Collision Avoidance Operations for LEO Satellites Controlled by GSOC

S. Aida[1], M. Kirschner[2], M. Wermuth[3] and R. Kiehling[4]

German Space Operations Center
DLR Oberpfaffenhofen
82234 Wessling, Germany

The German Space Operations Center (GSOC) is currently building up an operational proximity monitoring and mitigation system. Proximity events are detected based on the "Two-line Elements" (TLEs) and precise orbit information from locally operated missions. Despite evident deficiencies in the quality and timeliness of the available orbit information, TLEs are currently the only source of orbit information for the numerous space objects. The TLE uncertainty needs to be therefore carefully assessed for the collision risk estimation. Even after a realistic error analysis, the orbit information of a possible jeopardizing object has to be refined for a proper planning and implementation of collision avoidance maneuvers. For this purpose, the use of radar tracking is currently planned, for which an accuracy assessment is to be considered. In this paper, following the presentation of the collision avoidance procedure at GSOC, the orbit accuracy and the orbit refinement by a radar tracking is discussed followed by its application to the collision avoidance system. The paper concludes with the presentation of GSOC's collision risk monitoring system and how close approaches are handled.

Nomenclature

GSOC	=	German Space Operations Center
LEO	=	Low Earth Orbit
OD	=	Orbit Determination
OP	=	Orbit Prediction
RMS	=	Root Mean Square
POD	=	Precise Orbit Determination
TLE	=	Two-Line Elements
USSTRATCOM	=	US Strategic Command

I. Introduction

The ever increasing population of objects in the near Earth environment has created growing concerns among satellite owners and control centers about the safety of their missions. The GSOC is currently building up an operational proximity monitoring and mitigation concept.

Contrary to locally operated satellites, high accurate orbital parameters are not available for the bulk of other space objects. Currently, the TLE catalogue maintained by the USSTRATCOM constitutes the only publicly available and reasonably comprehensive orbit information. Despite evident deficiencies in the quality and timeliness of the available orbit information, it is currently a mandatory element for any operational proximity monitoring. The careful assessment of the TLE accuracy is therefore required to reveal the inherent modeling accuracy of the SGP4 analytical orbit model, as well as the orbit determination and orbit prediction accuracy for TLEs provided by USSTRATCOM.

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[1] Space Flight Technology, saika.aida@dlr.de.
[2] Space Flight Technology, michael.kirschner@dlr.de.
[3] Space Flight Technology, martin.wermuth@dlr.de.
[4] Space Flight Technology, reinhard.kiehling@dlr.de.

Even after a realistic error analysis, the exclusive use of TLE data is insufficient for a proper planning and implementation of collision avoidance maneuvers. The orbit information of a possible jeopardizing object has to be refined in due time before a predicted proximity, if a predefined threshold of collision probability or safety distance is violated. To this end, the use of radar tracking is foreseen. The orbit refinement using radar tracking is necessary for a consolidated decision and implementation of an evasive maneuver.

Following a presentation of GSOC collision avoidance procedure for LEO satellites, the paper will discuss the orbit accuracy as well as the improvement of the TLE orbit information by a radar tracking campaign. The orbit accuracy analysis is done by comparing corresponding orbit data with accurate orbit information from locally controlled space missions. The application to the collision risk monitoring system at GSOC is discussed hereafter, followed by the presentation of the monitoring system and the handling of close approaches.

II. Collision Avoidance Procedure at GSOC

GSOC has been implemented a collision avoidance system since 2008. The first version of the software for the close approach detection is running since January 2009 and operationally available since November 2009. A monitoring is currently performed twice a day in an automated process, detecting close approaches of operational LEO satellites against more than 14000 space objects listed in the TLE catalogue provided by USSTRATCOM.

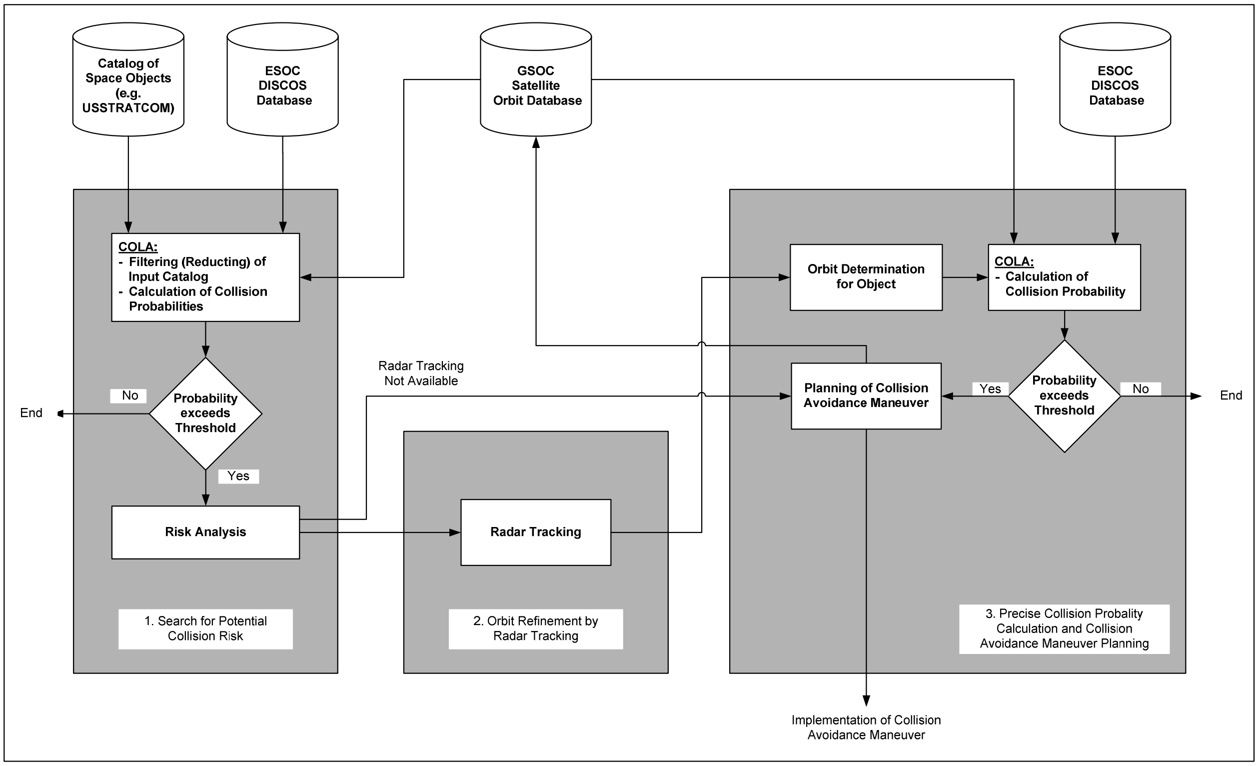


Figure 1 Collision Avoidance Procedure at GSOC

In the current collision avoidance system at GSOC (Figure 1), the procedure consists of mainly 3 steps. First, the potential collision risk of the operational satellites is detected over 7 following days using a TLE catalogue as well as precise orbit data of the operational satellites. Detected close approach events are listed in a report file, if the distance to a jeopardizing object is smaller than the pre-defined distance thresholds. The collision probability is also calculated for the potential close approach based on the method described in Ref. 1. If the resulting collision probability exceeds the probability threshold, which is currently set to 10^{-4}, the collision risk is closely evaluated by analyzing the geometry at the time of the closest approach, prediction histories among others. In case a high collision risk is expected from the analysis, the orbit refinement using a radar tracking is foreseen as the second step. The accuracy of radar tracking was investigated in Ref. 2. The close approach event is then further analyzed based on the precise and latest orbit information, and a collision avoidance maneuver is planned if required.

III. Analysis of Orbit Prediction Accuracy

In order to derive criteria for critical conjunctions an analysis for the OP accuracy was performed. First results have been given in Ref. 2.

Besides the large number of roughly 15000 catalogued objects in orbit, which requires proper search strategies for an efficient forecast of close approaches, users of the USSTRATCOM data have to cope with the limited accuracy of the provided orbit information, which is not publicly available. While an overly trust in the quality of the orbital data might result in an underestimation of the true collision risk, a pessimistic accuracy assessment would result in frequent close approach warnings. Any unnecessary collision avoidance maneuver would, in turn, notably increase the mission cost in terms of fuel consumption, reduced operational lifetime, man power and science data losses. Due to these constraints it is of advantage to have a good knowledge of the precision of the TLE orbits.

To investigate the TLE precision, model differences between the analytical SGP4 propagation and the numerical orbit propagation as well as propagation errors of ephemerides generated from USSTRATCOM TLEs and those generated by numerical orbit propagation were analyzed. The precise orbits of locally operated satellites CHAMP, GRACE-1, and TerraSAR-X (at an altitude of 320-410 km, 460-490 km and 510 km respectively) could be used to perform this analysis.

The well established OD 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.

A. Orbit Model

The differences between the two distinct orbit models, the analytical SGP4 and the numerical orbit propagator, were analyzed. The numerical orbit propagator was used to generate osculating ephemeris data, which served as measurement data for a SGP4 based OD. In other words the mean 2-line elements were determined from a best fit to the generated osculating trajectory.

The analysis was performed in two steps, where at first the mean 2-line elements were determined for fit periods of 1 to 7 days. In the second step the generated TLEs were used to propagate the orbit over up to 7 days.

For satellites operating in LEO, the atmosphere has an important influence on the evolution of an orbit. The atmospheric density itself is directly depending on the solar activity, which can fluctuate dramatically within a few days. To avoid an influence of these fluctuations, constant solar activity parameters were used for the analysis.

One main outcome of the fitting analysis was that the RMS errors in along-track, radial and normal direction are relatively constant for the different fit periods. An example of these errors is shown in Figure 2, which reflects clearly the model differences. More detailed results are shown in Ref. 2.

The main result of the propagation comparison is that a TLE fit should cover at least 2 days, otherwise the propagation of such a TLE orbit over more than 1 day makes no sense, as the error grows dramatically. Another important result is that the propagation error increases with the influence of the atmosphere, i.e. for lower altitudes or higher solar activity. For more details on this analysis please refer to Ref. 2.

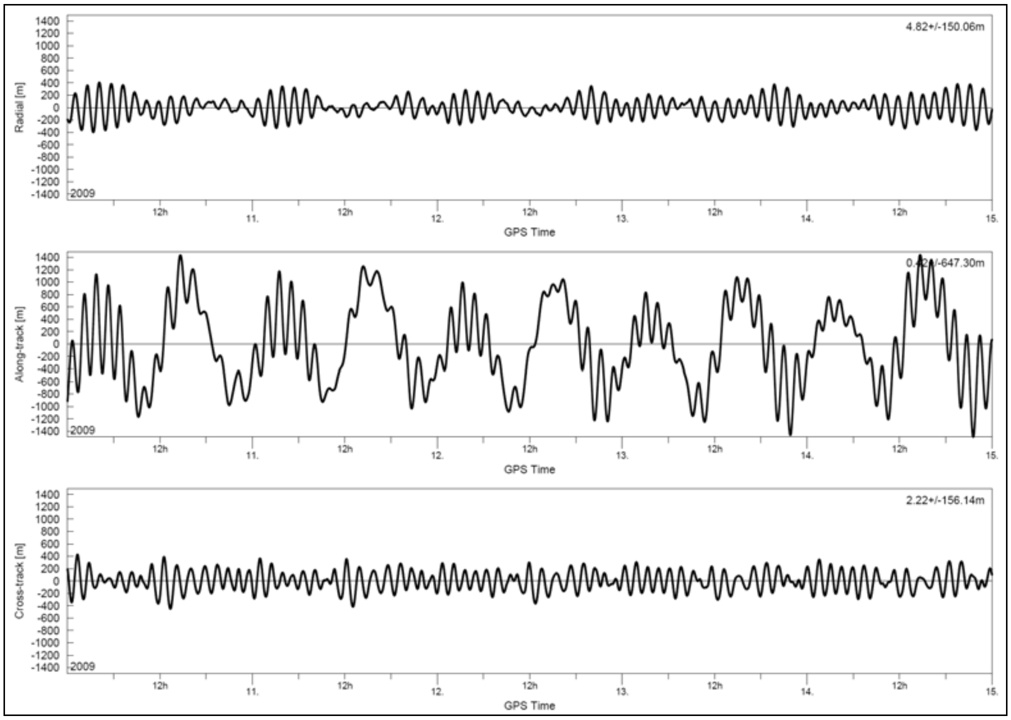


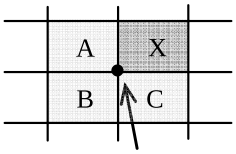
Figure 2 RTN (radial/along-track/normal) error of a 5-days-TLE-fit w.r.t. numerically propagated orbit

B. Influence of Solar Flux and Altitude on the TLE Orbit Accuracy

In the analysis of Ref. 2, errors of the propagated TLEs from POD orbits were investigated during a period of low solar flux. 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. The significant influence of the solar activity on the OP accuracy is also shown for the numerical propagation in Ref. 3. As the solar activity is slowly increasing since end of 2009, it is also important now to know more in detail the influence of the solar activity on the orbit prediction. Therefore the orbit prediction accuracy analysis was extended to get 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.

Likewise the analysis in Ref. 2, 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 orbit of CHAMP (April 2001-December 2009) and GRACE-1 (March 2002-November 2009), which are available at an interval of 30 seconds.

RMS errors sorted by the altitude and the solar flux at each POD epoch are shown in Table 1. Since data were not enough 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 (Figure 3). 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 Table 1, such extrapolated data are distinguished from the statistical results by the dark pattern.



$$\frac{A+C}{2}=\frac{B+X}{2}$$

Figure 3 Data Extrapolation

Table 1 TLE Propagation (RMS in [m])

		1 day prop					4 days prop					7 days prop				
			Altitude [km]					*Altitude [km]*					*Altitude [km]*			
R			*300-350*	*350-400*	*400-450*	*450-500*		*300-350*	*350-400*	*400-450*	*450-500*		*300-350*	*350-400*	*400-450*	*450-500*
	Flux	*-90*	356	249	234	333	*-90*	670	527	500	618	*-90*	1007	917	751	906
		90-140	257	249	213	290	*90-140*	552	511	465	562	*90-140*	1073	981	753	847
		140-190	285	278	189	376	*140-190*	581	540	434	651	*140-190*	1464	1373	1049	1064
		190-	325	317	116	315	*190-*	549	508	403	581	*190-*	1199	1107	783	930
T			*300-350*	*350-400*	*400-450*	*450-500*		*300-350*	*350-400*	*400-450*	*450-500*		*300-350*	*350-400*	*400-450*	*450-500*
	Flux	*-90*	2890	1472	983	1316	*-90*	12214	13983	6845	3845	*-90*	33897	41995	22600	8795
		90-140	2087	1567	1069	1394	*90-140*	20832	15864	9477	7227	*90-140*	65887	50026	32075	19715
		140-190	2314	1795	1678	2646	*140-190*	25942	20974	18566	15524	*140-190*	81216	65356	54208	42424
		190-	3064	2544	1415	2340	*190-*	22575	17607	15199	15564	*190-*	75632	59771	48623	47091
N			*300-350*	*350-400*	*400-450*	*450-500*		*300-350*	*350-400*	*400-450*	*450-500*		*300-350*	*350-400*	*400-450*	*450-500*
	Flux	*-90*	350	254	347	308	*-90*	401	267	355	344	*-90*	454	292	379	391
		90-140	236	309	367	293	*90-140*	247	309	349	290	*90-140*	271	325	355	309
		140-190	304	377	385	403	*140-190*	272	334	374	409	*140-190*	253	308	370	419
		190-	300	373	380	368	*190-*	274	336	376	363	*190-*	274	328	390	363

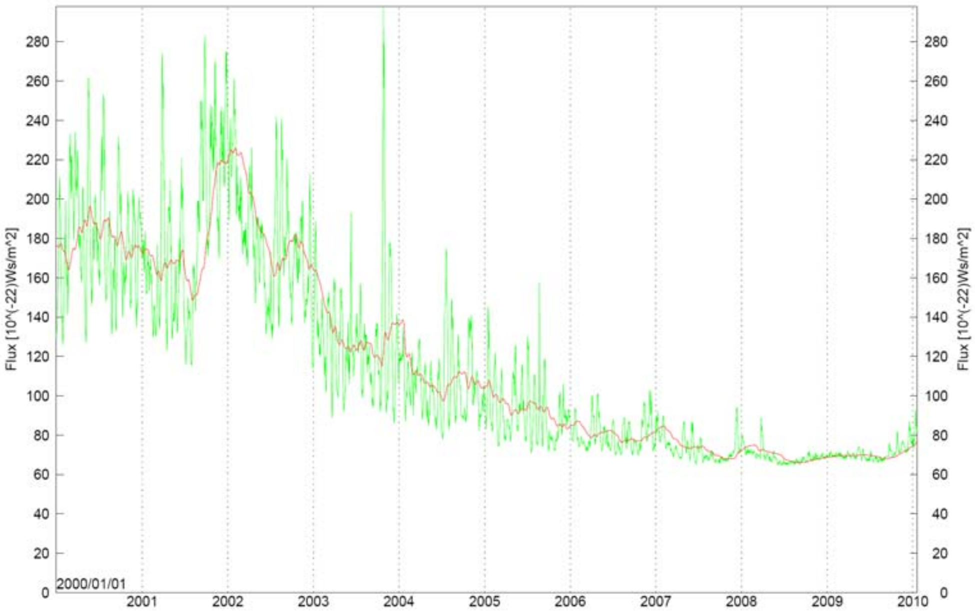


Figure 4 Solar Flux History as of January 2010

As a whole, the RMS errors of the along-track and radial components become larger at lower altitudes and also at higher solar flux periods and grows exponentially for longer prediction time. As shown in Figure 4, 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. However, at the very low altitude around 300–350 km, the accuracy could be improved as shown at the flux group <90, although other data at the higher solar flux were obtained only by extrapolation. As for the RMS error of the normal component, there is no distinct dependency on the solar flux and the altitude, but the error grows gradually with the propagation length.

C. Influence of Solar Flux and Altitude on 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 and GRACE-1. The orbits were propagated up to 7 days with the ODEM tool, and compared with the precise orbits used in B. For the numerical propagation, the predicted solar flux at the epoch of the database was used.

Table 2 Numerical Propagation (RMS in [m])

		1 day prop					4 days prop					7 days prop				
			Altitude [km]					*Altitude [km]*					*Altitude [km]*			
R			*300-350*	*350-400*	*400-450*	*450-500*		*300-350*	*350-400*	*400-450*	*450-500*		*300-350*	*350-400*	*400-450*	*450-500*
	Flux	*-90*	5	8	6	5	*-90*	34	43	24	12	*-90*	117	282	67	21
		90-140	7	10	7	6	*90-140*	60	69	40	19	*90-140*	293	458	170	52
		140-190	9	12	8	6	*140-190*	50	58	46	25	*140-190*	2126	2290	204	210
		190-	11	14	10	8	*190-*	75	84	71	50	*190-*	2042	2207	120	127
T			*300-350*	*350-400*	*400-450*	*450-500*		*300-350*	*350-400*	*400-450*	*450-500*		*300-350*	*350-400*	*400-450*	*450-500*
	Flux	*-90*	271	530	336	97	*-90*	7023	10199	6755	1670	*-90*	23958	34944	22552	5447
		90-140	464	668	466	218	*90-140*	9555	12730	9085	3798	*90-140*	29443	40479	28769	12395
		140-190	523	727	449	332	*140-190*	7468	10643	9697	5988	*140-190*	61325	72361	36506	22299
		190-	659	862	585	468	*190-*	10354	13529	12582	8874	*190-*	65638	76674	40819	26612
N			*300-350*	*350-400*	*400-450*	*450-500*		*300-350*	*350-400*	*400-450*	*450-500*		*300-350*	*350-400*	*400-450*	*450-500*
	Flux	*-90*	2	1	1	6	*-90*	5	4	4	14	*-90*	8	7	7	24
		90-140	2	1	1	6	*90-140*	5	4	4	14	*90-140*	8	8	8	24
		140-190	2	1	1	5	*140-190*	5	5	5	10	*140-190*	11	10	10	17
		190-	2	1	2	6	*190-*	5	5	6	11	*190-*	10	9	9	16

The resulting RMS errors in Table 2 show again the dominant prediction error in the along-track direction. Comparable to the TLE analysis, the radial and along-track errors become larger at the lower altitude and at the higher solar flux period, but not the case at the lowest altitude group of 300–350 km. The RMS error of the normal component doesn’t show the clear dependency on the solar flux and the altitude, but the error grows gradually with the propagation. By propagating orbits using the well-modeled propagator, errors are small especially for the radial and normal 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 lager at the higher solar flux period, but further analysis has to be done.

D. Radar Tracking

As shown in Ref. 2 the TLE orbit accuracy can be improved by a radar tracking campaign for the encountering object to the OD accuracy quality based on GPS navigation solution data. The main objective for such a campaign is the enormous reduction of the radial uncertainty by a factor of 10-30, which can lead to a reduction of the number of collision avoidance maneuvers.

IV. Application to Collision Avoidance System

The current GSOC software for the close approach detection is daily running, which performs a prediction of proximity events for operational satellites over the 7 following days.

In the current process, TLE propagation errors obtained in the analysis of Ref. 2 are used to generate the covariance matrix of space objects in the relevant altitude range. Since these orbit uncertainties were obtained based on the orbit data during the low solar activity period, they are expected to become worse when the solar activity gets higher as shown in III-B. Therefore propagation errors in Table 1 will be further implemented to provide covariance information of space objects at the corresponding solar flux as well as altitude. For operational satellites, the numerical propagation errors are available as shown in Table 2. They can be also applied as covariance information instead of propagating an initial covariance matrix, which could results in a too optimistic estimation orbit uncertainties. The collision probability is then calculated from orbital states and covariance information at the estimated collision epoch.

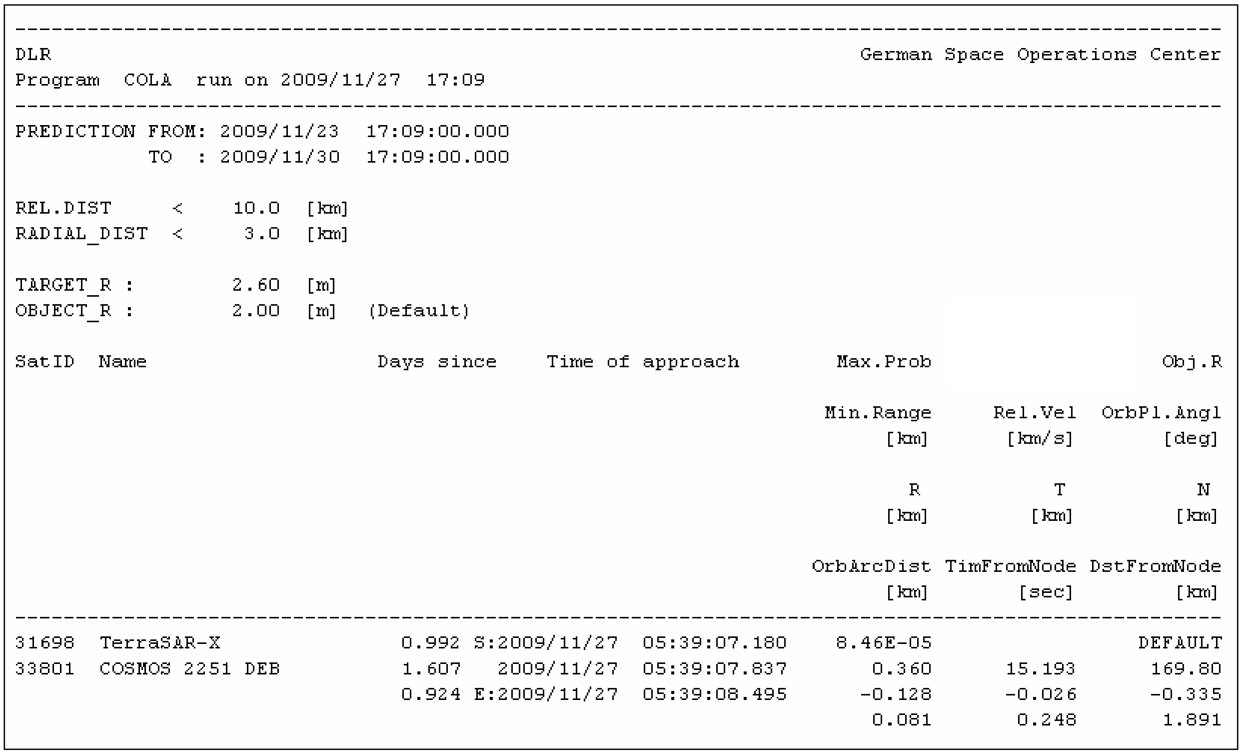
It was also found out that the numerical propagation can result in a large orbit error for the long time prediction, although it is still better than the TLE propagation. However, the accuracy in the radial and along-track direction is better for the shorter period of prediction around 2-3 days, and even better around 1-1.5 days, which is the decision point for radar tracking and the maneuver planning respectively.

In case of a high collision risk, it is planned to perform radar tracking around 1.5 days before the predicted closest approach to refine the orbit information. Since the OD quality of radar tracking data showed the same quality as that based on GPS navigation solution data, a radar tracking can be an effective way to detect the critical close approach and reduce unnecessary collision avoidance maneuvers.

V. Collision Risk Monitoring at GSOC

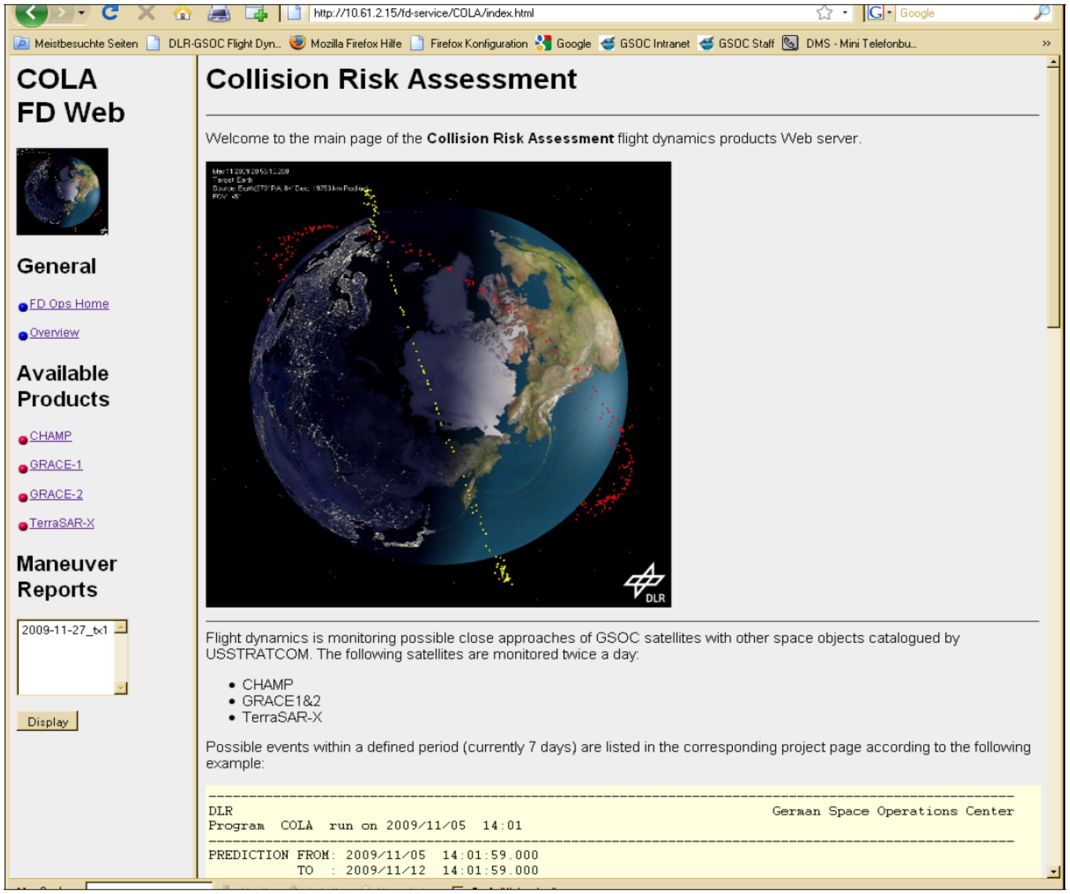
The collision risk of the operational satellites is daily monitored against space objects in the TLE catalogue. The upcoming events are listed in the report file when both distance thresholds, currently set to relative distance <10 km and radial distance <3 km, are violated. These thresholds were determined from the preliminary analysis of the TLE propagation errors. An example of the prediction results for TerraSAR-X is shown in Figure 5. Following the prediction epoch, distance thresholds and size information, close approach events are described along with the maximum probability and the close approach geometry. The important parameters for an assessment of the collision risk are the collision probability (“Max.Prob”), the radial distance between the two orbital arcs (“OrbArcDist”), which is the possible minimum distance between the two objects, the total distance (“Min.Range”) as well as the fly-by direction given by the angle between the two orbital planes (“OrbPl.Angl”). The estimated orbit uncertainty at the corresponding propagation time (“Days since”) is also considered for the risk assessment. R/T/N give the relative distances of the object in the local orbital frame relative to the own spacecraft (radial/tangential/normal). This report is updated twice a day using the latest orbit information.

The latest prediction report is available on the internal flight dynamics website, so that GSOC staff can share the information about the upcoming close approach. The main page of the GSOC collision risk assessment is shown in Figure 6. By selecting a name of the satellite on the left-hand side, a prediction report for the corresponding satellite is shown. Reports for the past maneuvers can be also shown, containing the event summary, the collision probability history, and details of the implemented maneuvers.



```
----------------------------------------------------------------------------------------------------
DLR                                                                   German Space Operations Center
Program  COLA  run on 2009/11/27  17:09
----------------------------------------------------------------------------------------------------
PREDICTION FROM: 2009/11/23  17:09:00.000
           TO  : 2009/11/30  17:09:00.000

REL.DIST     <    10.0  [km]
RADIAL_DIST  <     3.0  [km]

TARGET_R :        2.60  [m]
OBJECT_R :        2.00  [m]  (Default)

SatID  Name                   Days since    Time of approach        Max.Prob                   Obj.R

                                                                   Min.Range     Rel.Vel  OrbPl.Angl
                                                                        [km]      [km/s]       [deg]

                                                                          R           T           N
                                                                        [km]        [km]        [km]

                                                                  OrbArcDist TimFromNode DstFromNode
                                                                        [km]       [sec]        [km]
----------------------------------------------------------------------------------------------------
31698  TerraSAR-X               0.992 S:2009/11/27  05:39:07.180    8.46E-05                 DEFAULT
33801  COSMOS 2251 DEB          1.607   2009/11/27  05:39:07.837       0.360      15.193      169.80
                                0.924 E:2009/11/27  05:39:08.495      -0.128      -0.026      -0.335
                                                                       0.081       0.248       1.891
```

Figure 5 Results of Close Approach Prediction



COLA
FD Web

General

- FD Ops Home
- Overview

Available Products

- CHAMP
- GRACE-1
- GRACE-2
- TerraSAR-X

Maneuver Reports

2009-11-27_tx1

Collision Risk Assessment

Welcome to the main page of the **Collision Risk Assessment** flight dynamics products Web server.

Flight dynamics is monitoring possible close approaches of GSOC satellites with other space objects catalogued by USSTRATCOM. The following satellites are monitored twice a day:

- CHAMP
- GRACE1&2
- TerraSAR-X

Possible events within a defined period (currently 7 days) are listed in the corresponding project page according to the following example:

```
------------------------------------------------------------------------------------------
DLR                                                              German Space Operations Center
Program  COLA  run on 2009/11/05  14:01
------------------------------------------------------------------------------------------
PREDICTION FROM: 2009/11/05  14:01:59.000
           TO  : 2009/11/12  14:01:59.000
```

Figure 6 Snapshot of GSOC’s Website for Collision Risk Assessment

VI. Handling of Close Approach

If a maximum probability exceeds the current probability threshold of 10^{-4}, the event is analyzed closely to assess its criticality. When a critical approach is expected after the analysis, a radar tracking campaign is performed if available to refine orbit information of the encountering object. The collision risk is then assessed again using the refined and latest orbit information, and collision avoidance maneuvers are planned if necessary.

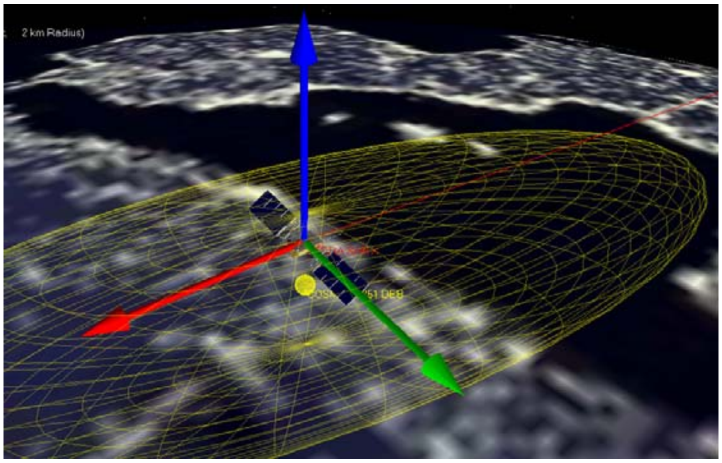


Figure 7 Visualization Tool

A. Risk Analysis

In case the probability threshold is violated, the criticality of the event is assessed carefully by computing the actual collision probability and also by analyzing the geometry at the closest approach and the TLE of the encountering object. Some tools for the event analysis are currently under development, such as 3D visualization and TLE history analysis. Figure 7 is a snapshot of the visualization tool, where the satellite and the encountering objects are shown along with the combined covariance ellipsoid. Such tools are helpful for the better understanding of the close approach geometry and accordingly for the implementation of collision avoidance maneuvers. The TLE history has also to be analyzed, since the orbit information of each TLE is not always consistent. Therefore the past TLEs of the encountering object are assessed along with the latest TLE and used for computation of the collision probability and the closest position.

B. Collision Avoidance Maneuver for TerraSAR-X

Table 3 TerraSAR-X Close Approach

Object		COSMOS 2251 DEB (ID 33801)
Object size	[m]	Unknown (RCS 0.037)
Time of the closest approach	[UTC]	2009/11/27 05:39:07.837
Min. distance	[km]	0.360
Relative position	[km]	-0.128, -0.026, -0.035
Orbital arc distance	[km]	0.081
Relative velocity	[km/s]	15.193
Angle of orbital plane	[deg]	169.80

On November 27 2009, TerraSAR-X had a close approach against a Cosmos 2251 debris, which resulted in the first report of the collision avoidance maneuver since the operational collision monitoring system started. As shown in Table 3, the distance of two orbital arcs was about 80 m, and all components of the relative position were within the estimated orbit uncertainty of the encountering object, which were ~0.25 km in radial, ~1.70 km in along-track, and ~0.45 km in normal direction. The collision probability history is shown in Figure 8, where the probability was approaching the threshold of 10^{-4}. Although it was once lowered 1.5 day before the time of the closest approach, the latest prediction showed the close probability again. Therefore an avoidance maneuver was planned to enlarge the radial distance by nearly 250 m. Two maneuvers were performed half an orbit before and after the closest approach in the along-track direction. The first maneuver was for the altitude increase, and the second one was for the altitude decrease, which was necessary to come back to the nominal orbit, and each maneuver was about 8 cm/s. The collision probability after the maneuver is also shown in Figure 8, where the probability was lowered enough from the threshold.

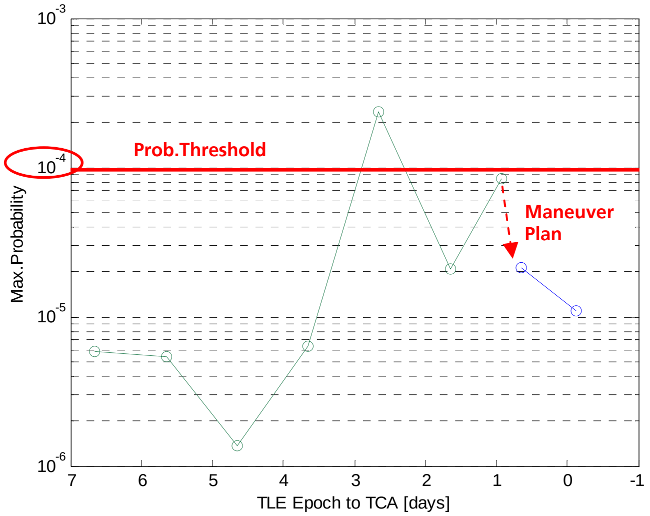


Figure 8 Probability History

VII. Conclusion

At GSOC, the collision avoidance system is operationally available since November 2009. The monitoring is currently running twice a day in an automated process, detecting close approaches of LEO satellites operated at GSOC against space objects in the TLE catalogue provided by USSTRATCOM.

For the proper collision risk assessment, the orbit precision and the TLE orbit refinement by a radar tracking campaign were discussed. In the orbit precision analysis, the SGP4 and numerical propagation were compared with POD orbits, and the dependency of the RMS error on the solar flux as well as the altitude was shown according to the orbit propagation length. The application of these results into the collision avoidance system at GSOC was addressed and the collision risk monitoring as well as the close approach event handling was presented.

References

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