HANDLING OF CONJUNCTION WARNINGS IN EUMETSAT FLIGHT DYNAMICS

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Abstract: *Metop is the space segment of the EUMETSAT Polar System (EPS), Europe's first polar orbiting operational meteorological satellite system.*
Since end of 2008, EUMETSAT has been receiving conjunction warning messages from JSpOC (Joint Space Operations Centre of the US Air-Force) for Metop-A based on the high accuracy orbits estimated by the US space surveillance network.
EUMETSAT Flight Dynamics team started then developing a set of software prototypes and operational procedures to properly handle the conjunction warning messages to first identify conjunctions with unacceptable level of collision risk and then, if deemed necessary, compute the optimal maneuver permitting to reduce the collision risk to negligible values.
The paper will present in detail the received data and the analysis performed to evaluate their suitability for operational use, the functionalities of the developed software prototypes, the status of the operational procedures and the results obtained for the most interesting operational cases.

Keywords: *Conjunction warning, risk assessment, avoidance maneuver*

1. Introduction

Metop is the space segment of the EUMETSAT Polar System (EPS), Europe's first polar orbiting operational meteorological satellite system. On 19th October 2006, the first Metop satellite, Metop-A, was successfully launched from the Baikonur Cosmodrome by a Soyuz/Fregat launcher.

The definition of a collision avoidance system for Metop-A was de-scoped during the Ground Segment development phase; at this point in time the available technologies, based only on two lines elements (TLE), were considered insufficient to provide a satisfactory risk mitigation without a large impact on satellite operations, fuel budget and mission return (see [1]).

On Christmas 2008, however, EUMETSAT received a first conjunction warning message from JSpOC (USSTRATCOM's Joint Space Operations Centre) for Metop-A. Thanks to the support provided by the National Oceanic and Atmospheric Administration (NOAA), EUMETSAT's U.S. partner, and the excellent support provided by the JSpOC personnel, the service was improved remarkably since then: currently EUMETSAT is daily receiving conjunction screening messages both through NOAA (since mid of 2009) and directly from JSpOC (since end of 2010), identifying all objects flying close to Metop-A. These messages are not based on TLE information but on the high accuracy orbit estimated by the US space surveillance network; their accuracy is therefore more than sufficient to provide a clear understanding of the real risk on the spacecraft and to define efficient mitigation action. Moreover, detailed data, including full covariance information, is provided via the Space-Track website for those objects getting dangerously close to the Metop-A satellite (since end of 2010).

Detailed analyses have been performed on detailed Metop-A conjunction data generated by JSpOC (during the first months of 2009 some preliminary sets of data have been delivered to EUMETSAT), confirming the excellent performances of the service.

EUMETSAT Flight Dynamics team developed a set of software (SW) prototypes and operational procedures to properly handle the conjunction warning messages to first identify conjunctions with unacceptable level of collision risk and then, if deemed necessary, compute the optimal maneuver permitting to reduce the collision risk to negligible values. The overall Flight Dynamics process can be summarized in four steps:

1) analysis of the conjunction geometry: the depth of intrusion (DoI) of the conjunction is computed (see Section 3.1) conjunctions presenting a DoI below 1 deserve detailed analysis;
2) computation of the probability of collision (PoC); if the computed PoC (see Section 3.2) goes over a certain threshold (1 / 10000) then a collision avoidance maneuver is prepared;
3) computation of collision avoidance maneuver: the optimal maneuver reducing the residual error to negligible values (below 1 / 10^9) is computed (see Section 3.3);
4) post-maneuver analysis: it is ensured that the selected collision avoidance maneuver does not cause an unacceptable increase of collision risk with the other objects (see Section 3.4).

Once ready, the maneuver can be uploaded to the satellite; a special system level procedure, ensuring minimum impact in the mission, was developed by the satellite team for that (see [2]). Up to today no avoidance maneuver was necessary for the Metop-A satellite; few times, however, the observed risk was high enough to require Flight Dynamics intervention; in all cases the last received data permitted to exclude the need of a maneuver and the procedure was stopped (see section 4.3).

2. Received data

EUMETSAT Flight Dynamics receives daily the following screening messages via e-mail:

1) Conjunction Assessment Summary Reports through NOAA (see Section 2.1);
2) Conjunction Assessment Results directly from JSpOC (see Section 2.2).

Within these data files all objects flying close to Metop-A (with miss-distance respectively within 1km and 5km for 5 days in the future) are identified.

In case an object with miss-distance from the Metop-A satellite within a so-called “high risk ellipsoid” (HRE, see Section 2.3) is detected then detailed data, including full covariance information for both the asset (Metop-A) and the offending object, are provided by JSpOC; these data are contained into a so-called Conjunction Summary Message (see Section 2.3).

2.1. NOAA Conjunction Assessment Summary Reports

Conjunction Assessment Summary Reports for Metop-A, received daily through NOAA, are generated, based on JSpOC data, by “a.i solutions”, subcontractors of Goddard Space Flight Center (GSFC); these messages contain:

- All objects with miss-distance within 1km for 5 days in the future
- Time of close approach (TCA)
- Total miss-distance and components in the asset orbital frame
- Probability of collision, based on 20m collision radius for the asset
- Evolution in time of the provided parameters

It is to be noted that neither velocity nor covariance information is provided; nevertheless this information permits already to perform interesting analysis on the conjunction:

- analysis of the conjunction geometry (see Section 3.1);
- preliminary estimation of the accuracy of the object orbit (see Section 3.1);
- preliminary evaluation of the level of risk from the provided PoC, by scaling down the provided result with the square of ratio of the assumed radius and the real radius of the asset.

That report is provided in PDF format; therefore its suitability for automatic operation is questionable. On another hand, thanks to its good readability, it is suitable for manual operations; that message is therefore also delivered daily to the on-duty Metop-A satellite controller, who, based on that data, can trigger intervention of the on-duty Flight Dynamics engineer (see Section 4.2). A sample of this message is presented in Fig. 1.

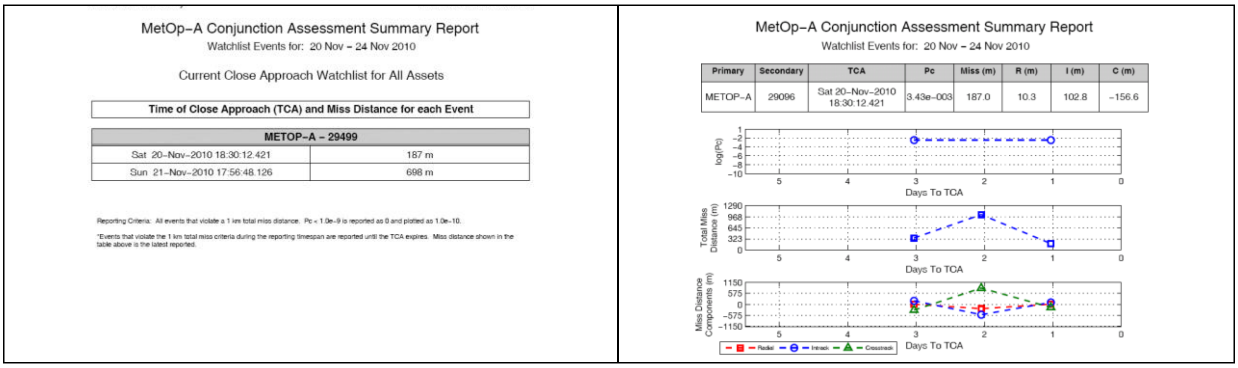

Figure 1. NOAA Conjunction Assessment Summary Report Sample

2.2. JSpOC Conjunction Assessment Results

Conjunction Assessment Results for Metop-A received daily directly from JSpOC contain:

- All objects with miss-distance within 5km for 5 days in the future
- Time of close approach (TCA)
- Total miss-distance and components in the asset orbital frame

Their content is very similar to the one of the NOAA Conjunction Assessment Summary Reports (see Section 2.1); therefore the first two analyses presented there can be performed using these data too; being the screening volume sufficiently large, these data are also used to assess the effect of a collision avoidance maneuver on future conjunctions (see Section 3.4).

Being the message provided in plane ASCII format, it is suitable for automatic operations. A sample of this message is presented in Fig. 2.

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METOP-A SP Screening Results for 19Nov
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CONJ#  Conjunction Time (UTC)  Miss (Radial, In-Track, and Cross-Track)

 4653  21 NOV/21:35:12.077     2563m (1429.7 1963.3 821.1)
29096  20 NOV/18:30:12.421     187m (10.3 102.8 -156.6)
31535  23 NOV/00:12:45.895     4218m (410.5 -611.2 -4153.6)
31714  23 NOV/23:28:03.832     4542m (4074.0 1859.1 759.7)
32120  21 NOV/14:00:08.900     1093m (203.0 1067.9 -123.2)
33636  21 NOV/08:58:04.112     4262m (-628.5 -3637.8 -2131.3)
33730  20 NOV/08:09:34.385     4345m (1322.3 -3628.7 -1992.2)
33849  21 NOV/17:56:48.126     698m (-626.5 16.4 309.2)
33849  21 NOV/19:38:30.728     4030m (727.0 -194.9 -3959.6)
33849  21 NOV/16:15:05.471     4762m (-1997.5 213.8 4318.6)
33865  22 NOV/01:11:45.678     3728m (2724.1 153.9 -2540.4)
34468  20 NOV/08:23:03.221     3046m (-3004.6 237.0 -445.9)
34508  21 NOV/14:06:05.521     3403m (-3399.8 -32.5 -145.2)
34735  24 NOV/15:25:57.421     2901m (-353.9 -1169.1 2631.8)
35000  20 NOV/08:23:03.965     4134m (-3487.7 -1011.3 1976.3)
36195  21 NOV/12:18:05.068     4101m (770.7 -3676.4 1646.7)
36542  22 NOV/17:22:20.835     3173m (2739.1 -103.8 1600.2)
81322  22 NOV/01:44:38.452     2095m (1178.3 -1601.7 -660.1)
87884  24 NOV/04:30:13.816     4515m (-4460.3 197.0 -675.4)
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Figure 2. JSpOC Conjunction Assessment Results Sample

2.3. JSpOC Conjunction Summary Messages

A Conjunction Summary Message (CSM) is generated by JSpOC for any offending object whose miss-distance falls within a so-called "high risk ellipsoid" around the Metop-A satellite defined as:

- semi-major axis in the along-track direction in Metop-A orbital frame of 2500m;
- semi-major axis in the cross-track direction in Metop-A orbital frame of 1250m;
- semi-major axis in the radial direction in Metop-A orbital frame of 300m;

One file is generated for each identified conjunction and posted by JSpOC via the Space-Track website in the partition dedicated to the EUMETSAT Flight Dynamics user. At the same time an e-mail is sent to the EUMETSAT Flight Dynamics team to make aware of the availability of the data the on-duty engineer, who can then collect them manually from the Space-Track website.

A Conjunction Summary Message contains, for the identified conjunction:

- Time of close approach (TCA)
- Total miss-distance and components in the asset orbital frame
- Relative velocity and components in the asset orbital frame
- Full state vector for the asset and the object at TCA
- Full covariance matrix of the position for the asset and the object at TCA
- Statistic information on available, used and rejected observations in the orbit determination
- Information on the age of the last accepted observation in the orbit determination
- Information on optimal and used span in the orbit determination
- Information on the residual of the observations used in the orbit determination
- Information on the dynamic model used in the orbit determination
- Information on the size of the asset and the object

The complete orbital information available (state vector and covariance matrix) permits to perform a very accurate analysis of the probability of collision of the offending object with the Metop-A satellite (see Section 3.2). Moreover, the auxiliary information on the performed orbit determination provides a clear indication of the reliability of the data and thus of the computed PoC.

Being the message provided in XML format, it is suitable for automatic operations. A sample of this message as shown in the Space-Track website is presented in Fig. 3 (header) and Fig. 4 (body).

Conjunction Summary Report v1.0	
CLASSIFICATION:	UNCLAS
SUBJECT:	METOP-A
MESSAGE TYPE:	REAL
CREATION DATE:	2010-11-19 17:58:24
FROM:	CMOC, JSpOC
MESSAGE VERSION:	CSM V1.0, Derived From: OCM V3.0
TIME OF CLOSEST APPROACH:	2010-11-20 18:30:12.421
MISS DISTANCE: (M)	187
RELATIVE SPEED: (M/S)	12545
RELATIVE POSITION (M)	10.30 102.80 -156.60
RELATIVE VELOCITY (M/S)	74.30 -10594.00 -6720.10
JSpOC Unique ID	20103238036
Notes	NULL

Figure 3. JSpOC Conjunction Summary Message (CSM) Header

Primary Object	
CATALOG NUMBER:	29499
INTERNATIONAL DESIGNATOR:	2006-044A
COMMON NAME:	METOP-A
TIME OF LAST ACCEPTED OBSERVATION:	Less Than (<) 24 Hours
RECOMMENDED LENGTH OF UPDATE INTERVAL FOR DIFFERENTIAL CORRECTION:	3.47
ACTUAL OBSERVATION SPAN USED FOR DIFFERENTIAL CORRECTION:	3.47
PERCENTAGE OF RESIDUALS USED FROM THE ACTUAL DIFFERENTIAL CORRECTION SPAN:	97.7%
NUMBER OF OBSERVATIONS AVAILABLE IN THE DIFFERENTIAL CORRECTION SPAN:	1169
NUMBER OF OBSERVATIONS USED IN THE DIFFERENTIAL CORRECTION SPAN:	1155
APOGEE: (KM)	818
PERIGEE: (KM)	808
INCLINATION: (DEGREES)	98.7
RADAR CROSS SECTION: (M^2)	Large (> 1m sq)
WEIGHTED ROOT MEAN SQUARED FROM THE LATEST DIFFERENTIAL CORRECTION	0.9
BALLISTIC COEFFICIENT (M^2/KG)	0.030714
ENERGY DISSIPATION RATE (WATTS/KG)	2.6324e-05
SOLAR RADIATION COEFFICENT	0.019095
GEOPOTENTIAL MODEL	EGM-96 36Z,36T
DRAG MODEL	JACCHIA70DCA
LUNAR SOLAR PERTURBATION	ON
SOLAR RADIATION PRESSURE PERTURBATION	ON
SOLID EARTH TIDES PERTURBATION	OFF
IN-TRACK THRUST PERTURBATION	OFF
EFG POSITION (M)	2234478.80 735336.68 6795962.46
EFG VELOCITY (M/S)	-4787.57 -5390.52 2153.09
PRIMARY OBJECT COVARIANCE: (1,1) TO (6,6) (M^2, M^2/S, M^2/S^2)	

U	V	W	Udot	Vdot	Wdot
7.692	-.953	0.997	0	0	0
-.953	245.6	0.00559	0	0	0
0.997	0.09559	1.786	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0

Secondary Object	
CATALOG NUMBER:	29096
INTERNATIONAL DESIGNATOR:	1993-016AK
COMMON NAME:	SL-16 DEB
TIME OF LAST ACCEPTED OBSERVATION:	Greater Than (>) 48 Hours
RECOMMENDED LENGTH OF UPDATE INTERVAL FOR DIFFERENTIAL CORRECTION:	27.78
ACTUAL OBSERVATION SPAN USED FOR DIFFERENTIAL CORRECTION:	27.78
PERCENTAGE OF RESIDUALS USED FROM THE ACTUAL DIFFERENTIAL CORRECTION SPAN:	100%
NUMBER OF OBSERVATIONS AVAILABLE IN THE DIFFERENTIAL CORRECTION SPAN:	36
NUMBER OF OBSERVATIONS USED IN THE DIFFERENTIAL CORRECTION SPAN:	34
APOGEE: (KM)	856
PERIGEE: (KM)	696
INCLINATION: (DEGREES)	70.9
RADAR CROSS SECTION: (M^2)	Small (<0.1m sq)
WEIGHTED ROOT MEAN SQUARED FROM THE LATEST DIFFERENTIAL CORRECTION	1.5
BALLISTIC COEFFICIENT (M^2/KG)	0.578636
ENERGY DISSIPATION RATE (WATTS/KG)	0.00075432
SOLAR RADIATION COEFFICENT	0.237128
GEOPOTENTIAL MODEL	EGM-96 36Z,36T
DRAG MODEL	JACCHIA70DCA
LUNAR SOLAR PERTURBATION	ON
SOLAR RADIATION PRESSURE PERTURBATION	ON
SOLID EARTH TIDES PERTURBATION	OFF
IN-TRACK THRUST PERTURBATION	OFF
EFG POSITION (M)	2234306.60 735375.90 6796025.79
EFG VELOCITY (M/S)	-2534.61 6791.52 172.86
SECONDARY OBJECT COVARIANCE: (1,1) TO (6,6)i (M^2, M^2/S, M^2/S^2)	

U	V	W	Udot	Vdot	Wdot
1357	59410	610	0	0	0
59410	9.579e+06	2608	0	0	0
610	2608	542.6	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0

Figure 4. JSpOC Conjunction Summary Message (CSM) Body

Several analyses have been performed on the data, which permitted to characterize their quality and internal consistency (see Section 2.4).

2.4. Analysis of JSpOC Data Quality

These analyses were performed on the trial data provided by JSpOC in the first quarter of 2009.

The accuracy of the Metop-A orbit computed by JSpOC is directly computed by comparison with the operational orbit, whose accuracy is of the order of 1 meter (GPS based); these differences are correlated with the time interval between the epoch of the determined vector and the TCA. Moreover, the reliability of the Metop-A covariance is also assessed by comparison of the orbital difference computed above with the covariance itself. The results are presented in Fig.5.

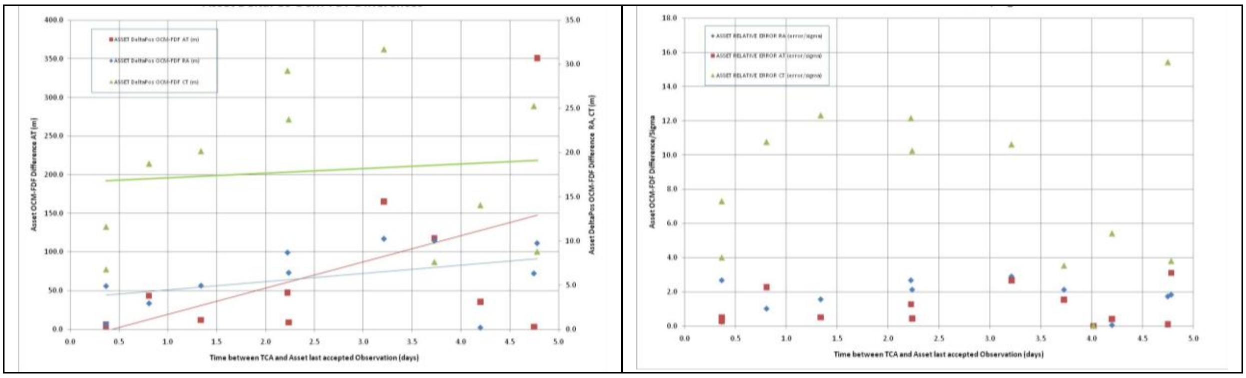

Figure 5. Metop-A Orbit and Covariance assessment

It can be observed that the differences in orbit are quite limited, above all for determination times sufficiently close to the TCA, as the error is decreasing the closer we get to TCA (left); for around two days of propagation the differences are below 50, 10 and 30 meters in along track, radial and cross-track respectively. When these differences are compared with the covariance in the same direction along-track and radial are well confined in the 3-sigma region (right), demonstrating the reliability of the covariance information. Much larger values are observed for the cross-track, very probably due to the fact that the Earth Orientation Parameters used by EUMETSAT are slightly different from those used by JSpOC; nevertheless, being the cross-track covariance the one with less importance in the probability computation, the observed differences are considered as acceptable.

For the offending object the consistence between position and covariance is assessed by computation of the displacement of the object in its own orbital frame between two consecutive datasets and comparison with the reported covariance. The results are presented in Fig.6.

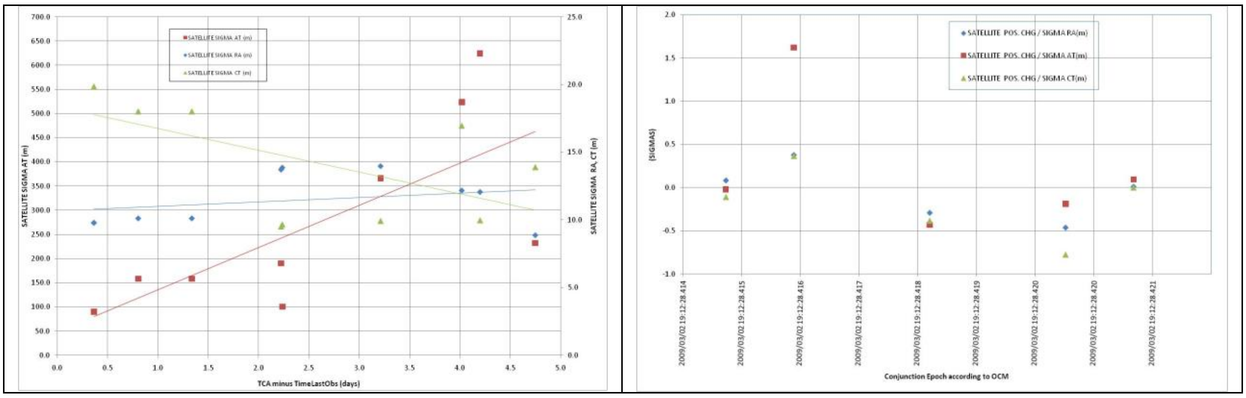

Figure 6. Offending object Orbit and Covariance assessment

It can be observed that the reported covariance decreases the closer we get to the TCA, as the object observability improves and the deterioration due to propagation decreases (left); the displacement of the object in its orbital frame between two consecutive datasets is always well bounded within the 3-sigma region (right), proving the reliability of the provided information.

3. Conjunction Analysis Process

For analyzing the data received from JSpOC two prototype tools have been developed by the EUMETSAT Flight Dynamics team using Visual Basic embedded in Excel:

- First filter tool, used for the analysis of the conjunction geometry (see Section 3.1) and the post maneuver analysis (see Section 3.4)
- Probability of collision tool, used for the PoC computation (see Section 3.2) and the computation of the collision avoidance maneuver (see Section 3.3)

3.1. Analysis of the Conjunction Geometry

For all conjunctions reported in the latest received JSpOC Conjunction Assessment Results file (or NOAA's Summary Report, if JSpOC's file is not available), the trajectory of the Metop-A spacecraft within the orbital frame of the object is computed. In order to reconstruct the object's velocity, not available in the screening messages, the following assumptions are made:

- Orbital velocity of the object same as of Metop-A (around 7.4km/s)
- No relative radial velocity

These assumptions, corresponding to assuming the object flying on a nearly circular orbit, are nearly always verified and permit to compute geometrically the velocity of the object in the along-track/cross-track plane of Metop-A with good accuracy; being the impact velocity normal to the miss-distance, the object velocity is the mirror image of the Metop-A velocity with respect to the miss-distance. It is then straight forward to compute the relative velocity of the Metop-A satellite in the object reference frame and generate the Metop-A trajectory in this frame.
This representation, in comparison with the standard representation of approach direction of the object within the asset orbital frame, permits to better understand how deep the spacecraft itself

cruises through the object covariance ellipsoid (static in the object frame). For all objects a reference covariance of 250m, 2000m and 250m in the radial, along-track and cross-track direction is assumed. As a risk factor the so-called depth of intrusion (DoI), measuring the scale factor to be applied to the object covariance ellipsoid in order to have the spacecraft trajectory tangent to it, is used. The overall process is described in Fig. 7 (a case with no radial separation is presented).

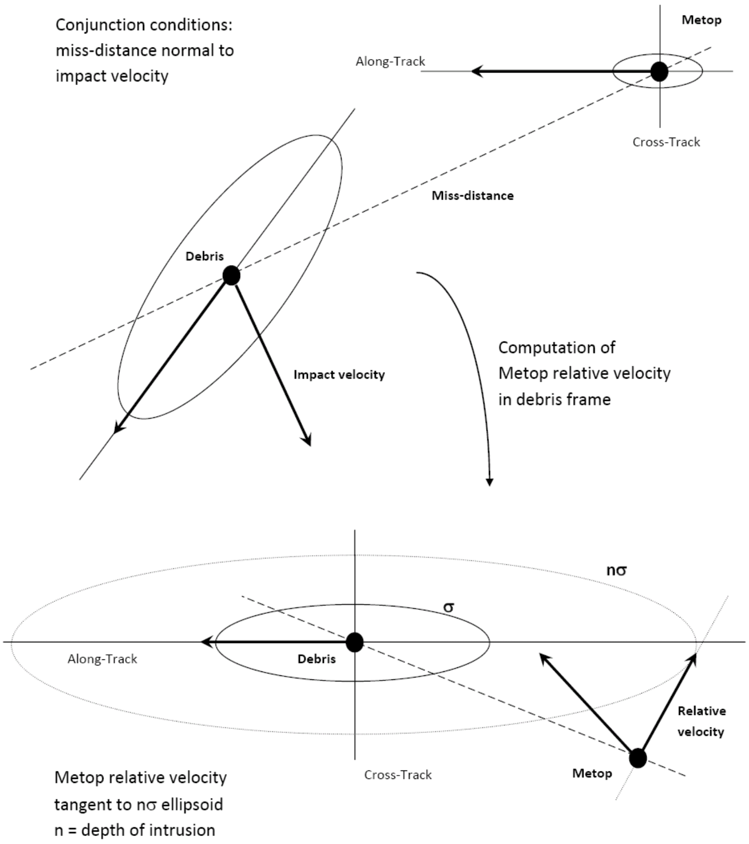

Figure 7. Depth of Intrusion Process description

Conjunctions having a depth of intrusion below 1 deserve a deeper analysis (see Section 3.2).

Applying a similar procedure it is possible to perform a preliminary estimation of the accuracy of the object orbit, even without any covariance information; the displacement of the object in its own frame can be computed from miss-distance data from consecutive screening messages only, if accurate timing information on the TCA is available and assuming the displacement of the asset negligible, as shown in Fig. 8.

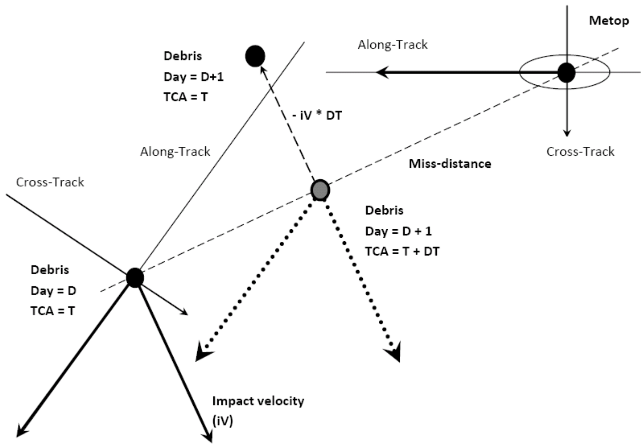

Figure 8. Computation of Object Displacement in its Orbital Frame

An excellent match can be observed with the displacement computed from the full state vector of the object (see Section 2.4). Being this displacement correlated with its covariance (see Section 2.4), then an indication of the covariance of the object can be derived.

3.2. Computation of the Probability of Collision

The probability of collision is computed for those events having a depth of intrusion below 1. The dimensions of the “high risk ellipsoid” have been tuned to ensure that it contains all objects with depth of intrusion below 1; in this manner a CSM should be always available for the PoC computation.

For the PoC computation the standard Alfriend’s approach (see [4]), the same used by the Centre National d'Études Spatiales (CNES), European Space Operations Centre (ESOC) and Goddard Space Flight Center (GSFC) is taken: the combined covariance ellipsoid of both offending object and asset is projected in the collision plane along the impact velocity; then the probability computation is performed on the collision plane by integration of the probability density over the combined impact area on the collision plane itself. The process is depicted in Fig. 9.

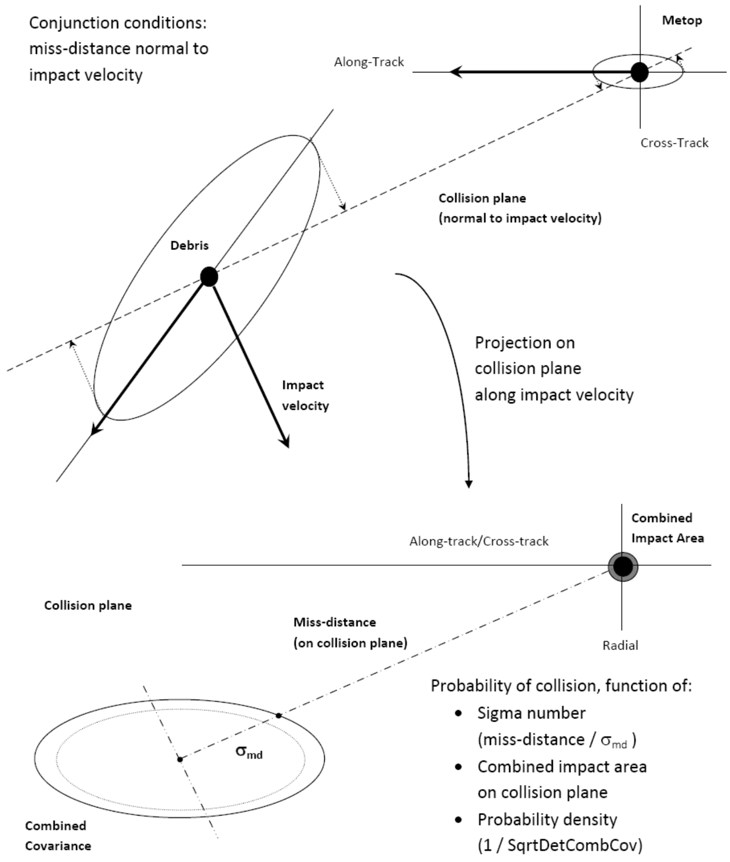

Figure 9. Computation of Probability of Collision

As covariance information is often not available, at least not in all directions, an analysis of worst case is performed by scattering the size of the covariance ellipsoid of the object in the three orbital directions around reference values derived from the analysis performed on the data received by JSpOC in 2009 (see Section 2.4).

If only the covariance in the radial direction is known (as was the case for critical conjunctions before availability of the CSM), the scattering is performed only on the two remaining orbital directions, assuming that covariance in these directions is linked to the one in the radial direction (cross-track covariance having the same order of magnitude as the radial and along-track covariance being between one and two orders of magnitude larger).

Moreover, accurate computation of the Metop-A surface projected on the collision plane is performed, taking into account the commanded satellite attitude and the solar panel rotation at TCA.

The PoC reported in NOAA Conjunction Assessment Summary Reports can be used, when available (not all the events in the "high risk ellipsoid" are within one km), as a sanity check of the computed PoC, by scaling the obtained result with the ratio of the assumed impact area; normally very consistent results are obtained.

Cross-comparison campaigns have been successfully conducted with ESOC, CNES and GSFC. Little differences have been identified due to the different way the probability is integrated in the impact area; whereas ESOC, CNES and GSFC perform an exact integration of the probability density on the impact surface, EUMETSAT perform an approximated integration considering a fixed value equal to the probability density in the centre of the combined impact area; therefore EUMETSAT results are over-optimistic for conjunctions where the miss-distance and the impact area radius are of similar size. In order to get to more conservative results, the probability density at the closer edge of the impact area can be considered in these cases.

If the PoC is higher than 1/10000, a collision avoidance maneuver is computed (see Section 3.3).

3.3. Computation of Collision Avoidance Maneuver

The effect of a Metop-A maneuver in the conjunction geometry can be modeled using the Clohessy-Whiltshire equations (see [5]). These equations describe the evolution of the position of a spacecraft subject to a maneuver with respect to the position of the same spacecraft in unperturbed evolution in the orbital frame of the unperturbed spacecraft, as depicted in Fig. 10.

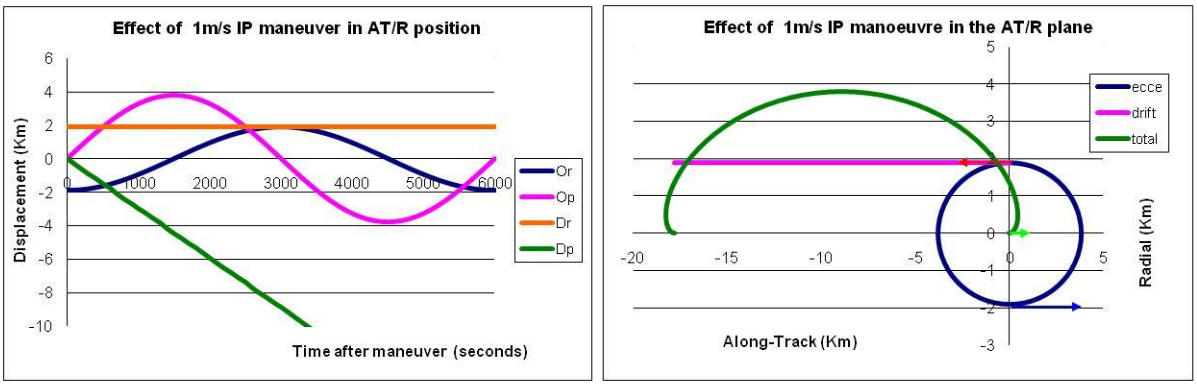

Figure 10. Maneuver effects on Orbital Evolution (1m/s along-track maneuver)

A maneuver in along-track Δv_{at} causes a change in semi-major axis Δa_{at} proportional to the size of the maneuver and a correlated change in eccentricity Δe_{at} ($\Delta a_{at} = a\Delta e_{at}$): therefore the following perturbations are observed in the satellite position:

- a displacement in radial position Δr_{at} equal to Δa_{at} (~1.9km for $\Delta v_{at} = 1.0$m/s)
- an oscillation in radial position Or_{at} with orbital pulsation and amplitude equal to $a\Delta e_{at}$ and thus to Δa_{at} (minimum at maneuver time to compensate the radial displacement above)
- a displacement in along-track position Δp_{at} proportional to Δa_{at} and thus to Δv_{at} and to the time elapsed from the maneuver (~17.8km for $\Delta v_{at} = 1.0$m/s after one orbit)
- an oscillation in along-track position Op_{at} with orbital pulsation and amplitude equal to $2a\Delta e_{at}$ and thus to $2\Delta a_{at}$ (null at maneuver time)

A maneuver in radial Δv_r causes a change in eccentricity Δe_r proportional to the size of the maneuver (half of eccentricity change caused by a maneuver in along-track of the same size and with π/2 of perigee shift): therefore the following perturbations are observed in the satellite position:

- an oscillation in radial position Or_r with orbital pulsation and amplitude equal to $a\Delta e_r$ (~0.95km for Δv_r = 1.0m/s, null at maneuver time)
- a displacement in along track position Δp_r equal to $-2a\Delta e_r$
- an oscillation in along-track position Op_r with orbital pulsation and amplitude equal to $2a\Delta e_r$ (maximum at maneuver time to compensate the along-track displacement above)

A maneuver in cross-track Δv_{ct} causes a change in inclination Δi proportional to the size of the maneuver: therefore the following perturbation is observed in the satellite position:

- an oscillation in cross-track position Oc_{ct} with orbital pulsation and amplitude equal to $a\Delta i$ (~0.95km for Δv_{ct} = 1.0m/s, null at maneuver time)

It is therefore possible to compute the change of position of the asset at TCA in its frame assuming a maneuver occurring a certain number of orbits (not necessarily as an integer) before TCA itself; the new geometry with respect to the offending object can therefore be easily computed. Also the degradation of the covariance of the satellite at TCA caused by the maneuver execution uncertainties can be modeled using the same equations.

The computation of the post maneuver probability of collision based on the new position and covariance of the asset can be performed with the same procedure described in Section 3.2. It is important to notice that the standard conjunction condition of miss-distance normal to the impact velocity is no more verified; however, being the change in impact velocity and TCA negligible, the PoC computation, based on projection along the impact velocity, is only marginally affected.

This approach permits to evaluate the reduction of PoC for an extremely high number of maneuvers in a very limited time. A scattering in the maneuver size and in the maneuver execution time (number of orbits before the conjunction) can therefore be performed, as depicted in Fig. 11; all the maneuvers reducing the residual PoC to negligible values (below 1E-9) can be easily identified.

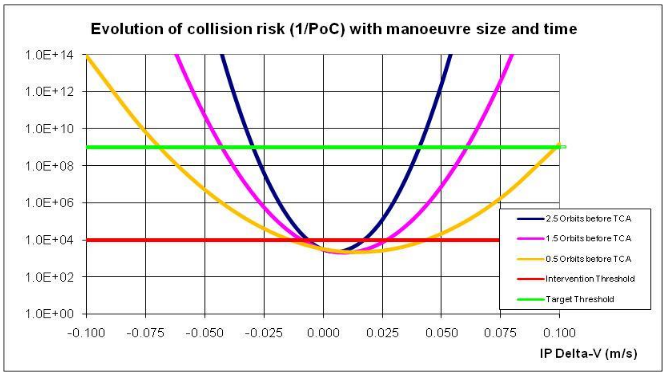

Figure 11. Residual PoC Plot for Maneuver Scattering

Maneuver performed N+0.5 orbits before TCA are normally considered (N being 0, 1 and 2 in the presented case), providing the extra half orbit the maximum displacement in radial direction; being the covariance in the radial direction normally the smallest, a large reduction in the PoC is then achieved. For lateral conjunction however, to increase the displacement in along-track by providing more time between maneuver execution and TCA is clearly beneficial; the larger the impact angle (being impact angle 0 a perfectly frontal collision), the bigger the benefit of anticipating the maneuver. Therefore it is sometimes interesting to consider a maneuver N+0.75 orbits before the TCA, to increase the along-track separation with little change in the radial one.

3.4. Post Maneuver Analysis

Using a procedure similar to the one described in Section 3.3 the displacement of the asset within the orbital frame of all the objects reported in the conjunction screening messages is computed; only the displacement in the along-track direction caused by Δv_{at} is considered, being the oscillatory terms caused by eccentricity and inclination negligible for large propagation times. The depth of intrusion can then be computed for the new asset position, following the same procedure described in Section 3.1, to ensure that the collision avoidance maneuver does not cause an unacceptable reduction of the DoI with the other surrounding known objects.

4. Operations

When defining operations for conjunctions handling it is necessary to keep in mind that EUMETSAT is an operational agency, committed to provide near real time meteorological products with the highest possible availability. As any collision avoidance maneuver implies a disruption of the operational service, it is necessary to limit the maneuvers to the strictly necessary to ensure spacecraft safety when a reliable indication of an unacceptable high risk is present.
Moreover, high operational reactivity is required, to be able on one side to plan an avoidance maneuver as late as possible, based thus in the most reliable data possible, affecting as little as possible the mission return (see [2]), on another side to cancel at any point in time a foreseen maneuver before the upload on board (and, if possible, even later), if latest data prove it useless.
Therefore the EUMETSAT Flight Dynamics team is requested to provide a 24 hours/day, 7 days/week on-call service to ensure fast processing of the received data; support from the controller is also foreseen in case of unexpected late data delivery.

4.1. Benefit of using High Accuracy data

No conjunction handling system was considered necessary for Metop-A up to end of 2008 as, till this point in time, the only source of information on the objects orbiting close to Metop-A was the publicly available TLE.
The large uncertainty of the TLE obliges to define risk threshold very pessimistic not to miss any really dangerous conjunction, causing as a consequence a high level of false alarms; moreover, the avoidance maneuver needed for mitigating the risk is much larger than what would be sufficient with accurate orbital information, with consequent large impact on the satellite operations, fuel budget and mission return.
Using high accuracy data, as those provided by JSpOC in the last two years, it is possible to clearly identify a real risk, limiting thus the number of avoidance maneuvers linked with false alarms, as shown in Fig. 12.

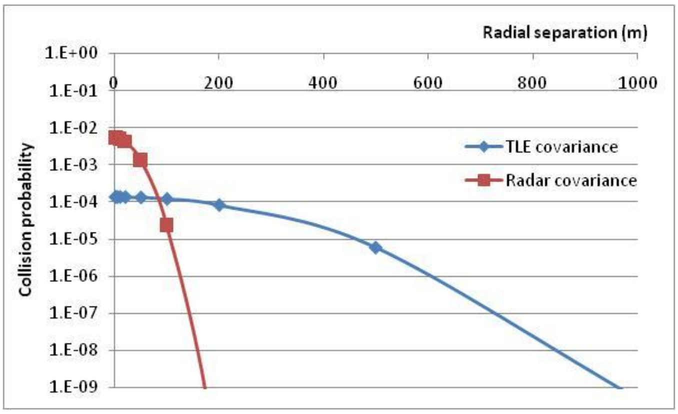

Figure 12. Measured Risk for Frontal Collision

If TLE data are used the level of risk measured is very limited also in case of zero miss-distance and remains flat also for large separation; the usage of high accuracy data permits to clearly identify the risk for little miss-distance, which vanishes very fast if the miss-distance increases.
Moreover, the risk reduction that can be achieved is much higher for the same maneuver size, especially for lateral conjunction geometries (much more frequent than frontal ones), where a displacement in the along-track direction is extremely beneficial (see Section 3.3).
More details on that subject can be found in [1].

4.2. Operational Flow

The overall operational flow in case of a conjunction warning is received is depicted in Fig. 13.

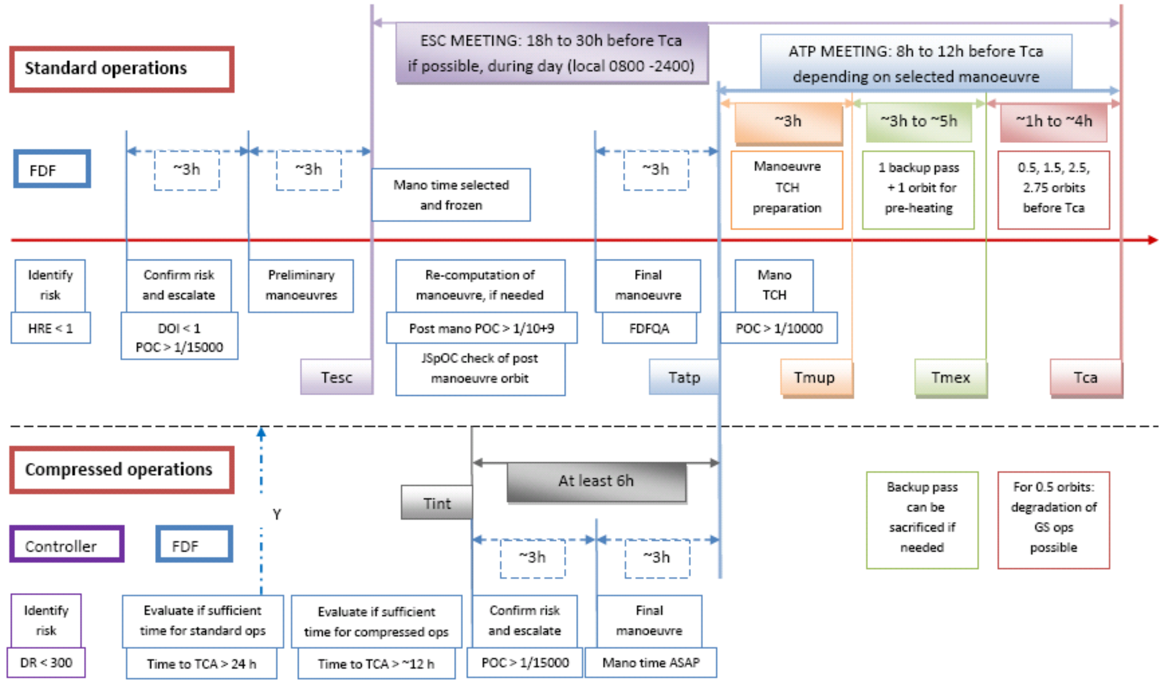

Figure 13. Operational Conjunction Handling Flow

Without entering into details, which would require a full paper on its own, the main feature of the operational flow can be so summarized; if still at least 24 hours before TCA are available when a conjunction warning is received, standard operations are implemented:

- A risk is identified by the Flight Dynamics Engineer (FD) if the object falls in the HRE
- A risk is confirmed by FD if the DoI is below 1 and the PoC is larger than 1/15000
- If a risk is confirmed, the risk is escalated at managerial level and an “escalation meeting” is called around 24 hours before TCA, involving ground and space segment management
- FD analyzes how different maneuvers at different time before TCA reduce the risk
- During the “escalation meeting” the optimal collision avoidance maneuver is selected for implementation and its time is frozen; the smallest maneuver ensuring satisfactory risk reduction, with the earliest execution time compatible with operational constraints (mainly time needed to prepare and validate the maneuver tele-command and to safely upload it on board) is selected for implementation. At the same time however it is recommended not to perform an avoidance maneuver too early, to wait for the most accurate information on the conjunction, often available only shortly before the conjunction time itself
- An “authorization to proceed” meeting is called between 8 and 12 hours before TCA, depending on the time of execution (and thus of upload) of the collision avoidance maneuver
- During the time before the “authorization to proceed” meeting FD continues processing the refined conjunction data received from JSpOC; the size of the maneuver is adjusted if

needed; refined conjunction data may also prove the execution of a collision avoidance maneuver as useless

- The effect of foreseen collision avoidance maneuver on the known objects around asset is analyzed; the post maneuver orbit is provided to JSpOC for analysis; a dedicated interface has been put in place via the space-track web for the Flight Dynamics user
- Shortly before the "authorization to proceed" the final maneuver is implemented in Flight Dynamics and validated operationally
- If the "authorization to proceed" meeting outcome is to proceed with the maneuver execution (not only the computed risk is taken into account, but also the confidence on the received data and the risk at satellite and mission level are considered), FD generates the corresponding telecommand and send them to the mission control system for upload on board (see [2])

In case, however, the first information on the conjunction is received very late (less than 24 hours before TCA) then it is necessary to compress the operations as follow:

- The risk is identified directly by the controller who calls the on-duty FD (based on NOAA data, if the radial distance is smaller than 300m)
- If the risk is confirmed, escalation is performed directly to the "authorization to proceed" meeting; FD selects the optimal maneuver to be implemented; if necessary the maneuver is executed only 0.5 orbits before the TCA (which implies a risk in terms of mission return due to the large drift generated by the relatively large maneuver) and the backup pass for upload of the maneuver is scarified

4.3 Operational Examples

In the last 14 months 3 high risk conjunctions, whose PoC went over 1/10000 at a certain point of the process, have been recorded. No collision avoidance maneuvers have been performed yet.

<u>High risk conjunction on 28/12/2009</u>
The computed PoC was around 1/8000 and the radial miss-distance around 40m; as no covariance information was available a worst case covariance was assumed. It was then decided to prepare an avoidance maneuver to mitigate the risk.
Before the "authorization to proceed" meeting FD prepared the maneuver and was ready to generate the telecommand, to be transferred to Mission Control System as soon as authorized; shortly before the meeting, new information on the radial error (around 80m) was received and, based on it, FD re-computed the risk for the worst case covariance in the other two directions; the resulting risk of 1/13000 (worst case) was considered too low to execute the maneuver, which was not performed.
Even if the miss-distance was within the combined covariance on the collision plane, the density of probability was so small due to the large covariance of the object that the risk was small. That proves that an approach based on miss-distance only may lead to useless maneuvering.

<u>High risk conjunction on 09/09/2010</u>
Two days before the TCA the computed PoC was around 1/8000 and the radial miss-distance around 50m; being the miss-distance small and the covariance still relatively large the sigma number (see Fig. 9) was relatively small (around 1.6)
On following days miss-distance increased and covariance reduced; therefore the sigma number doubled (around 3.2) and collision risk dropped to around 1/60000, making useless the preparation of any mitigation action.
This behavior, of covariance getting smaller and smaller the closer we get to the TCA and miss-distance not converging toward zero, and thus having the PoC dropping, is observed very often.

High risk conjunction on 20/11/2010

Three days before the TCA the computed PoC was around 1/7000 and the radial miss-distance around 8m, with a total miss-distance of around 350m; the covariance was still large (~40m radial, ~3000m along-track, ~1100m on miss-distance direction) and thus the sigma number was quite small (~0.3).

On following day the reported miss-distance very large (~1000m total, ~220m radial); moreover that change not consistent with covariance reported on previous day, leading to think that the provided data were unreliable. Also the reported covariance was bigger than on the previous day (~150m radial, ~ 3000 m along-track), which proved that the data were not a refinement of the previous set.

Detailed analysis of the CSM showed that a reduced observation arc was used (12 days instead of the 28 days of the previous day); so it was confirmed that the data were to be considered unreliable.

On the last day a new CSM was received similar to the first one (PoC ~ 1/7000); the CSM data showed that the latest used observable was older than 48 hours and thus that no further tracking was performed since the first received data set.

At the “authorization to proceed” meeting it was decided not to perform any maneuver due to age of the available data, providing thus low confidence on their reliability. An activity was then started to consolidate how to evaluate the level of confidence of the CSM based on the auxiliary information contained (see 4.4).

4.4. System Evolution

The conjunction messages handling system presented in this paper is still in a prototyping phase. Several activities are still on-going within EUMETSAT on this field.

As shown in Section 4.3, the need evaluating the quality of the received data is clearly identified; a data quality factor, based on the orbit determination auxiliary information provided in the CSM, is being thus currently prepared; the following 4 parameters are considered for its definition (in brackets the expected value of the parameter can be found):

- age of the last observation accepted in the orbit determination (less than 24 hours)
- ratio between used orbit determination arc and optimal orbit determination arc (close to 1.0)
- number of accepted observation per day of orbit determination arc (at least 1 per day)
- weighted Root Mean Square of the residual of the orbit determination process (close to 1.0)

A quality coefficient is associated with each parameter; if a parameter is not in line with the expected value, then a coefficient smaller than 1 is associated with it (1 otherwise). The product of the 4 coefficients provide the quality factor of the data, which is directly multiplied with the computed PoC to provide the operational PoC used in the operational decision flow.

Full integration within the operational Flight Dynamics SW of Metop-A of the algorithms developed in the prototypes is being performed (see [3]); in this manner the same operational approach used for all the other SW modules can be adopted (as described in [6]). Once this activity completed, automation of the conjunction handling operations (including collection, ingestion and processing of the received data and generation of alarms in case of detection of dangerous conjunctions) will be carried out.

The interface currently in place with JSpOC for providing post-maneuver orbital data in case of a collision avoidance maneuver (see Section 4.2) can be also fruitfully used in case of routine maneuver; not only to increase the safety of the Metop-A satellite in this critical cases, but also to ease the tracking operations of JSpOC, permitting a faster re-convergence of the orbit determination process after the maneuver. It is foreseen to improve that interface adding the orbital covariance to the data flow; the operational Flight Dynamics SW is being modified to be able to generate the needed covariance information, both in the determination and in the propagation arc.

As EUMETSAT also operates four geostationary satellites, for which CSM data are available, the process described in this paper is being adapted to these cases; however, the applicability of the used algorithms is still under investigation, due to the intrinsic differences of a conjunction in GEO and LEO orbit (mainly on impact velocity, conjunction geometry and covariance shape and size)

5. Conclusions

Two years ago the first conjunction warning for the Metop-A satellite was received by EUMETSAT from JSpOC; since then the Flight Dynamics team developed a full set of SW prototypes and procedures based on the JSpOC data permitting to accurately evaluate the real risk posed by the conjunction and, if deemed needed, to define an efficient mitigation action. Up to today three high risk cases have been identified but no collision avoidance maneuver has been necessary.

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Without their help we would never have managed to achieve the results presented in this paper.

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