of TerraSAR-X is presented as an example of the event handling together with the radar tracking results performed for the debris, followed by the operational experiences for the last 1.5 years.

Keywords: *Collision risk, Space debris, Orbit accuracy, Radar tracking, TLE.*

1. Introduction

The ever increasing number of objects in the near Earth region has been causing growing concerns about the space environment and therefore about the safety of future space missions. Since most of orbital debris stay in the orbit for years, even a single collision between space objects could seriously increase the debris population, making further collision events more and more likely. The encounter of IRIDIUM 33 with COSMOS 2251 in January 2009 was the first accidental collision between two artificial satellites, which created roughly 1500 tracked debris and other small fragments still orbiting in the wide range of the LEO. In early 2010, the close approach of 8000 kg ENVISAT (controlled by ESA) with a 1500 kg upper stage from a Chinese rocket would have lead to serious consequences, if no proper avoidance maneuver would have been performed (for details refer to [1]). These recent accidents clearly indicate the critical situation of the current debris environment as well as the importance of the operational collision avoidance.

GSOC has been implementing a collision avoidance system since 2008. The close approach monitoring is daily running in an automated process since November 2009, which detects the upcoming conjunction events of the operational four satellites in the altitude range of 460-510 km against roughly 15000 space objects listed in the TLE catalogue provided by USSTRATCOM. In addition, the warning from the Joint Space Operations Center (JSpOC) is currently an additional source for the close approach prediction, providing detail orbit information in the Conjunction Summary Message (CSM), which has become available for GSOC since July 2010. In the daily close approach monitoring, a detected collision risk is analyzed more in detail, when the pre-defined thresholds are violated. In case of a warning from JSpOC, the prediction is updated based on the precise orbit of the locally operated satellite together with the orbit data of the object given by JSpOC. Even after the careful risk assessment, an overly trust in the orbit information is not adequate for the decision of the maneuver planning due to its uncertainty. For this reason, orbit refinement using a radar tracking is foreseen. The influence of recent maneuvers of active satellites should not also be dismissed. In the collision avoidance operation at GSOC for nearly 1.5 years so far, the avoidance maneuvers were done for three cases for TerraSAR-X, and one for TanDEM-X, which was launched in June 2010 and flies now in a close formation with TerraSAR-X, where the minimum distance is about 450 m.

Following the presentation of the operational collision avoidance procedure at GSOC, this paper will discuss the orbit prediction accuracy including the operational aspects. In addition to the orbit propagation accuracy both for TLE and numerical propagator, the radar tracking accuracy is also discussed based on the comparison with precise orbit data. An exemplary event handling of TerraSAR-X is furthermore addressed together with the radar tracking campaign performed for the debris, followed by the operational results of the collision avoidance for the LEO satellites in the past 1.5 years.

2. Collision Avoidance Procedure

As of January 2010, four operational LEO satellites are monitored in the collision avoidance system at GSOC; TerraSAR-X (514 km), TanDEM-X (514 km), and GRACE-1&2 (460 km). 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. In the daily monitoring, predicted conjunction events in the upcoming 7 days are listed in a report file, if a distance to a jeopardizing object violates the pre-defined distance thresholds; the minimum distance < 10 km and the radial distance < 3 km. These thresholds were derived from the TLE accuracy analysis described in [3]. The prediction is updated twice a day automatically, and reports are sent to the FD staff. The latest prediction report is also available on the internal flight dynamics website, so that the GSOC staff can share the information about the upcoming close approach. When a collision probability exceeds the current threshold of 10^{-4}, the criticality of the event is closely analyzed. In addition to the daily TLE-based prediction, the warning message (CSM) from JSpOC has been another source for detection of the critical close approach since mid of 2010. 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 as described in [2]. 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 is expected from the risk assessment in the previous step. The accuracy of such a radar tracking was investigated in [3], showing enormous reduction of the orbit uncertainty compared to TLEs. Even for JSpOC warnings, which provide a relatively high orbit accuracy, the given covariance is often too large for a proper decision of taking a maneuver especially for small objects. Therefore, a radar tracking is performed if available to get the latest and the more precise orbit of the object.

At the final step, the prediction is updated based on the latest information. The criticality of the conjunction is assessed again in terms of the collision probability as well as the proximity geometry, and a collision avoidance maneuver is planned when necessary. The maneuver decision is made 0.5-1.0 day prior to the Time of the Closest Approach (TCA).

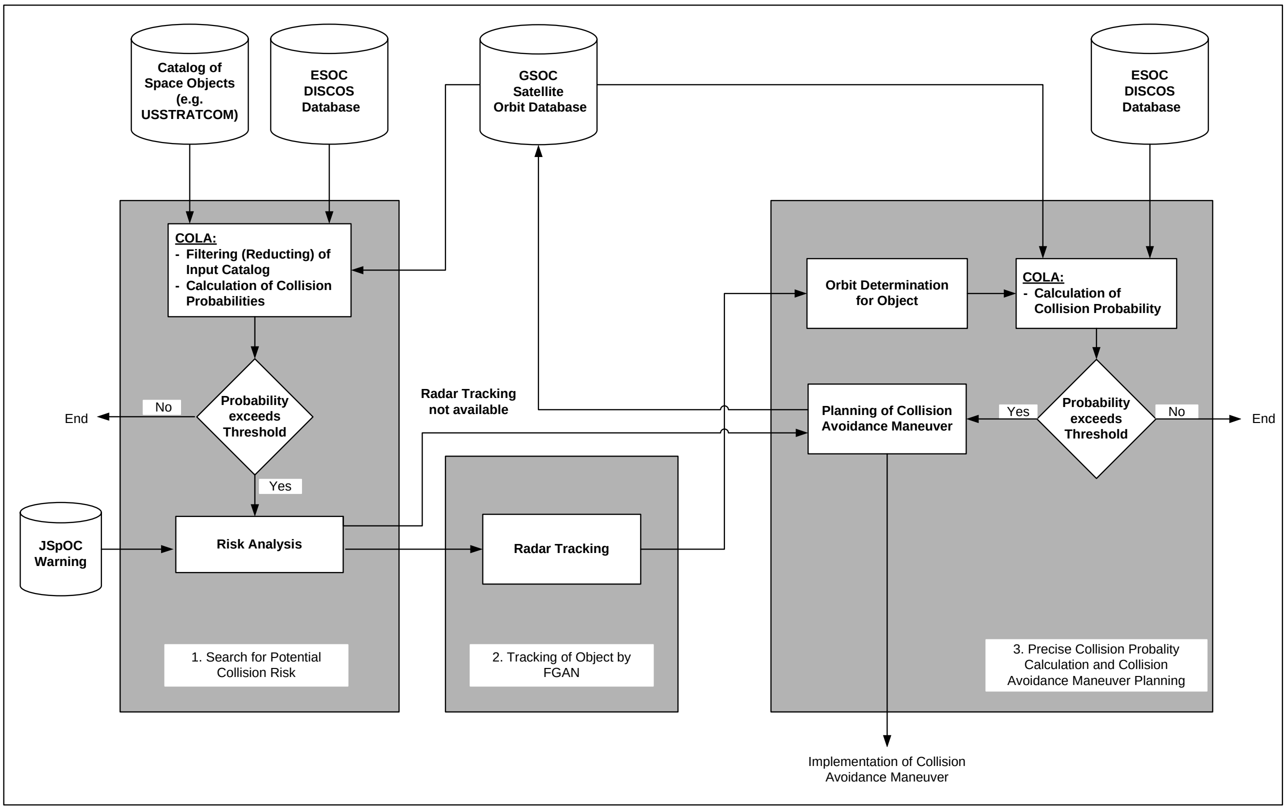

Figure 1. Collision Avoidance Procedure

3. Orbit Prediction Accuracy Analysis

In order to derive criteria for critical conjunctions, an analysis for the OP (Orbit Prediction) accuracy was performed. Propagation errors of ephemerides generated from USSTRATCOM TLEs and those generated by numerical orbit propagation were investigated by comparing the orbits with the precise orbits of locally operated satellites CHAMP and GRACE-1 (at an altitude of 270-430 km, and 460-500 km respectively). By using the long period of data, the dependency of the prediction accuracy on the altitude as well as the solar flux was obtained as shown in [4]. This analysis was extended for TerraSAR-X to get the prediction error at a higher altitude of 510 km. The resulting RMS can be operationally used to generate the covariance of space objects in the relevant altitude and solar flux range. In addition, the numerical propagation errors can be also applied as a covariance information of the locally operated satellites instead of propagating an initial covariance matrix, which does not include the influence of the solar flux prediction error and could results in a too optimistic estimation of orbit uncertainties.

The well established OD (Orbit Determination) and OP software ODEM (Orbit Determination for Extended Maneuvers) was used to generate ephemerides based on numerical propagation. The OD inside ODEM is formulated as a sequential non-linear least-squares problem based on Givens rotations and the OP is based on a standard numerical integration method for initial value problems. In particular an Adams-Bashforth-Moulton method for numerical integration of ordinary differential equations is adopted. This method employs variable order and step-size and is particularly suited for tasks like the prediction of satellite orbits. The numerical orbit propagator is using a comprehensive model for the acceleration of an Earth orbiting spacecraft under the influence of gravitational and non-gravitational forces.

The ‘real orbit’ as reference was generated by the software modules POSFIT or RDOD, which are part of the GHOST (GPS High Precision Orbit Determination Software Tool) package developed by GSOC/DLR. POSFIT performs a reduced dynamic orbit determination from a given a priori orbit. It estimates initial conditions, dynamical model parameters and empirical accelerations in a least squares fit. In addition, RDOD uses raw GPS measurements as observations for a precise orbit determination (POD). The position accuracy of the orbits based on POSFIT and POD is better than 2 m and 10 cm, respectively.

3.1. TLE Orbit Propagation Accuracy

Errors of the propagated TLEs w.r.t. POD orbits in the LEO region were investigated for a period of low solar flux in [3]. On the other hand, the analysis of the TLE fit against osculating orbit ephemerides showed that the solar activity can have an important influence on the prediction error. As the solar activity is slowly increasing since end of 2009, it is also important to know more in detail the influence of the solar activity on the orbit prediction. Therefore the orbit prediction accuracy analysis was extended to investigate the dependency of the prediction accuracy not only on the altitude but also on the solar flux, using orbit data of a long period. For two satellite missions at GSOC, CHAMP and GRACE, GPS orbits are available during the whole bandwidth of the solar activity, since CHAMP was launched in 2000 and GRACE in 2002.

In the analysis, TLEs for each satellite were propagated to the corresponding POD epoch up to 7 days (forwards) using the SGP4 propagator. The resulting orbits were compared with the precise orbits of CHAMP (April 2001-July 2010), GRACE-1 (April 2002-July 2010) and also TerraSAR-X (July 2007-July 2010) which are available at an interval of 30 seconds.

Table 1. RTN Error of TLE Propagation (RMS in [m])

		1 day prop					4 days prop					7 days prop				
			Flux					*Flux*					*Flux*			
R			*-90*	*90-140*	*140-190*	*190-*		*-90*	*90-140*	*140-190*	*190-*		*-90*	*90-140*	*140-190*	*190-*
	Altitude [km]	*-300*	309	208	275	225	*-300*	748	622	682	636	*-300*	2693	2498	3227	3446
		300-350	353	252	320	269	*300-350*	667	541	601	555	*300-350*	1007	812	1541	1761
		350-400	285	234	301	251	*350-400*	579	507	566	520	*350-400*	988	955	1684	1904
		400-450	351	305	214	163	*400-450*	559	491	451	405	*400-450*	835	780	764	983
		450-500	333	293	369	317	*450-500*	622	558	628	591	*450-500*	912	836	953	884
		500-	219	178	254	203	*500-*	330	267	337	299	*500-*	466	389	506	438
T			*-90*	*90-140*	*140-190*	*190-*		*-90*	*90-140*	*140-190*	*190-*		*-90*	*90-140*	*140-190*	*190-*
	Altitude [km]	*-300*	2925	1721	2035	2256	*-300*	40669	45697	50981	57079	*-300*	168530	136560	168530	189108
		300-350	2963	1758	2073	2294	*300-350*	12159	17187	22471	28568	*300-350*	35184	38817	70787	91365
		350-400	1528	1564	1878	2099	*350-400*	14163	15652	20936	27034	*350-400*	45122	47606	79577	100154
		400-450	1396	1438	1348	1569	*400-450*	8572	10802	12476	18574	*400-450*	30609	36578	37855	58432
		450-500	1312	1358	2343	2476	*450-500*	3830	6799	10747	18224	*450-500*	8240	17694	34904	43721
		500-	1207	1254	2239	2372	*500-*	2519	5489	9436	16913	*500-*	5456	14910	32120	40937
N			*-90*	*90-140*	*140-190*	*190-*		*-90*	*90-140*	*140-190*	*190-*		*-90*	*90-140*	*140-190*	*190-*
	Altitude [km]	*-300*	482	409	495	502	*-300*	575	477	514	530	*-300*	669	453	451	481
		300-350	375	302	388	395	*300-350*	431	334	370	386	*300-350*	490	274	272	302
		350-400	248	300	386	393	*350-400*	256	303	340	356	*350-400*	283	320	318	348
		400-450	338	347	375	383	*400-450*	334	323	359	375	*400-450*	338	310	357	387
		450-500	324	290	401	367	*450-500*	358	289	393	368	*450-500*	402	309	390	401
		500-	418	383	494	461	*500-*	461	392	496	470	*500-*	499	406	486	497

RMS errors sorted by the altitude and the solar flux at each POD epoch are shown in Tab. 1. Since not enough data were available to cover all the altitude-flux sets, some RMS errors were substituted with the estimated value using linear extrapolation just to see the tendency of the error growth at the wider range of the altitude-flux set. The missing data was estimated from at least 3 surrounding cells in a 2×2 square data set, using the value at the intersection point of the two diagonals. When more than one square data set exists, the average from each square data was taken. This process was continued until all possible data are filled. In Tab. 1, such extrapolated data are distinguished from the statistical results by the dark pattern.

As a whole, the RMS errors of the along-track and radial components become larger at the lower altitude and also at the higher solar flux period and grow exponentially for the longer prediction time. On the other hand, fluctuation of the solar flux is much larger during the higher flux period compared to the lower one. Due to this behavior and since the solar flux has a severe influence on the atmospheric density, the along track and also radial prediction errors are expected to become larger when the solar flux is higher and also when the altitude is lower. As for the RMS error of the cross-track component, there is no distinct dependency on the solar flux and the altitude, but the error grows gradually with the propagation length.

3.2. Numerical Orbit Propagation Accuracy

As done in the TLE analysis, the orbit prediction error was analyzed as well for the numerical propagation using the orbit database of CHAMP, GRACE-1 and TerraSAR-X. The orbits were propagated up to 7 days with the ODEM tool, and compared with the same precise orbits. For the numerical propagation, the predicted solar flux at the epoch of the database was used.

Table 2. RTN Error of NUM Propagation (RMS in [m])

		1 day prop					4 days prop					7 days prop				
			Flux					*Flux*					*Flux*			
R			*-90*	*90-140*	*140-190*	*190-*		*-90*	*90-140*	*140-190*	*190-*		*-90*	*90-140*	*140-190*	*190-*
	Altitude [km]	*-300*	19	22	23	25	*-300*	223	248	238	263	*-300*	1505	1681	3514	3430
		300-350	5	7	9	11	*300-350*	36	62	51	77	*300-350*	125	301	2133	2050
		350-400	8	10	12	14	*350-400*	43	69	58	84	*350-400*	282	458	2290	2207
		400-450	6	7	8	10	*400-450*	24	40	46	71	*400-450*	67	170	204	120
		450-500	5	6	6	8	*450-500*	12	19	25	50	*450-500*	22	52	210	127
		500-	1	2	3	5	*500-*	8	14	20	46	*500-*	3	34	192	108
T			*-90*	*90-140*	*140-190*	*190-*		*-90*	*90-140*	*140-190*	*190-*		*-90*	*90-140*	*140-190*	*190-*
	Altitude [km]	*-300*	1204	1390	1449	1584	*-300*	28388	30919	28833	31719	*-300*	97621	103106	134988	139301
		300-350	278	463	522	657	*300-350*	7244	9775	7689	10575	*300-350*	24695	30179	62062	66375
		350-400	530	668	727	862	*350-400*	10199	12730	10643	13529	*350-400*	34994	40479	72361	76674
		400-450	337	466	449	585	*400-450*	6747	9085	9697	12582	*400-450*	22520	28769	36506	40819
		450-500	97	217	332	468	*450-500*	1652	3796	5988	8874	*450-500*	5382	12395	22299	26612
		500-	22	142	257	392	*500-*	376	2520	4712	7598	*500-*	951	7964	17868	22181
N			*-90*	*90-140*	*140-190*	*190-*		*-90*	*90-140*	*140-190*	*190-*		*-90*	*90-140*	*140-190*	*190-*
	Altitude [km]	*-300*	3	3	3	4	*-300*	10	10	10	11	*-300*	19	19	21	20
		300-350	2	2	2	2	*300-350*	5	5	5	6	*300-350*	8	9	11	10
		350-400	1	1	1	1	*350-400*	4	4	5	5	*350-400*	7	8	10	9
		400-450	1	1	1	2	*400-450*	4	4	5	6	*400-450*	7	8	10	9
		450-500	6	6	5	6	*450-500*	14	14	10	11	*450-500*	23	24	17	16
		500-	1	1	1	1	*500-*	4	4	1	1	*500-*	5	6	0	0

The resulting RMS errors in Tab. 2 show again the dominant prediction error in the along-track direction. Comparable to the TLE analysis, the along-track and radial errors become larger at the lower altitude and at the higher solar flux period. The RMS error of the along-track component does not show the clear dependency on the solar flux and the altitude, but the error grows gradually with the longer propagation. By propagating orbits using the well-modeled propagator, errors are small especially for the radial and along-track components and also for the along-track component during the short-term propagation. However, the longer propagation results in a bad orbit prediction especially in the along track direction. The reason could be a prediction error of the solar flux, which becomes larger at the higher solar flux period.

Table 3 shows the difference (in the mean and the standard deviation) between the predicted and the real solar flux values for different prediction periods. Flux data of the last 10 years (January 2001–July 2010) was taken for the analysis, where for each day a dedicated flux file was used containing 8-day-prediction data available at that day. These flux files are based on archived daily short-term predictions by ESOC. The results clearly show the growing prediction error for higher solar flux values, leading to the large along-track and radial error in the numerical propagation, even with the well-established model of the propagator.

Table 3. Solar Flux Prediction Error (in 10^{-22}[Ws/m^2])

		1 day pred.		2 day pred		3 day pred	
		Mean	1σ	*Mean*	1σ	*Mean*	1σ
Flux	*-90*	0.5	3.0	1.3	4.9	1.8	5.9
	90-140	1.4	11.6	3.5	16.8	5.3	19.2
	140-190	1.3	12.6	1.4	20.6	2.6	25.3
	190-	-6.4	21.7	-15.4	33.3	-23.6	39.1

In the operational close approach prediction, the obtained RMS errors are implemented as a covariance information of the numerical orbit propagation for the operational satellites, for which the precise orbits are known. On the other hand, this analysis showed that the numerical propagation can result in a large orbit error for the long time prediction, although it is still better than the TLE propagation. However, the orbit prediction in the radial and along-track direction for the numerical propagation is very precise for the shorter period of the prediction around 2-3 days, and even better around 1-1.5 days, which is the decision point for the radar tracking and the maneuver planning respectively.

3.3. Radar Tracking Accuracy

In case of a critical conjunction, orbit refinement of the jeopardizing object using a radar tracking is foreseen. A test campaign was performed for the operational satellites TerraSAR-X (514 km) and CHAMP (330 km) and the resulting accuracy was compared with the GPS navigation solution data, as presented in [3]. For the radar tracking, the Tracking and Imaging Radar (TIRA) system of FHR was used. This is the only radar in Germany, capable to observe non-cooperative objects in space. The pattern of ground contacts is typical for near polar orbits and ground station locations like the FHR one, where up to three subsequent orbits with visibility are followed by at least 9 hours with no visibility.

The main outcome of this campaign was that the quality to the same order as the GPS navigation solution was achieved by the radar tracking. The orbit accuracy after 1.0 day orbit propagation is shown for TerraSAR-X in Tab. 4. A maximum of five passes covering 24 hours were used for the orbit determination based on the radar tracking data. Compared with the corresponding TLE propagation errors (1-day prop., Altitude > 500 km and Flux < 90 in Tab. 1), the orbit accuracy could be clearly improved, which leads to a reduction of collision avoidance maneuvers as well as to a proper planning of a maneuver.

In the operational collision avoidance strategy, a radar tracking has to be performed timely prior to the TCA. While a later timing reduces the time for the maneuver planning, an earlier one increases the prediction length, leading to a less orbit accuracy. For this reason, a radar tracking is supposed to be completed 0.5-1.0 day before the TCA. In total, four passes are planned for one tracking campaign to obtain the minimum data arc of 12 hours for the orbit determination, which is necessary due to the estimation of the ballistic coefficient under the significant influence of the atmosphere in the LEO region.

Table 4. RMS after 1.0 day TerraSAR-X Orbit Propagation (in [m])

	32×32 gravity field			70×70 gravity field		
	Radial	Along-track	Normal	Radial	Along-track	Normal
FHR (12h OD)	4	83	5	1	40	1
FHR (24h OD)	6	181	7	2	101	2
GPS (12h OD)	4	45	6	1	49	1
GPS (24h OD)	4	83	5	1	61	1

4. Collision Avoidance 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 most chosen, because a separation is achieved in a shorter period and with a smaller maneuver compared to the out-of-plane direction. Additionally, orbit prediction is generally more accurate in the radial direction as shown in chapter 3. After a collision avoidance maneuver, another maneuver is often required to come back to the nominal orbit like TerraSAR-X and TanDEM-X, which are controlled against a reference orbit inside a control tube of 500 m diameter. These satellites are flying in a close formation with the relative distance of < 500 m.

When a significant risk (i.e. 10^{-4}) remains for TerraSAR-X (TSX) or TanDEM-X (TDX), the following precautions exist in principle (for details refer to [6]). If the risk applies only to TSX, there are three collision avoidance scenarios:

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

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

B.1 TDX replicates the maneuvers (fuel-expensive), or
B.2 TDX 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 TSX and/or TDX before command upload. If solely TDX is affected, TSX remains passive and TDX has to perform maneuvers for collision avoidance and formation re-acquisition.

5. Event handling

The recent close approach of TerraSAR-X to a Pegasus debris is discussed in this chapter, which lead to a collision avoidance maneuver. In addition to an alert from the daily monitoring, a warning from JSpOC was also received and a radar tracking of the debris could be performed. The summary of this event is shown in Tab. 5.

Table 5. Summary of Events

Object		Pegasus debris (ID 24978)
Estimated size		~10 cm (RCS: 0.010 m^2)
Eccentricity, Inclination		*e*: 0.044, *i*: 81.5°
Perigee/Apogee altitude	[km]	464 / 1181
TCA	[UTC]	2010/08/07 13:19:35
Relative velocity	[km/s]	15.1
Orbital plane angle	[deg]	160

5.1. Close Approach of TerraSAR-X

The event had been constantly predicted since the earliest prediction of 7 days before the TCA, with the maximum probability of ~10^{-4} (Tab. 6-A). On the other hand, the flight dynamics staff received a warning from JSpOC ~1.5 days before the TCA, with a minimum distance of 90 m (Tab. 6-B). The event was analyzed using the precise orbit of TerraSAR-X (accuracy of a few meters in the radial direction as shown in Tab. 2, for a 1-day prop., altitude > 500 km and flux < 90), together with the orbit information of the debris provided by JSpOC (Tab. 6-C). On the other hand, the orbit information of TerraSAR-X from JSpOC is based on independent radar tracking data and with the given 1σ-errors (3 m in radial, 151 m in along-track, and 2 m in cross-track). As these small 1σ-errors show, the GSOC analysis (C) is comparable with the JSpOC prediction (B). After the analysis, an orbit refinement using the TIRA system was decided to get a better orbit information of the debris. The radar tracking was planned covering four passes 1-2 days before the 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 10 hours and the close approach prediction was updated (Tab. 6-D).

Table 6. Close Approach Prediction

	A: Daily prediction (TCA-1d)	B: JSpOC warning (TCA-1.5d)	C: GSOC analysis (TCA-1.5d)	D: FHR tracking (TCA-1d)
TX1 orbit	TX1 precise	JSpOC	TX1 precise	TX1 precise
Debris orbit	TLE (TCA-2.7d)	JSpOC	JSpOC	Radar tracking
Probability	1.39E-05	N/A	3.44E-04	1.13E-03
Min.distance	1.064	0.090	0.081	0.216
R (Radial)	0.166	0.069	0.071	-0.019
T (Along-track)	-0.184	-0.007	0.005	-0.031
N (Cross-track)	-1.035	-0.058	0.039	-0.213
Orbital arc dist.	0.197	N/A	0.070	0.013

Even though 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 the TCA to separate the radial distance by

~150 m, and then to come back to the nominal orbit. The final prediction after the maneuver planning is shown in Tab. 7. Both of the along-track and out-of-plane components were also enlarged consequently.

Table 7. Prediction incl. Avoidance Maneuver

	E: After maneuver planning (TCA-0.8d)
TX1 orbit	TX1 precise
Debris orbit	Radar tracking
Probability	1.77E-05
Min.distance	0.337
R (Radial)	-0.165
T (Along-track)	-0.046
N (Cross-track)	-0.291
Orbital arc dist.	0.174

5.2. Radar Tracking Accuracy of Debris

For the operational orbit refinement using a radar tracking, four passes are currently planned to be necessary for the determination of an orbit using a 12-24 hours data arc. The minimum length of the 12 hours arc is required for the estimation of the ballistic coefficient under the influence of the atmosphere.

In the radar tracking campaign performed for the Pegasus debris, 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. The orbit of the debris was determined using the 10 hours data arc of these 1.5 passes with the estimated RMS as shown in Tab. 8. The RMS at the TCA was obtained by numerically propagating the initial value over a 1-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 at the corresponding column in Tab. 1 (1-day prop., Altitude > 500 km and Flux < 90), the accuracy improvement is enormous, although other parameters such as eccentricity and inclination (for details refer to [5]) and also the object size have to be considered for more details.

The reason for the relatively poor accuracy in the out-of plane component can be explained by the positional constraints of the used passes. Figure 2 shows the azimuth (angular direction) and the elevation (radial direction) of the passes in the polar coordinate frame. The point of origin represents 90 degrees of the elevation. Both lines pass near the origin, reaching the maximum elevation of 89 degrees and 84 degrees for each pass. It means that the observation plane is almost identical to the orbital plane of the debris. Accordingly, lack of tracking information in the out-of-plane direction lead to the reduction of the orbit determination accuracy.

Compared with the test campaign results of the TerraSAR-X radar tracking as shown in Tab. 4, the RMS accuracy of the debris is comparable, even with its relatively small size (~10 cm) and eccentric orbit. However, it has also to be mentioned that the RMS of the radar tracking in Tab. 8 was calculated by numerically propagating the initial error, whereas the results in Tab. 4 was obtained by comparing the orbits with the precise orbit data of TerraSAR-X.

Table 8. RMS of the Pegasus Debris at TCA (in [m])

	Radial	Along-track	Normal
Radar tracking	2.5	16.3	29.4
JSpOC	12	135	18

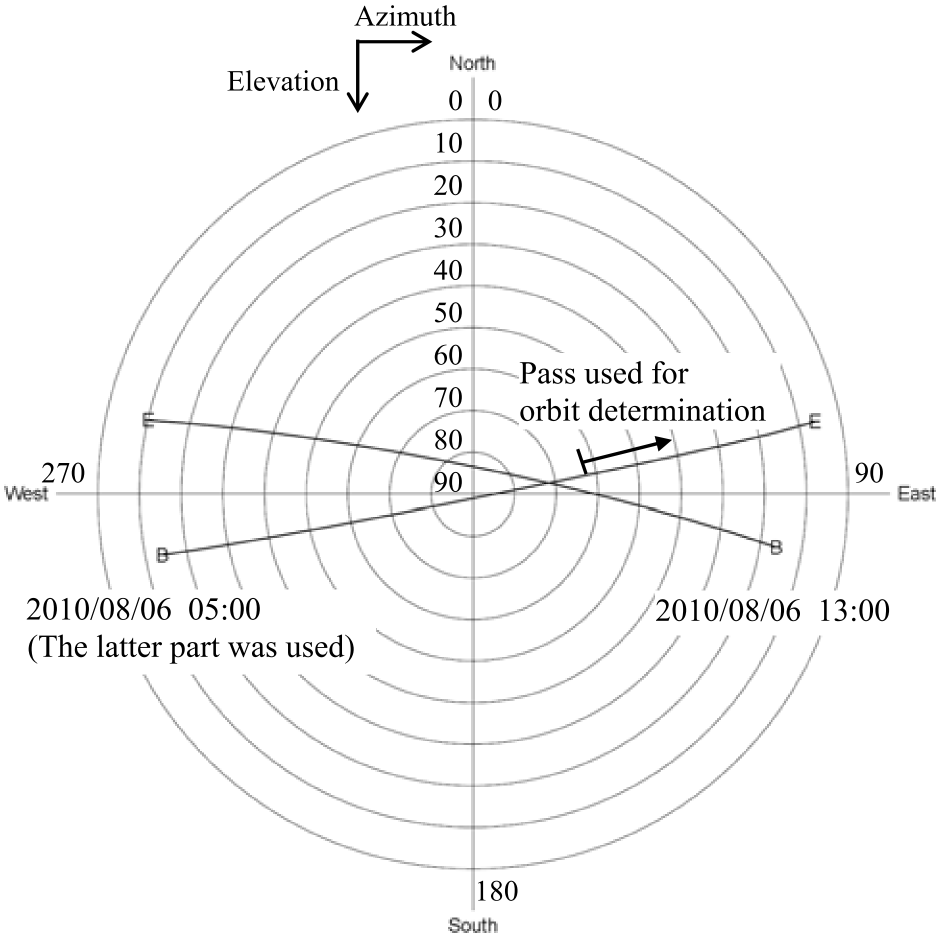

Figure 2. Radar Tracking Pass (in degree)

6. Operational Results

Close approaches of the operational LEO satellites TerraSAR-X, TanDEM-X (since June 2010), GRACE-1&2, and CHAMP (until September 2010) have been monitored and handled for nearly 1.5 years since 2009. Some cases were alarmed from daily monitoring results or from warnings by JSpOC, resulting in a further risk assessment. The past analyzed events as of January 2011 are listed in Tab. 9.

In total, three cases lead to an avoidance maneuver for TerraSAR-X, and one for TanDEM-X. These two satellites are kept in a very close formation with a relative distance of < 500 m. No collision avoidance maneuvers have been planned for them since the close formation was established in December 2010, but the risk analyses were already performed against two space debris. In most of the cases, the analysis has to be done for both two satellites, when one of them gets an alarm. It has also to be mentioned that two close approaches for TanDEM-X on 2010/06/27 were handled by one avoidance maneuver during its LEOP, based only on TLE information. The maneuvers were executed as part of the re-planned maneuver sequence for the eccentricity correction necessary to bring the satellite into the formation with TerraSAR-X. Therefore no fuel in addition to the nominal target orbit acquisition budget was necessary. The number of the 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.

The relative distance and its radial component before the maneuver decision are also listed, together with the value provided by JSpOC. The jeopardizing objects are shown as well as their estimated size calculated from the radar cross section. Most are derived from debris; 4 out of 15 are Cosmos 2251 debris and 2 are Fengyun 1C debris. As shown in Tab. 10, the estimated object size is mostly smaller than 1 m, often even smaller than 10 cm, causing the large error in the orbit prediction. Even for large objects, given orbit accuracies of active satellites could be worse due to maneuvers. Since such orbit errors grow according to the prediction length, orbit refinement using a radar tracking is an effective way to get a more accurate orbit information. A contact to a control center can also be an alternative for the orbit refinement, if a controlled satellite is approaching.

Table 9. Analyzed Close Approaches

TCA [UTC]	Sat.	Object	Size [m]	Dist. [m]	R.Dist. [m]	dV [km/s]	JSpOC warning	Maneuver
2009/08/24	TSX	Fengyun 1C debris	0.11	605(799)	191(19)	13.9	x	yes
2009/09/16	TSX	Cosmos 252 debris	0.19	946(346)	549	13.9	x	no
2009/11/27	TSX	Cosmos 2251 debris	0.20	360	81	15.2		yes
2010/03/13	TSX	PSLV debris	0.14	2059	131	14.6		no
2010/06/27	TDX	Timed debris	0.25	1196	33	12.8		yes
2010/06/27	TDX	SL-8 R/B	2.38	684	145	14.1		yes
2010/07/22	TSX	Delta 2 R/B	3.21	1122	230	12.7		no
2010/07/25	TSX	CZ-4C debris	0.05	142	63	1.1		no
2010/08/07	TSX	Pegasus debris	0.08	216(77)	13(76)	15.1	x	yes
2010/08/20	TDX	Delta 1 debris	0.15	1718(1936)	178(160)	12.9	x	no
2010/11/25	TSX	Cosmos 2251 debris	0.08	120	119	15.0		no
2010/12/01	GR1	EXPLORER 8	0.65	208(3609)	62(75)	6.1	x	no
2010/12/12	TDX	Cosmos 2251 debris	0.20	492(360)	297(20)	14.8	x	no
2010/12/12	TSX	Cosmos 2251 debris	0.20	202	19	14.8		no
2010/12/28	GR1	Cosmos 2251 debris	0.01	(443)	(58)	14.9	x	no
2011/01/23	TSX	Fengyun 1C debris	0.02	745	76	14.1		no
2011/01/23	TDX	Fengyun 1C debris	0.02	990	176	14.1		no

* ( ) given by JSpOC

Table 10. Estimated Object Size

	< 10cm	10cm - 1m	> 1m	Total
Number	4	9	2	15

7. Conclusion

Operational close approach monitoring is performed using TLEs and warnings from JSpOC as the orbit source. Potential events are analyzed carefully, and a radar tracking campaign is planned in a critical case. Based on the latest and the most precise orbit available at the time, a collision avoidance maneuver is decided.

The Orbit prediction accuracy for the TLE orbit propagation as well as for the numerical propagation showed the strong dependency on the altitude and the solar flux, especially in the radial and along-track direction. The lower altitude and the higher solar flux resulted in a poor prediction accuracy due to the higher atmospheric influence. The accuracy was also influenced by the solar flux prediction error. The resulting RMS errors are currently used in the operational close approach monitoring as a covariance information at the relevant altitude and the solar flux. The radar tracking accuracy analysis showed that an orbit refinement with the same precision compared to orbits based on GPS navigation solution data could be achieved for large objects.

A close approach of TerraSAR-X against a Pegasus debris was handled based on the radar tracking results of the debris. Even for the small non-cooperative object, the orbit accuracy was clearly improved compared with JSpOC and TLE orbits.

In the past collision avoidance operation for nearly 1.5 years at GSOC, three cases lead to an avoidance maneuver for TerraSAR-X and one for TanDEM-X. Most analyzed events were caused by small debris, for which an accurate orbit information is often not available. Therefore, a radar tracking is the only effective way for an orbit refinement.

8. Reference

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