Evolution of EUMETSAT LEO Conjunctions Events Handling Operations

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This paper provides an overview of the evolution of operations conducted at EUMETSAT in case of dangerous conjunction events with space debris in LEO: from ignoring the problem to developing a set of validated software prototype tools and operational procedures, with which so far three Metop-A collision avoidance maneuvers have been successfully executed; and from that solid basis to the development of an enhanced Conjunction Analysis software, integrated in the operational flight dynamics facility, that shall become operational in the near future. The functionalities of the new modules of that software (CWINGEST, CONANA and FRAME) are addressed in the paper. The new software is currently executed off-line for validation purposes and to support conjunction event operations, which are still conducted with the validated prototype tools. In particular it was used during the preparation of the second and third Metop-A collision avoidance maneuvers, executed in 2012. This paper highlights the improvements achieved in the operations due to the enhanced features of the new software and identifies new functionalities that could be included in future software versions.

Nomenclature

BIA	=	Best Information Available
CAM	=	Collision Avoidance Maneuver
CONANA	=	Conjunction Analysis module
CSM	=	Conjunction Summary Messages
CWINGEST	=	Collision Warning Ingestion module
CWM	=	Conjunction Warning Messages
DoI	=	Depth of Intrusion
EPS	=	EUMETSAT Polar System
EUMETSAT	=	European Organisation for the Exploitation of Meteorological Satellites
FDF	=	Flight Dynamics Facility
GFSC	=	NASA's Goddard Space Flight Center
JSpOC	=	USSTRATCOM's Joint Space Operations Centre
LEO	=	Low Earth Orbit
LOF	=	Local Orbital Frame
MCS	=	Mission Control System
MIAMI	=	Manual In-plane Avoidance Maneuver Insertion
NOAA	=	National Oceanic and Atmospheric Administration
PoC	=	Probability of Collision
TCA	=	Time of Closest Approach
TDR (EFG)	=	Earth-fixed rotating state-vectors referenced to the true equator of date.
TLE	=	Two Line Elements

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I. Handling of Metop's Conjunction Events

METOP is the space segment of the EUMETSAT Polar System, Europe's first polar orbiting operational meteorological satellite system, flying in a LEO Orbit. Metop-A (the first of a series of 3 satellites) was launched on 2006 and Metop-B is currently scheduled for the second half of 2012.

The definition of a conjunction analysis system for Metop-A was de-scoped during the Ground Segment development phase. The available algorithms and technologies were based only on TLEs and were considered insufficient to provide satisfactory risk mitigation without a large impact on satellite operations, fuel budget and mission return (Ref. 4).

On Christmas 2008, however, EUMETSAT received the first conjunction warning message from JSpOC for Metop-A. Since then the service has remarkably improved and currently EUMETSAT is receiving daily conjunction screening messages both through AI-Solutions at GFSC (Conjunction Assessment Summary Reports, including PoC estimation, since mid of 2009), and directly from JSpOC (CWMs, since end of 2010), identifying the catalogued objects flying close to Metop-A. These messages are not based on TLE but on the high accuracy orbit estimated by the US space surveillance network. Furthermore, CSMs containing very detailed data including full covariance information are provided since end of 2010 via the Space-Track website for objects flying through a high risk region defined around Metop satellites. These high accurate data permitted EUMETSAT to define operational procedures for conjunction risk assessment and for implementation of mitigation action, if deemed necessary (Ref. 2).

The EUMETSAT Flight Dynamics team has developed (2009) a set of operational procedures and software prototypes in Excel VBA to handle the different conjunction messages, which has proven to be very successful:

1) *First filter tool*, used for the analysis of the conjunction geometry, the computation of the DoI (describing how deep, in terms of sigma, the Metop satellite will be flying within the covariance of the debris) and the post maneuver analysis (maneuver impact on DoI of surrounding objects). It identifies the conjunctions with unacceptable level of collision risk.
2) *Conjunction Analysis tool*, used for the computation of the PoC and of the optimal collision avoidance maneuver that permits to reduce the collision risk to negligible values. It can perform input data quality assessment and parameter evolution analysis.

These software prototypes have been validated against equivalent systems of CNES, ESA and NASA.

The overall Flight Dynamics process can be summarized in four steps:

1) *Analysis of the conjunction geometry*: the DoI of the conjunction is computed. Conjunctions presenting a DoI below 1 deserve detailed analysis.
2) *Computation of the probability of collision*: if the computed PoC is above a certain threshold (1/10000) then a collision avoidance maneuver is prepared. Expected scenarios, considering the possible evolution of the debris covariance and of the miss-distance, are simulated as well, to evaluate the probability of the risk to disappear in future.
3) *Computation of collision avoidance maneuver*: the optimal maneuver reducing the residual PoC to negligible values (below $1/10^9$), taking also into account ground-track evolution and impact on the mission, is computed.
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 near-by known objects.

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 (target 98% for most products). 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. High operational reactivity is required to be able to plan an avoidance maneuver as late as possible, making use of the latest and most reliable data possible. At the same time a consistent management of the entire satellite and ground system has to be ensured in case of implementation of a collision avoidance maneuver, even in a short time. The MIAMI procedure was developed to this aim (Ref. 3).

In the mean time, Metop-A has executed three collision avoidance maneuvers in almost 6 years of operations (2011/05/01, 2012/03/02 and 2012/04/14). Flight Dynamics intervention has been required in some more conjunctions, where very high risk was observed, but, finally, the last set of data received permitted to exclude the need of a maneuver and the procedure was stopped, thus not affecting the mission return. Therefore the EUMETSAT Flight Dynamics team (among other system and facility teams) is requested to provide a 24 hours/day, 7 days/week on-call service to ensure fast processing of the received data.

II. New Conjunction Analysis Software

A new Conjunction Analysis software, mapping most of the functionalities of the former prototype tools and with enhanced features, has been developed by the EUMETSAT FD team (Ref. 1). Parallel off-line operations are being performed in the EUMETSAT development platform since last Quarter of 2011. In particular the new software has supported the last two CAMs executed in 2012. The system architecture for the final integration in the Ground Segment (i.e. setting up automatic files ingestion: JSpOC's CWMs and CSMs and NORAD's TLEs and SATCAT catalogues) is being designed. Full deployment of the new Conjunction Analysis software in the operational environment is currently foreseen for late 2012.

The new software is integrated into the EUMETSAT EPS FDF. As a consequence it can make direct use of all FDF features like TLE orbit generation, orbit file interpolation, processes sequencing and usage of central body, physical constants and satellite databases.

In addition, once the software is installed in the Ground Segment, it will be able to directly access the operational context (e.g. on-orbit position telecommand), to operate autonomously (the prototype requires manual intervention), making use of the same Flight Dynamics monitoring protocol (i.e. info, warning and alarms messages) and automatically (daily screening of the received CWMs).

The Debris Conjunction Analysis software consists of two separated modules: CWINGEST and CONANA. FRAME is an additional independent tool that completes the needs identified. The core software of the Debris Conjunction Analysis tools is written in Fortran 90, whereas the MMI language is TCL/TK.

A. Collision Warning Ingestion Tool (CWINGEST)

CWINGEST is in charge of ingesting CWMs and CSMs, provided by JSpOC and accumulating the relevant information into a so-called Miss Distance File. File equivalent conjunction information can be also input manually. TLE catalogues and Satellite Situation Report Files (SATCAT), from NORAD, can additionally be parsed for the NORAD IDs of the debris objects present in the Miss Distance File. CWINGEST provides function for filtering the events based on TCA epoch and for maintenance of the input files and catalogues.

CWINGEST converts the ingested input data into standardized internal input files for the second module of the Conjunction Analysis software, CONANA. CWINGEST design is such that only a few changes in the code are required to ingest conjunction information from other agencies or formats. In this way it will be quite straight forward to add, for instance, the Conjunction Data Message (CDM) or any other operator or national agency conjunction data file without affecting the conjunction computation core. The output generated and the functioning of CONANA, that relies on internal interfaces only, remain unaltered.

B. Conjunction Analysis Tool (CONANA)

CONANA processes the detailed conjunctions information generated by CWINGEST and is in charge of performing the collision risk analysis of the identified conjunction events. The main functions of CONANA are:

1) Enhanced events filtering by TCA, issue date, miss distance and latest entry per event.
2) High flexibility of input data and automatic selection of Best Information Available (BIA). For instance, if a CSM is available, debris velocity is taken from the CSM. Otherwise it is retrieved from the TLE orbit.
3) Analysis of the conjunction geometry with enhanced graphical representation.
4) Preliminary estimation of the collision risk via computation of the DoI.
5) PoC computation applying Alfriend formula, including correction to consider worst case probability density within the impact area (Ref. 5). An enhanced implementation is foreseen in next software version.
6) Ingestion of Metop's solar panel and on-orbit-position telecommand to accurately model the collision area. This is the only spacecraft dependent feature. Manual entry of the spacecraft radius is in any case available.
7) Detailed conjunction analysis of multiple events. Warnings and alarms are raised in the Mission Control System (MCS) on violation of user-defined DoI or PoC thresholds to trigger FDF engineer intervention.
8) Enhanced handling of debris covariance information: default values definition, either manually or from look-up table as function of time to TCA; capability to perform a scatter around default values and identification of worst case PoC with graphical representation of the resulting PoC for all cases analyzed.
9) Capability to perform a scatter for in-plane maneuvers as function of the execution time and the size of the maneuver itself with graphical representation of the resulting PoC for all cases analyzed.
10) In-plane maneuver application with associated execution uncertainty and re-computation of geometry, DoI and PoC for all assessed conjunction events.
11) Capability of modifying the position of the debris in its along-track and radial direction.

The high level run modes options (also referred to as automatic loops) of CONANA are then:

1) Multiple or Single Event.
2) Single Covariance (user input, CSM, look-up table) or Covariance Scattering (only for the debris).
3) No Maneuver, Single Maneuver or Maneuver Scattering.

CONANA is able to run on Multiple Events with Maneuver Scattering and Covariance Scattering, but the output is too difficult to handle and of no operational interest. Operationally the following configuration modes are set up:

1) *Multiple Events, Single Covariance, No Maneuver*: daily screening to analyze all future reported conjunction events, using default debris covariance (or from look-up table) and computing the DoI and PoC, raising warnings and alarms to the MCS. This mode shall run automatically as a scheduled task.
2) *Single Event, Covariance Scattering, No Maneuver*: to analyze a single conjunction event with potential high risk performing a systematic scattering in the covariance matrix of the secondary object to identify worst case conditions in terms of risk. Covariance scattering is performed whenever covariance information is not available (no CSM), incomplete (only radial covariance) or unreliable (sparse tracking). Resulting PoC values shall lead to a recommendation on whether to execute a mitigation action or not. This mode shall run manually, in case of a potential high risk situation.
3) *Single Event, Single Covariance, Maneuver Scattering*: to analyze the effect of a set of in-plane maneuvers (scattered in execution time prior to TCA and size) in terms of risk reduction. Covariance Scattering can be performed at the same time if covariance information is not of adequate quality, as mentioned above. This mode shall be run manually when the conjunction assessment recommends a CAM.
4) *Multiple Events, Single Covariance, Single Maneuver*: assesses the new DoI and PoC of the known future events for updated post-maneuver Metop state vector and covariance, to ensure that the future maneuver does not unacceptably increase the collision risk with the surrounding objects. This mode shall be run manually whenever a maneuver is planned.

Making use of the capabilities of modifying the position of the debris in its in-track and radial direction and of the flexibility in the covariance definition it is also possible to analyze the range of expected PoC at a future time (normally the next foreseen CSM delivery), under the assumption that the debris will move in its local orbital frame according to the latest (in CSM) available position uncertainties and that the new position error covariance matrix will fit the evolution observed (if several CSMs are available) or predicted (from look-up table being the time to TCA smaller). This analysis provides a very good indication of whether the high risk is likely to persist or rather to vanish upon new data update and is sometimes an input for whether to wait for updated information or start collision avoidance operational activities straight once maneuver has been selected. This analysis is currently run manually, requiring one run (in mode *Single Event, Single Covariance, No Maneuver*) per possible debris displacement (assuming zero, 1-sigma positive and 1-sigma negative displacement for the in-plane and the radial direction, 9 cases have to be analyzed).

C. TDR to J2000 State Vector Transformation Tool (FRAME)

The FRAME tool has been developed for supporting reference frame transformation needed for conjunction analysis operations and not yet available in the EPS FDF software:

1) State Vector from/to J2000 (EPS FDF reference) to TDR (also referred to as EFG, CSM reference) frames.
2) Covariance Matrix (3x3) from/to J2000 (EPS FDF reference) to Local Orbital (Radial/Along-track/Cross-track, CSM reference) frames.

III. Operational cases

The analyses for the last two Metop-A Collision Avoidance Maneuvers (CAM#2 executed on 2012/03/02 and CAM#3 on 2012/04/14) were mainly conducted using the prototype tools, which are still the operational software. The analyses were supported by the use of CWINGEST, CONANA and FRAME, which has served several goals:

1) To confirm the results obtained with the prototypes and then validate the new software.
2) To make use of the new features enhancing the analyses.
3) To detect some missing features in the new software, which are available in the prototype tools.

A summary of the most relevant analyses performed, covering software as well as operational aspects, follows. The examples shown correspond to the latest CSM received (#3) for CAM#2, if not otherwise indicated.

A. CONANA standard output

The CONANA standard output, shown in Table 1, is divided in several sections: Main Conjunction Parameters, Primary and Secondary Object Parameters, Primary-Secondary Combined Parameters and Perpendicularity Parameters.

The standard output permits to easily assess the most relevant parameters of the conjunction like the TCA, miss-distance, DoI (based on the selected covariance), PoC (and 1/PoC), relative velocity, approach angle, combined sigmas in the conjunction plane (including projection in the miss-distance direction) and combined radius. Moreover, the source of each used input data is reported (in the case presented, BIA was selected, which means: CSM for position, velocity and covariances; telecommands for the satellite radius, SATCAT Radar Cross Section, RCS, for the debris radius) and the internal consistence between miss-distance and relative velocity is verified.

Table 1. CONANA standard output

```
==========================================================================================================================
|                                    Event Id 000036 (MANUAL) and Entry Id 000007 (MANUAL)                               |
|------------------------------------------------------------------------------------------------------------------------|
|                                               MAIN CONJUNCTION PARAMETERS                                              |
|                                                                                                                        |
| Primary Object ID                          =      M02                                                                  |
| Secondary Object ID                        = 33874 (MISS DISTANCE FILE)                                                |
| TCA                                        = 2012/03/02-23:58:11.770 UTC (MISS DISTANCE FILE)                          |
| PoC                                        = 3.827E-04                                                                 |
| 1/PoC                                      = 2.613E+03                                                                 |
| DoI                                        = 1.810E+00                                                                 |
| DoI-TCA time difference                    =  2.356E-02 sec                                                            |
| Debris Miss Distance (Conj. Plane)         =        207.580 m                                                        |
| Debris Miss Distance (S/C Radial)          =         27.119 m                                                        |
| Debris Miss Distance (S/C Along-Track)     =        122.852 m                                                        |
| Debris Miss Distance (S/C Cross-Track)     =       -165.120 m                                                        |
| Combined 1-Sigma (Miss Distance)           =  1.078E+02 m                                                             |
| Combined 1-Sigma (Perp. Miss Distance)     =  1.788E+01 m                                                             |
| Combined 1-Sigma (Perp. Conj. Plane)       =  4.079E+01 m                                                             |
| Relative Velocity                          =  12025.847848 m/s                                                         |
| Debris Relative Velocity (S/C Radial)      =    -66.365921 m/s                                                         |
| Debris Relative Velocity (S/C Along-Track) =  -9706.954199 m/s                                                         |
| Debris Relative Velocity (S/C Cross-Track) =  -7098.707785 m/s                                                         |
| Maneuver applied                           = NO                                                                        |
|                                                                                                                        |
|------------------------------------------------------------------------------------------------------------------------|
|                                                PRIMARY-OBJECT PARAMETERS                                               |
|                                                                                                                        |
|          Position           Velocity                                 Covariance                            Covariance  |
|           J2000.0            J2000.0                    Local Orbital Frame (RAC)  MissDist, Perp. MissDist, Perp. Conj.Plane  |
|               (m)              (m/s)                                      (m^2)                                 (m^2)  |
|    CSM TABLE (BIA)    CSM TABLE (BIA)                              CSM TABLE (BIA)                       CSM TABLE (BIA)  |
|        839056.906        4128.386583    1.656E+01   -1.846E+01    3.260E+00    2.009E+02    3.932E+01   -2.726E+02  |
|        720069.146       -6192.344973   -1.846E+01    5.823E+02   -3.288E+00    3.932E+01    2.388E+01   -5.100E+01  |
|       7104743.171         140.314006    3.260E+00   -3.288E+00    3.102E+00   -2.726E+02   -5.100E+01    3.772E+02  |
|                                                                                                                        |
| Radius        =    4.119 m (TELECOMMAND (BIA))                                                                         |
| Orbital Period =    0.000 sec (NOT USED)                                                                               |
|                                                                                                                        |
|------------------------------------------------------------------------------------------------------------------------|
|                                               SECONDARY-OBJECT PARAMETERS                                              |
|                                                                                                                        |
|          Position           Velocity                                 Covariance                            Covariance  |
|           J2000.0            J2000.0                    Local Orbital Frame (RAC)  MissDist, Perp. MissDist, Perp. Conj.Plane  |
|               (m)              (m/s)                                      (m^2)                                 (m^2)  |
|    CSM TABLE (BIA)    CSM TABLE (BIA)                              CSM TABLE (BIA)                       CSM TABLE (BIA)  |
|        838992.166       -7111.477195    3.141E+02   -1.513E+03    4.697E+01    4.445E+04    6.329E+03    6.134E+04  |
|        719879.536       -1998.427708   -1.513E+03    1.301E+05    8.475E+01    6.329E+03    1.204E+03    8.872E+03  |
|       7104797.479         975.500625    4.697E+01    8.475E+01    4.116E+01    6.134E+04    8.872E+03    8.480E+04  |
|                                                                                                                        |
| Radius        =   0.176 m (RCS TABLE (BIA))                                                                            |
|                                                                                                                        |
|------------------------------------------------------------------------------------------------------------------------|
|                                          PRIMARY-SECONDARY COMBINED PARAMETERS                                         |
|                                                                                                                        |
|         Combined covariance       Eigenvalues           Angles        DoI-A & B       DoI-2D & 3D                      |
|     MissDist, Perp. MissDist        Conj.Plane       Conj.Plane                                                        |
|                        (m^2)               (m)            (deg) (m^4/s^2 & m^4/s)                                      |
|     4.465E+04      6.369E+03         2.135E+02           -8.173        6.547E+12         9.672E-01                      |
|     6.369E+03      1.228E+03         1.770E+01           81.827       -3.084E+11         1.810E+00                      |
|                                                                                                                        |
| Combined Radius =   4.295 m                                                                                            |
|                                                                                                                        |
|------------------------------------------------------------------------------------------------------------------------|
|                                               PERPENDICULARITY PARAMETERS                                              |
|                                                                                                                        |
| Angle (Miss Distance, Relative Velocity)    =   90.509 deg                                                             |
| Angle (S/C along-track, Relative Velocity)  = -143.822 deg                                                             |
| Angle (Relative velocity, Horizontal Plane) =    0.316 deg                                                             |
| Perpendiculary condition                    = VERIFIED                                                                 |
|                                                                                                                        |
|                                                                                                                        |
==========================================================================================================================
```

B. Conjunction geometry

CONANA can produce detailed views of the conjunction geometry through projections in the conjunction, horizontal and lateral planes (wrt the debris orbital frame). Also the standard view on the conjunction plane (wrt the satellite orbital frame and considering combined covariance) is provided.

Either default (Fig. 1) or CSM (Fig. 2) covariances can be considered (depending on the selected source and available data); similarly velocity from CSM, from TLE or estimated from miss-distance can be used.

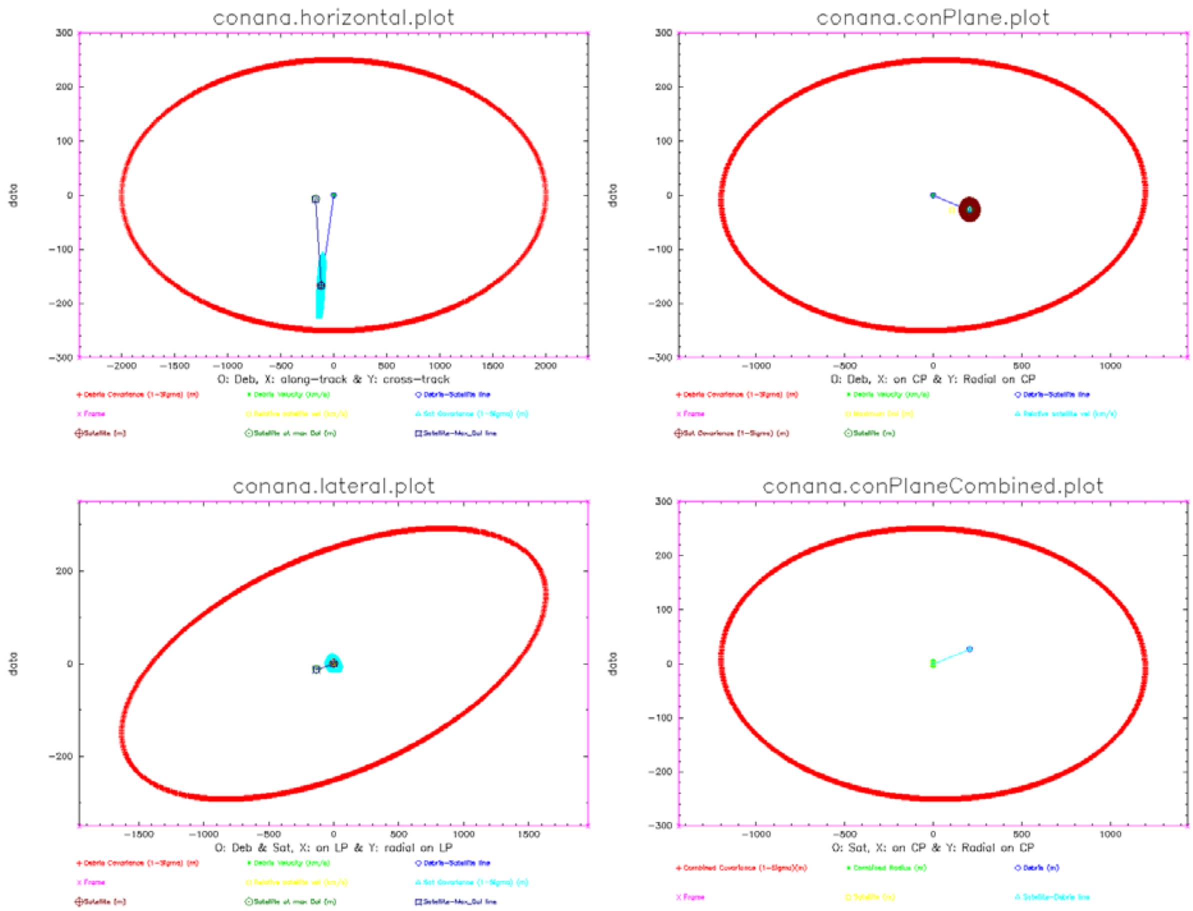
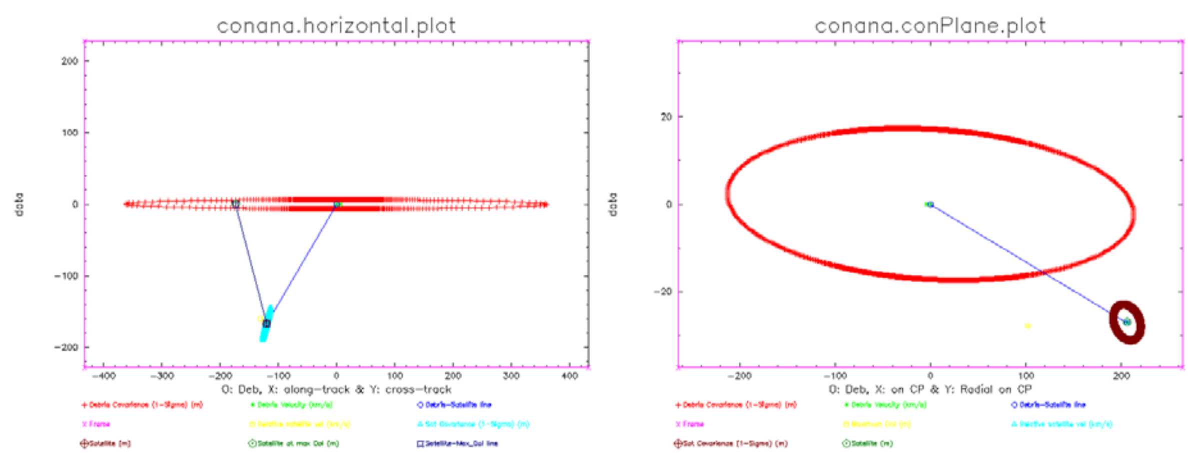


Figure 1. Conjunction geometry views using default covariance and velocity from TLE



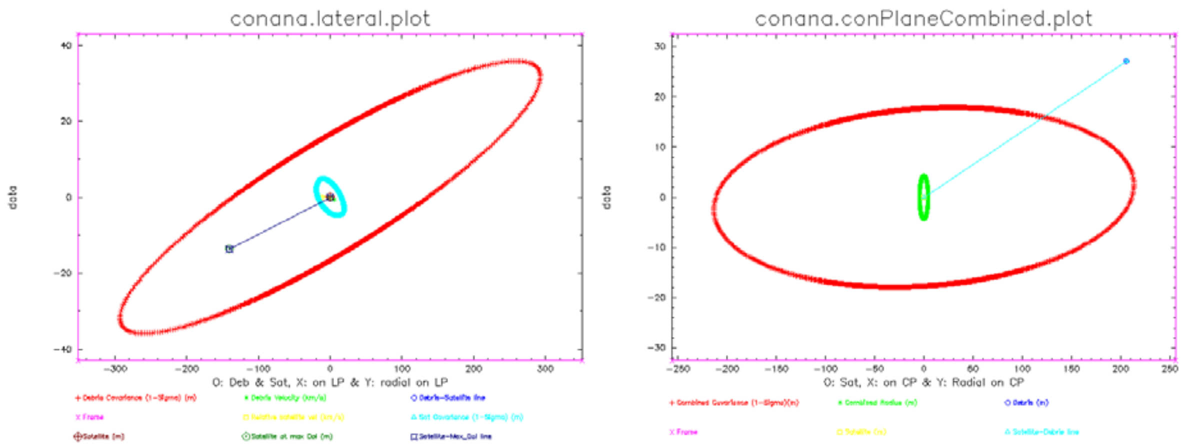


Figure 2. Conjunction geometry views using covariance and velocity from CSM

It is also worth to point out that the computation of the relative velocity in CONANA (using velocity information either from TLE or from CSM) is more accurate than in the First Filter tool (velocity computed assuming no radial relative component and fixed module). This is particularly relevant for cases where relative velocity is very low (approach angle close to 90 deg) as seen during CAM#3 analysis, and shown in Table 2.

Table 2. Relative velocity comparison (First Filter versus CONANA)

	CAM#2 relative velocity angle -143.824 deg			*CAM#3 relative velocity angle 94.234 deg*		
m/s	*1st Filter CWM*	*CONANA TLE*	*CONANA CSM*	*1st Filter CWM*	*CONANA TLE*	*CONANA CSM*
radial	0	-67.3	-66.4	0	-51.0	-51.7
along-track	-9571.9	-9706.5	-9707.0	-79.1	-22.2	-22.4
cross-track	-7125.3	-7098.0	-7098.7	1082.1	302.4	302.8

C. Main conjunction parameters evolution

The plots in Fig. 3 show the evolution of the main parameters describing the conjunction geometry, miss distance and DoI (computed assuming a default covariance matrix with sigma 300m, 2500m, 1250m in radial, along-track and cross-track directions), as generated by the prototype tools. The new conjunction analysis software does not currently handle historic evolution of conjunction parameters, which has demonstrated to be very useful. Enhancement on this direction is already being designed for the new conjunction analysis software.

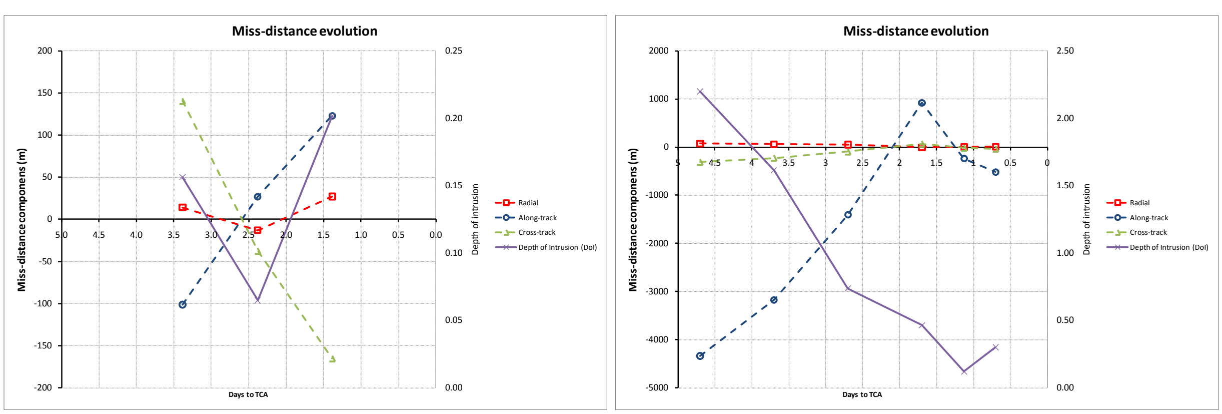


Figure 3. Conjunction miss distance and DoI evolution for CAM#2 (left) and CAM#3 (right)

D. Derived conjunction parameters evolution

The prototype tools include an advanced handling of history data for the considered conjunction. The evolution of conjunction derived parameters is analyzed to extract valuable information on the internal consistency of the dataset. In particular, how the position uncertainties decrease when getting closer to the TCA (and the propagation time decreases) and if the position changes are consistent with the declared sigmas. Plots in Fig. 4 show the situation for the 3 CSMs received for CAM#2. A linear decrease of the radial position uncertainty and a parabolic evolution for the along-track one, for both satellite and debris, can be observed, as expected. The changes in position in the respective orbital frames (CSM#2 versus CSM#1 and CSM#3 versus CSM#2) are within the two-sigma region, showing a good consistence of the dataset. Evolution of the PoC (and of the risk of collision, 1/PoC) is also presented, useful to evaluate the risk trend. These functionalities will be implemented also in the next version of the new conjunction analysis software.

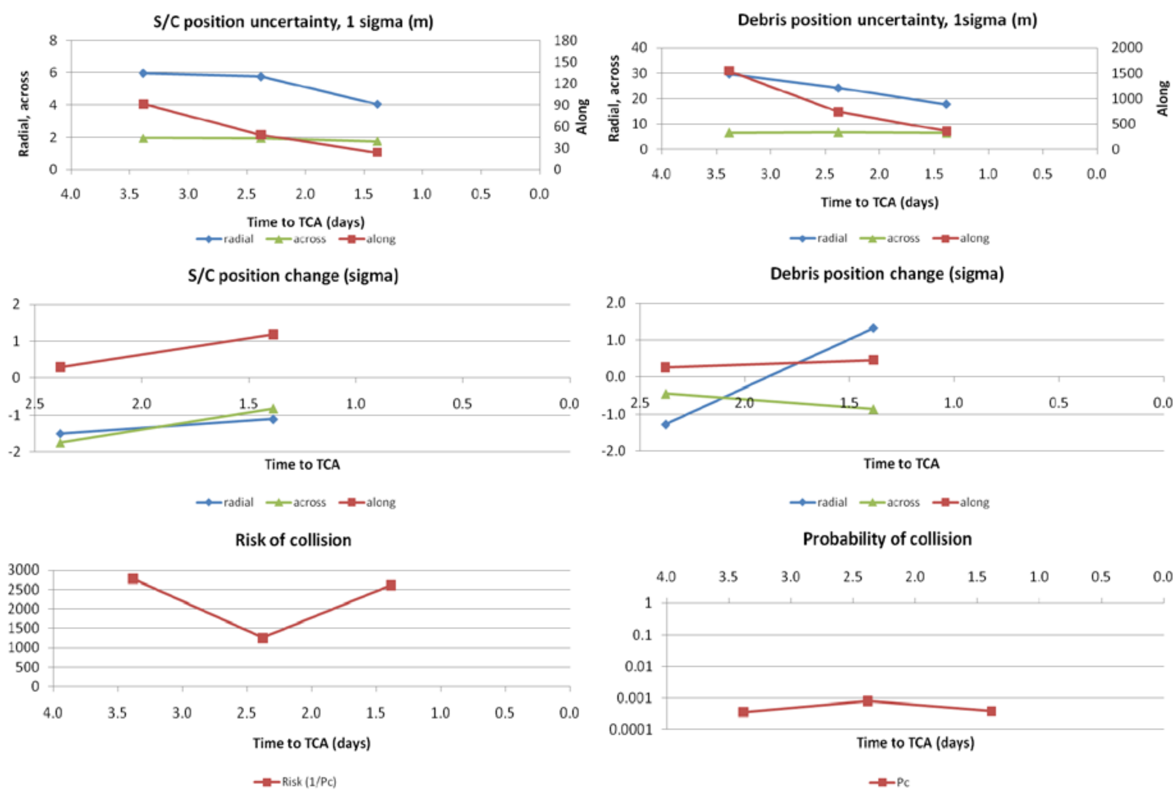


Figure 4. Evolution of conjunction derived parameters

E. Data Confidence Level

Another function, available in the prototype tool but not yet in the CONANA module (foreseen for the next version), is the weighting of the PoC threshold considered for intervention with the orbit determination performances reported in the CSM, namely: the Weighted RMS, the age of the latest observation used, the ratio between the arc length used versus the recommended arc and the ratio between the used versus the available observations. Each of these criteria has a factor associated (less or equal to 1).

The combined product (called Confidence Level) can be then applied to the PoC threshold. For example, the confidence level computed during the CAM#2 campaign was 1.0 for Metop-A and 0.91 for the debris. The computed PoC considered for recommending the execution of a maneuver increased from 1/10000 to 1/9100, making the decision to execute or not a CAM more stringent.

F. Cross validation of JSpOC Metop-A provided state

The Metop-A EFG coordinates at TCA from a CSM is compared with those extracted from the operational J2000 orbit file making use of FRAME to assess the accuracy of the information. In the case in analysis, the position difference was within the JSpOC provided sigma, showing very good agreement, as shown in Table 3.

Table 3. EFG coordinates comparison between JSpOC and EUMETSAT (CSM#2, CAM#2)

Metop-A Orbit Quality Check		Input EPS FDF EFG interpolated Cartesian coordinates				
	S/C EFG CSM	*S/C EFG FDF*	*diff EFG*	*diff LOF*	*diff LOF (sigma)*	*Local Orbital Frame*
x km	-543.511	-543.545	-0.034	-0.003	0.5	radial
y km	-955.412	-955.385	0.027	0.043	0.9	along
z km	7105.756	7105.754	-0.002	-0.001	0.4	cross
modulus	7190.270	7190.267	0.043	0.043	check OK	
vx km/s	-6.023422	-6.02342	-0.000002	-0.000050	N/A	radial
vy km/s	4.505060	4.505061	0.000001	0.000001	N/A	along
vz km/s	0.145281	0.145231	-0.000050	0.000008	N/A	cross
modulus	7.523183	7.523184	0.000050	0.000050	check OK	

It is foreseen to integrate this check within CONANA in the next version. It gives high confidence that the satellite analyzed is the correct one (especially having a small satellites fleet), and that the reported tracking accuracy fits EUMETSAT´s knowledge of the orbit.

G. Expected scenario upon CSM update

It is very interesting to analyze the possible scenarios expected upon arrival in the future of a new CSM, to evaluate the likelihood of a reported high risk to persist in the future or not. This information supports the decision to wait up to the maximum time allowed by the MIAMI procedure before commanding the execution of the CAM, to maximize the probability of receiving a further CSM beforehand. This procedure is backed by several operational cases where the latest conjunction information made the risk to disappear and permitted to cancel the CAM.

The target is to screen the possible future scenarios and advance whether the PoC is likely to get better or worse. This analysis is carried out via manual executions of CONANA, considering several cases:

1) same miss distance and expected covariance (based on observed evolution):
    a. lineal decrease in radial (~-20%) sigma;
    b. parabolic decrease in along-track (~-50%) sigma;
    c. constant cross-track sigma;
2) expected covariance and changes in debris position of one expected sigma in radial and along-track directions (displacement in cross-track is not performed as impact on PoC is normally negligible).

The results provided in Table 4 (CAM#2) indicated that the risk remains high for most of the considered changes in the debris position: 5 out of 9 scenarios would confirm the maneuver. For changes in the most unfavorable directions (negative displacement in radial) the risk can increase significantly (latest CSM taken as reference);

Table 4. Expected risk under several scenarios of debris error position covariance and miss distance

	miss distance (m)			*sigma debris (m)*			*1/Pc*
	radial	*along*	*cross*	*radial*	*along*	*cross*	
CSM#3 reference	27.1	122.9	-165.1	17.7	360.7	6.4	2610
expected σ	27.1	122.9	-165.1	14.5	180.0	6.5	4805
+ along 1 exp σ	27.0	68.2	-336.6	14.5	180.0	6.5	53400
- along 1 exp σ	27.0	177.6	6.4	14.5	180.0	6.5	1153
+ radial 1 exp.σ	41.0	122.9	-165.1	14.5	180.0	6.5	35730
+ radial 1 exp σ + along 1 exp σ	41.0	68.2	-336.6	14.5	180.0	6.5	401300
+ radial 1 exp σ - along 1 exp σ	41.0	177.6	6.4	14.5	180.0	6.5	8488
- radial 1 exp.σ	13.0	122.9	-165.1	14.5	180.0	6.5	1407
- radial 1 exp σ + along 1 exp σ	13.0	68.2	-336.6	14.5	180.0	6.5	16460
- radial 1 exp σ - along 1 exp σ	13.0	177.6	6.4	14.5	180.0	6.5	363

Automation of this process in CONANA is being designed and should be made available in the next version of the software. It could have been more consistent to use the sigma corresponding to latest available CSM (CSM#3), instead of the expected sigma, for the debris position displacement. This approach will be followed for future high risk conjunctions.

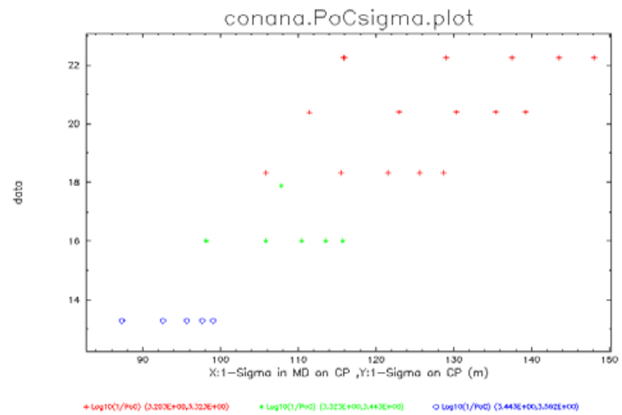


Figure 5. Covariance scatter plot

Furthermore, making use of CONANA facility to scatter the debris covariance around the latest CSM, (+/- 50% in all 3 components, equivalent to +22/-30% of sigma) it is possible to deeper analyze the case assuming fix miss distance; that leads to PoC in the interval (1/1596, 1/3648), as shown in Fig. 5.

The PoC range is shown via color code (as log10(1/PoC)) as function of the covariance size in the conjunction plane (one sigma in the miss-distance direction and in its normal). Improved representations are under study.

The combined analysis led to the conclusion that the chances of the conjunction risk to vanish if waiting to execute a maneuver till the very last moment, in order to eventually receive, process and analyze a latest CSM, were not favorable.

H. CAM execution decision process

The last two avoidance maneuvers illustrate other operational constraints considered in the decision process of whether to execute a CAM and when.

For CAM#2 the deviation of the ground-track was of more than 10 km wrt the reference at most of the latitudes, violating the ±5km mission corridor, without relevant impact in product processing. There was a clear risk of collision within the limits to intervene (PoC =1/2600) and two scenarios were considered for selecting the maneuver execution time:

1) To wait until the latest possible, to receive an additional CSM to confirm the final decision, with a maneuver ready to be generated and uploaded to the satellite during the night, for execution half an orbit before TCA.
2) To execute a maneuver during normal working hours, as early as 6.5 orbits before TCA, considering that the CSM could not arrive and that, if it arrived, the probabilities of reducing the risk are low (see Section IIIG).

Fig. 6 indicates that a negative maneuver is more convenient in terms of delta-V, as well as in terms of ground track evolution, because the radial separation built is in the favorable direction. Furthermore, anticipating the maneuver as much as 6.5 orbits allows for a 5mm/s reduction in the delta-V needed, leading to a longer period of time within the ground track and a smaller maneuver to restart a ground track cycle. Option 2) was selected, justified by these arguments. Fig. 7 shows the position difference built by the maneuver. Fig.8 shows the post maneuver ground-track evolution.

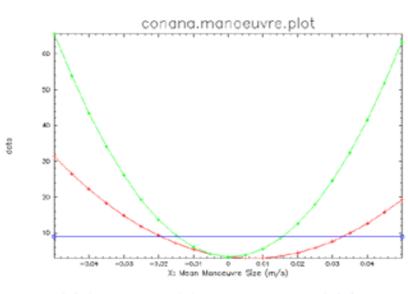


Figure 6. Collision risk vs maneuver size, for maneuver times TCA-0.5 and TCA-6.5 orbits

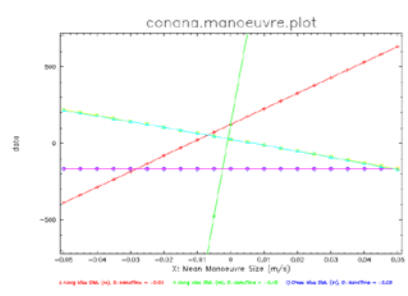


Figure 7. Evolution of miss distance components with maneuver size and time (zoom)

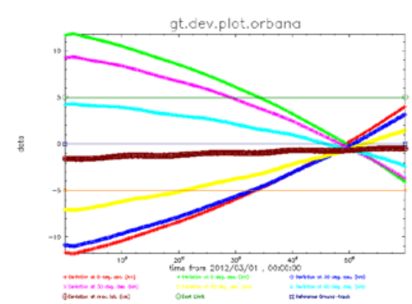


Figure 8. Effect in ground-track evolution of a -15mm/s in-plane maneuver at TCA-6.5 orbits

The CSM received the morning before the TCA for CAM#3 (CSM#2) showed a very high PoC of 1/1300. The threshold to prepare a maneuver was 1/8450 including a data confidence factor of 0.85 due to degraded WRMS in debris orbit determination (see Section IIIE), so there was a clear risk of collision within the intervention limits.

As an in-plane maneuver was planned for 2012/04/25, 10 days after the TCA, is was decided to execute the CAM not only to mitigate the collision risk but also to start a new ground track cycle for Metop-A and therefore with positive impact on the mission. The maneuver size and sign were fixed at +35 mm/s, value needed for the ground-track maintenance; this size was larger than the minimum required (25 mm/s) to bring the PoC below 10^{-9}, which is target condition for the CAM.

Two scenarios were considered for the maneuver execution time:

1) To wait until the latest possible, to receive an additional CSM to confirm the final decision, with a maneuver ready to be generated and uploaded to the satellite during night time, for execution half orbit before TCA.
2) To execute a maneuver during normal working hours, as early as 7.5 orbits before TCA, without waiting for the final CSM, considering that also in this case the probabilities of reducing the risk were very low.

It was decided to perform the maneuver at the earlier opportunity and not to wait for the next CSM. This also permitted to cancel the foreseen routine ground-track maintenance maneuver.

I. Effect of implemented maneuver on surrounding objects

As part of the CAM operations procedure, EUMETSAT generates Metop-A Ephemeris post maneuver and delivers them to JSpOC, which performs a new screening using EUMETSAT-provided ephemerides to confirm that the CAM does not cause a close approach of considerable risk, comparable to the one that the CAM tries to mitigate. In parallel an equivalent internal independent assessment is performed using CONANA. The internal analysis is however limited to the known surrounding objects available in the latest CWM (all objects within 5km miss distance in absence of maneuver). Both screening results are shown in Table 5.

Table 5. Post-maneuver screening results comparison (JSpOC versus CONANA)

CONJ#	Conjunction Time	Miss	radial	along	cross	DOI	CONANA TCA	MD(m)	radial	along	cross	DOI
4171	4MAR/06:13:08.057	4681	940.2	4144.6	-1963.4	4.5	WAS NOT IN PREVIOUS					
15774	4MAR/04:15:03.625	4402	4067.9	213.0	-1669.8	17.	04:15:04.029	7643	4065.7	-5994.7	-2440.0	17.
26283	2MAR/23:10:24.879	4559	266.3	-3086.2	-3345.6	3.5	23:10:24.992	4853	266.6	-4065.6	-2636.4	3.6
28288	5MAR/12:50:42.845	2469	1535.0	-705.8	-1801.5	6.6	12:50:43.984	11803	1549.6	-11700.2	-99.3	8.4
29812	4MAR/00:22:29.176	2581	2563.1	114.4	-284.6	10.	00:22:29.533	5872	2543.6	-4778.6	-2274.3	11.
30660	3MAR/05:05:14.580	3094	2445.7	-1240.2	1434.1	9.9	05:05:14.781	3908	2473.1	-2991.6	452.4	9.7
30740	3MAR/10:58:30.259	2631	2602.1	354.6	167.3	10.	10:58:30.515	2960	2590.9	-787.4	1196.3	10.
31346	5MAR/00:55:54.150	4441	-152.5	-3441.8	-2803.0	2.9	00:55:54.934	9089	-82.2	-9073.8	517.3	4.3
33874	2MAR/23:58:11.637	625	97.0	-367.2	496.5	0.6	23:58:11.770	1670	84.7	-1659.8	-165.1	0.8
37585	4MAR/23:18:22.924	4474	-2568.1	2956.9	-2163.3	11.	WAS NOT IN PREVIOUS					
82216	3MAR/11:49:45.526	774	-401.3	72.8	-657.9	2.6	11:49:46.855	3875	112.2	-3793.5	783.5	2.4

The following remarks can be made according to experience:

1) The new conjunction events (within 5km) reported by JSpOC and not previously detected, do not usually pose a significant risk. It is therefore acceptable if they are not considered.
2) Some objects may disappear in JSpOC screening. They correspond either to TCAs in the past or to conjunctions where either the updated debris position or the accumulated Metop-A drift built a miss distance difference outside the 5 km region.
3) CONANA assumes no shift in TCA when implementing an in-plane maneuver which can lead to remarkable differences in the along and cross track reported values. This is particularly true for frontal encounters, with relative velocities close to 14 km/s and large impact angle (around 160-180degrees). In these cases the TCA can shift up to a few seconds. Improvements on this direction are foreseen in future versions of CONANA for improving the consistency of the data.

Nevertheless, there is a great level of consistency among the matched events, especially in terms of DoI (which is less sensitive to TCA shifts, for it is computed projecting the satellite position along the relative velocity, nearly unchanged, through the covariance of the debris). This validates the independent approach of checking the effect of the maneuver on known surrounding objects.

IV. Improvements and Way Forward

The extensive usage of the new conjunction analysis software permitted to identify some functionalities that need to be added in the new Conjunction Analysis Software:

1) Probability of Collision computation averaged out within the impact area, to compensate for effects of the non linear evolution of the collision probability in the miss distance direction (see Section II B).
2) Maintenance of main conjunction parameter history and generation of evolution plots (see Section III C).
3) Maintenance of derived conjunction parameter history and generation of evolution plots (see Section III D).
4) Computation of a data Confidence Level factor, based on user-defined look-up tables correlating the observed CSM parameters with the individual multipliers, to weight the collision risk (see Section III E).
5) Data Quality Indicators based on the comparison between CSM-provided asset orbit with the operational orbit and on the changes in debris orbit versus the reported sigma (see Sections III D and III F).
6) Automation of the expected scenario analysis (see Section III G).
7) Graphical representation enhancements for the covariance scatter: for instance, PoC as function of the radial covariance, for fixed along-track/cross-track covariance values (see Section III G).
8) Enhanced software modularity to isolate platform dependent functions to easily support new platforms (e.g. Sentinel-3) just by plugging-in the new satellite model (see Section II B).
9) In case of maneuver, proper re-computation of new TCA and new conjunction conditions (see Section III A).

Furthermore, the maintenance of a complete set of conjunction parameters permits to perform statistical analysis on the historical data such as the estimation of the total daily neglected risk (summing up the estimated risk for all the conjunction reported in the following day for which no mitigation is implemented), of the total neglected risk from beginning of mission (summing up the corresponding daily risk records), or the estimation of the total mitigated risk via CAMs implementation. The implementation of this functionality is also being designed currently.

In order to fully deploy the software in the operational ground segment, the following activities are needed:

1) Consolidation of configuration for data ingestion, first filter of CWMs, analysis of CSMs events, covariance scatter; debris position change, maneuver selection…
2) Implementation of interface for ingestion of CWMs, CSMs, TLE, SATCAT catalogues, that will be retrieved manually until automatic data traffic to Flight Dynamics is set up.
3) Automation of daily operations (data ingestion and first filter) and integration in the MCS (alarm rising).

V. Conclusion

The new software, developed by EUMETSAT Flight Dynamics, to support conjunctions events operations is currently undergoing final validation. Several enhancements and missing functionalities with respect to the precursor prototypes have been identified by executing the new software using as example operational cases of collision maneuvers implementation. The new software will become operational in the next future to significantly ease support and decision making process for conjunction alarms in the Metop and future programs to come.

Acknowledgments

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Appendix A
Glossary

Best Information Available (BIA)	Feature of CONANA to automatically select the best of the available input data (regarding covariance matrix, position, velocity and size for primary and secondary objects). The sources of the data can be for example CSM, TLE, orbit file, miss distance and derived assumed velocity, manual input, telecommands, or covariance look-up database. The software handles the input data source prioritization if BIA is selected (the user can always force the selection of a certain data source).
Conjunction Summary Message (CSM)	File containing full state vectors, covariance matrices and orbit determination details for both objects (for Metop-A conjunctions within an ellipsoid of radial x along x cross 300x2500x1250m)
Collision Warning Message (CWM)	File containing TCA and miss distance information (total and components) for all (secondary) objects within 5km from Metop-A for the next 5 days.
Depth of Intrusion (DoI)	Scale factor to be applied to the debris covariance ellipsoid in order to have the spacecraft trajectory tangent to it (normally at a slightly different TCA). In other words, the DoI is the ellipsoidal distance (and not the spherical distance) expressed in debris position uncertainty standard deviation units.
SATCAT catalogues	File containing estimated Radar Cross Section (RCS) for all catalogued objects.