COLLISION AVOIDANCE STRATEGIES, IMPLEMENTATION AND OPERATIONAL EXPERIENCE FOR DEIMOS-1 AND DEIMOS-2 MISSIONS

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Abstract: Deimos Imaging (Spain), a subsidiary of UrtheCast Corp. (Canada), owns two commercial Earth Observation (EO) missions, DEIMOS-1 and DEIMOS-2. Deimos Imaging is in charge of operating both satellites and commercialising their imagery. Launched in 2009, DEIMOS-1 is a 100-kg satellite based on SSTL-100 platform equipped with a warm-gas resistojet, and currently at the beginning of its 5-year extended lifetime. Launched in mid-2014, DEIMOS-2 is a 300-kg satellite based on Satrec Initiative SpaceEye-1 platform equipped with a low-thrust Hall-Effect plasma thruster. Both missions fly on Sun-Synchronous Low Earth Orbit (LEO), with mean altitudes of 660 km for DEIMOS-1 and 620 km for DEIMOS-2. This orbit environment is known for its high density of operational and non-operational objects, and thus an efficient Collision Avoidance (CA) procedure is of key importance to assure the survivability of each mission. This paper presents an overview of Deimos Imaging Collision Avoidance activities, based on the operational experience for DEIMOS-1 and DEIMOS-2 missions. Operational tools, theories and procedures used are outlined, aided by real-life examples of conjunction events.

Keywords: *DEIMOS-1, DEIMOS-2, Collision Avoidance*

1. Introduction

DEIMOS-1 and DEIMOS-2 missions are fully owned and operated by Deimos Imaging (Spain), a subsidiary of UrtheCast Corp. (Canada). Successfully launched in July 2009, the DEIMOS-1 satellite is currently at the beginning of its 5-year extended lifetime, while the DEIMOS-2 satellite, launched in June 2014, is at the beginning of its 10 years of expected lifetime.

DEIMOS-1 is equipped with a multi-spectral optical instrument, having a spatial resolution of 22 m and a very wide swath of 650 km. Its imagery is mainly used for large-scale agriculture applications worldwide. DEIMOS-2 is an agile 300-kg satellite for very-high-resolution Earth Observation applications. It provides 75-cm pan sharpened images with a swath of 12 km at nadir, mainly for mapping, monitoring and security applications.

Both satellites are equipped with a propulsion system providing thrust in the millinewton range, with a specific impulse around 100 s for DEIMOS-1 (warm-gas resistojet), and 1000 s for DEIMOS-2 (Hall Effect Thruster). They both underwent a large orbit manoeuvring campaign just after launch, aimed at reaching the nominal operational altitude and ensuring an optimal natural (uncontrolled) evolution of the Local Time at Ascending Node (LTAN). After these initial campaigns had been successfully carried out, the activities of the Flight Dynamics (FD) team are centred on collision avoidance issues.

Both missions fly on Sun-Synchronous LEO, with mean altitudes of 660 km for DEIMOS-1 and 620 km for DEIMOS-2. This orbit environment is quite littered with space debris, and an efficient Collision Avoidance (CA) procedure is of key importance for assuring the survivability of each mission. In order to maximise the effectiveness of the CA, Deimos Imaging FD team is in constant communication with the Joint Space Operations Center (JSpOC). The need to give a quick and sensible answer to Conjunction Data Messages (CDMs) received from JSpOC drove the creation of the internal tools and operational procedures which are now the backbone of Deimos Imaging CA strategy.

A first set of tools, aimed at anticipating possible close approaches by using multiple TLEs to refine the orbit of an object, provide quick results and help the operators to easily assess the characteristics of any possible close approach. Additionally, tools to compute the collision probability and geometry at the B-plane based on CDM data are also available and used in actual operations to ease the decision-making process. Besides, tools implementing the latest developments in algorithms to create avoidance strategies are used to cross-check and refine the avoidance strategy. Finally, visualization and data-distribution tools are continuously being improved to guarantee that relevant information is made available to the appropriate people in a clear and concise manner.

This paper presents an overview of Deimos Imaging Collision Avoidance activities, based on the operational experience for DEIMOS-1 and DEIMOS-2 missions. Operational tools, theories and procedures used are outlined, aided by real-life examples of conjunction events.

2. Operational approach to collision avoidance

To face with collision alerts, the Deimos Imaging Flight Dynamics team has at its disposal two solutions:

- One internally developed, based on GPS data for the primary object (i.e. DEIMOS-1, DEIMOS-2) and Two Line Elements (TLEs) for the secondary object.
- One external, provided by the Joint Space Operations Center (JSpOC) and processed with Deimos tools.

Since the beginning of DEIMOS-1 mission, the latter one has been used as the baseline solution to make decisions while internal tools have been improving. Nowadays the collaboration with JSpOC is still active.

2.1. Nominal operations

The internal Flight Dynamics tool has the task of searching for the possible close approaches that can be predicted for the following days, and distributing the outcome among the team members. This close approach calculation has two phases:

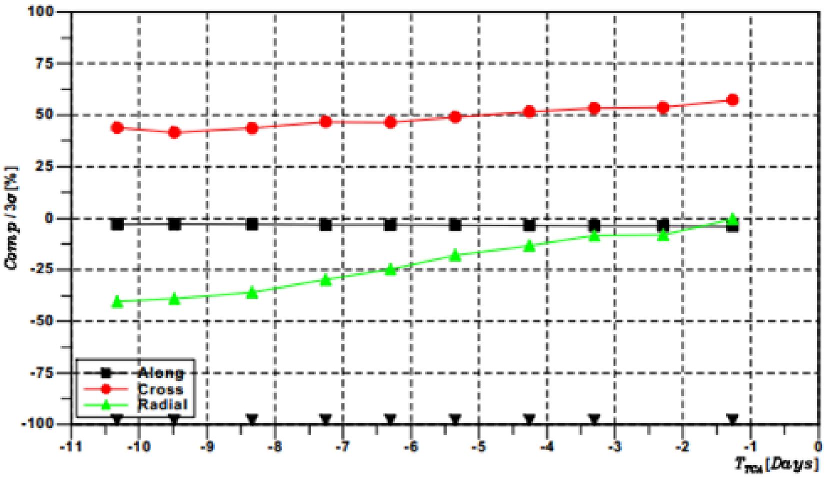
- A coarse analysis.

- A precise (smooth) analysis of each event detected by the coarse analysis.

Two main data sources are needed for that: one is the own satellites' GPS and the other is the last TLE of all the objects' registered in the spacetrack catalogue. Once the satellites' GPS data are downloaded, this data are fitted by means of a batch least square method to obtain the satellites' filtered state vectors.

The Coarse Close Approach Analysis compares the predicted DEIMOS-1 and DEIMOS-2 trajectories against the estimated trajectories of the objects listed in the spacetrack catalogue. It applies a series of filters to discard secondary objects which are going not approach the primary, monitoring only those close approaches with distances (radial, cross, along and total miss distance) below configurable thresholds. It is done as a 10-day forecast, such that the geometry evolution of the identified critical approach can be followed.

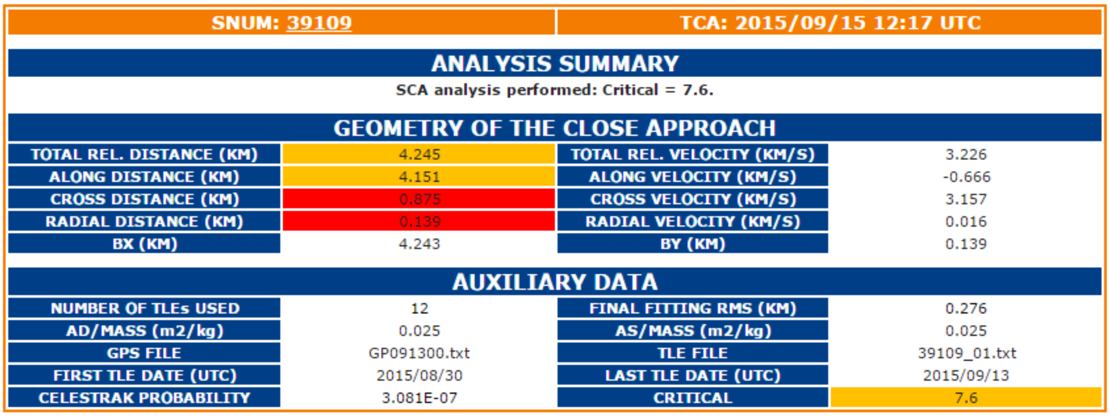
The next figure shows an example of the evolution of 3-sigma error components versus the remaining time to Time to Close Approach (TCA).



[1] 3σ values. Radial: 1.5km, Along: 5.0km, Cross: 5.0km, Total: 5.0km.
[2] Each data point is represented in the x-axis by the latest GPS data available.

Figure 1: Close approach geometry evolution.

An additional set of filters to tag close approaches as threats based on configurable distances and time-to-TCA thresholds is applied (nominally: Radial distance < 500 m, TCA < current time + 3 days) If the close approach is considered a "threat", the Smooth Close Approach Analysis retrieves and uses the historical TLE data of the identified secondary object, in order to better estimate its trajectory and provide fine information of the close approach geometry. Furthermore, not only distance and velocities are obtained but an external probability value (obtained from Celestrak.org) and criticality estimation (in a 0-10 scale) of the event calculated based on geometry, time-to-TCA and precision of the analysis is also provided in the report. The following figure shows an example of Smooth Analysis report sent to the operations team at the end of its execution.



SNUM: 39109		TCA: 2015/09/15 12:17 UTC	
ANALYSIS SUMMARY			
SCA analysis performed: Critical = 7.6.			
GEOMETRY OF THE CLOSE APPROACH			
TOTAL REL. DISTANCE (KM)	4.245	TOTAL REL. VELOCITY (KM/S)	3.226
ALONG DISTANCE (KM)	4.151	ALONG VELOCITY (KM/S)	-0.666
CROSS DISTANCE (KM)	0.875	CROSS VELOCITY (KM/S)	3.157
RADIAL DISTANCE (KM)	0.139	RADIAL VELOCITY (KM/S)	0.016
BX (KM)	4.243	BY (KM)	0.139
AUXILIARY DATA			
NUMBER OF TLEs USED	12	FINAL FITTING RMS (KM)	0.276
AD/MASS (m2/kg)	0.025	AS/MASS (m2/kg)	0.025
GPS FILE	GP091300.txt	TLE FILE	39109_01.txt
FIRST TLE DATE (UTC)	2015/08/30	LAST TLE DATE (UTC)	2015/09/13
CELESTRAK PROBABILITY	3.081E-07	CRITICAL	7.6

Figure 2: DEIMOS-1 Smooth Close Approach Analysis for September 14th, 2015.

Additionally to the mentioned capabilities, every day the Flight Dynamics tool is in charge of creating an ephemeris file per satellite automatically sent to JSpOC. In this way, the organization is provided with the most updated and accurate predicted orbit, allowing them to achieve a fine estimation of the collision risk with any operational or non-operational space object.

This exchange of information is coordinated monthly among the parties, so not only the file names and the times are set, but also the thresholds for JSpOC to apply for each spacecraft.

As an answer to these daily files, JSpOC sends an email with the summarized results of its computation, and updates the dedicated section within Space Track with the CDM for each event.

The full nominal process can be summarized as follows:

1. Download GPS data.
2. Download NORAD catalogue.
3. High precision DEIMOS satellites orbit propagation.
4. Send both high precision orbit propagations to JSpOC.
5. Close approaches detection for the next 10 days (Coarse Close Approach Analysis).
6. Close approach in-depth analysis for detected events occurring at TCA<current time + 3days (Smooth Close Approach Analysis).

2.2. Conjunction Alert Notification reception and operational procedure

When a Close Approach Notification (CAN) is received from JSpOC, the event data are processed and rewritten in the form of a Conjunction Summary Message (CSM) report, containing a summary of the geometry of the event and the collision risk information. Considering the covariance matrix and the position and velocity of both objects provided in the CDM, a plot of the geometry in the B-plane is created, as Figure 3 shows.

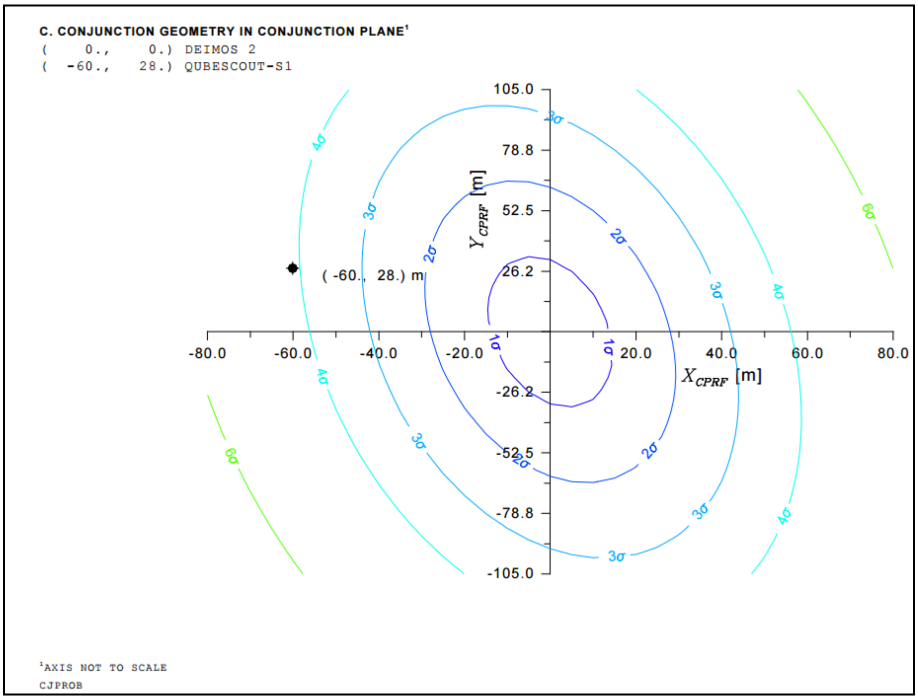


Figure 3: Example of collision probability calculation between DEIMOS-2 and QUBESCOUT-S1, based on a CDM.

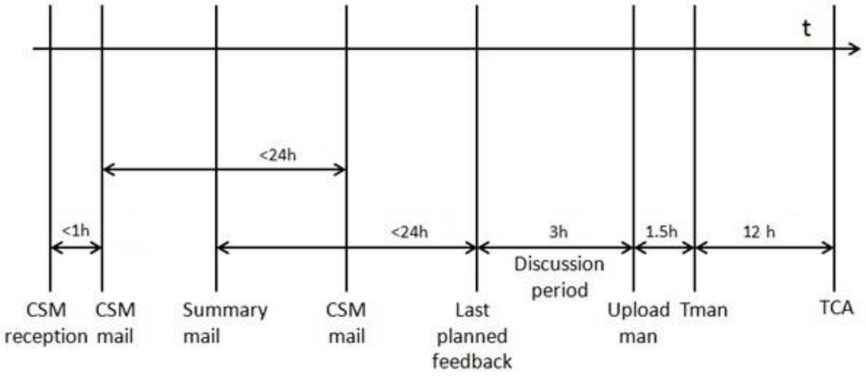


Figure 4: Procedure to CAN reception.

In parallel, the procedure whose main steps are outlined in Figure 4, starts. Based on the experience of the operations team, the procedure has the objective to guarantee that the relevant information is passed in a clear way to the management levels and to avoid missing important deadlines because of the stress of such a situation.

Since the reception of the first CAN, the time for a collision avoidance manoeuvre (Tman) and the corresponding pass to eventually upload it to the satellite, is identified (Upload man). This allows the collection of information as well as the iteration with JSpOC having a predefined deadline in mind since beginning: 16.5 h to definitely decide if performing a manoeuvre, 12 h between Tman and TCA.

The procedure foresees that as soon as a new GPS file is downloaded from the involved satellite, new orbit propagation is sent to JSpOC in order to allow them to update their calculation with the most recent data.

In case the secondary object is not a debris but an operational satellite, the operations team will contact with the operators of that satellite to exchange orbit information and agree on the possibility of manoeuvring or not. Management levels are informed by reports at every step of the analysis.

2.3. Manoeuvring criteria

If from the CAN analysis the event is considered critical, several aspects must be considered to decide if a manoeuvre is necessary.

- At first, the available time between the notification reception and the TCA. It is required quite a time to:
    - Perform the analysis to evaluate which is the best collision risk mitigation strategy.
    - Compute the manoeuvre and generate a simulated propagation.
    - Send a new propagation to JSpOC in order to cross-check the result and verify that the manoeuvre does not provoke another conjunction event with an additional object.
    - Generate the command file to be uploaded to the satellite.
    - Verify its correct execution at subsystem level.
    - Generate new propagation to evaluate the effect

  This time is generally around two days. However, if the close approach is critical and the notification is received with less time, the iterative process with JSpOC shall be obviously minimized.

- At second, the evolution of the conjunction event.

- At third, the relative velocity.
  What is important is to know how the second object is approaching DEIMOS satellites taking into account also the relative position between them. For example, if the second object is approaching the satellite from a negative radial distance, a manoeuvre is much more advisable if the relative velocity is positive than if it is negative.

- At fourth, the trajectory prediction.
  It is important to make calculations to know if the manoeuvre is going to leave the satellite in a better situation or, on the contrary, there is going to be a more dangerous close approach with the same object or with others secondary objects.

- Finally, the covariance matrices.
  If the covariance ellipsoids intersect and the collision probability is high, the avoidance manoeuvre must be considered.

After collecting all these information, a decision about doing or not the manoeuvre shall be made. It is not a decision based only on values not exceeding determined limits, since a critical analysis is needed, studying each aspect separately before reaching the final decision.

2.3. Manoeuvre implementation

With reference to the following table, there are two main effects to be considered when planning a collision avoidance manoeuvre: the radial displacement and the phasing movement.

Table 1: Effects of the avoidance manoeuvre.

	Radial separation	**Along track separation**
Description	Separate by increasing/decreasing the SMA.	Separate by increasing/decreasing the period
Position	Opposite to the conjunction event position	Flexible
Advantages	➢ Radial miss-distance has best determination ➢ The effect is independent from the time between the manoeuvre and the TCA	➢ High separation when manoeuvre time is far from TCA.
Disadvantages	➢ Low change in SMA with DEIMOS thrusters ➢ Manoeuvre location fixed	➢ Time is a critical constraint. ➢ Along and Cross miss-distances not so well determined

If the decision by the end of the "Discussion period" (see Figure 4) is finally to perform a manoeuvre, the main parameters to take into consideration are:

- The time in which the manoeuvre shall be done
- The sign of the tangential manoeuvre (i.e. +/- DV)
- The manoeuvre location

It is worth mentioning that the duration of the manoeuvre and number of manoeuvres could be parameters to be considered, but as a result of previous manoeuvres campaigns with both satellites, it has been defined a fixed radial and along track displacement as baseline in such a way the operational procedure to generate the manoeuvres is already defined. With 12 h between Tman and TCA a gap in phasing of about 1 km and a radial displacement of 15 m is obtained. This corresponds to a manoeuvre of 60 s for DEIMOS-1 and to a manoeuvre of 240 s for DEIMOS-2.

With respect to the direction in which the manoeuvre shall be performed, the geometry of the event shall be considered in order to choose the most appropriate kind of manoeuvre (+DV or -DV)

Table 2: Effects of a positive and a negative tangential manoeuvre.

Effect	**+DV**	**-DV**
Radial separation	Increase SMA/radial distance	Decrease SMA/radial distance
Along separation	Increase period/SC arrives later	Decrease period/SC arrives earlier

Regarding the decision of where the manoeuvre shall be done, it is important to take into account the following aspects:

- The manoeuvres can be executed at any orbital position, but to ensure the maximal radial separation at TCA, it has to be performed at the orbital position diametrically opposed to TCA.
- Satellite's battery voltage must be higher than a reference value imposed by the manufacturer. This point shall be considered because if this threshold is not

fulfilled some payload activities shall be cancelled or the manoeuvre time shall be displaced to fulfil this requirement in case the payload activities had priority.

- Satellites payload cameras must lie in a very accurate range of temperatures avoiding sun-pointing so as not to damage the sensors. As a consequence, the manoeuvre shall be allocated in a safely region according to surveillance protocols.
- Manoeuvring require additional pre-manoeuvre operations (pointing and propulsion subsystem preparation). This has to be taken into account as well as the available pass to upload the manoeuvre to establish the earliest manoeuvre possible time.

3. DEIMOS Satellites' Operational Experience

3.1. DEIMOS-1 Operational Experience

Since the launch of DEIMOS-1, more than 50 CSMs/CANs have been received, with a total of 15 proved to be risky, and 5 finally needing a manoeuvre to avoid the collision.

One remarkable close approach conjunction was a dual conjunction between DEIMOS-1, a FENGYUN-1C debris and an H-2A debris whose closest approaches were separated by a short time period, with notice of only one day before the first TCA. This case falls within a category of events where an avoidance manoeuvre led to worsen the situation with the second-event object.

The first conjunction took place on 8th November 2012 at 08:42 UTC and the second one on 9th November at 06:11 UTC.

The conclusions that arose after analysing both notifications were:

- There were two possible conjunctions within 22 hours. The first one would happen only 26 hours after the first warning received.
- Secondary determination errors were quite low.
- The overall distance for the first alert was 52 meters, with 12 meters in radial.

The key data obtained from the first are summarized in Table 3. Bi-dimensional analysis in the conjunction plane is shown in the following figures.

Table 3: Evolution of the Probability Conjunction for DEIMOS-1 with FENGYUN-1C and H-2A debris.

Probability of conjunction (P_C)	**First Object**	**Second Object**
Before manoeuvre	1.5 e-4	1.6 e-21
After manoeuvre	1.6 e-18	no conjunction

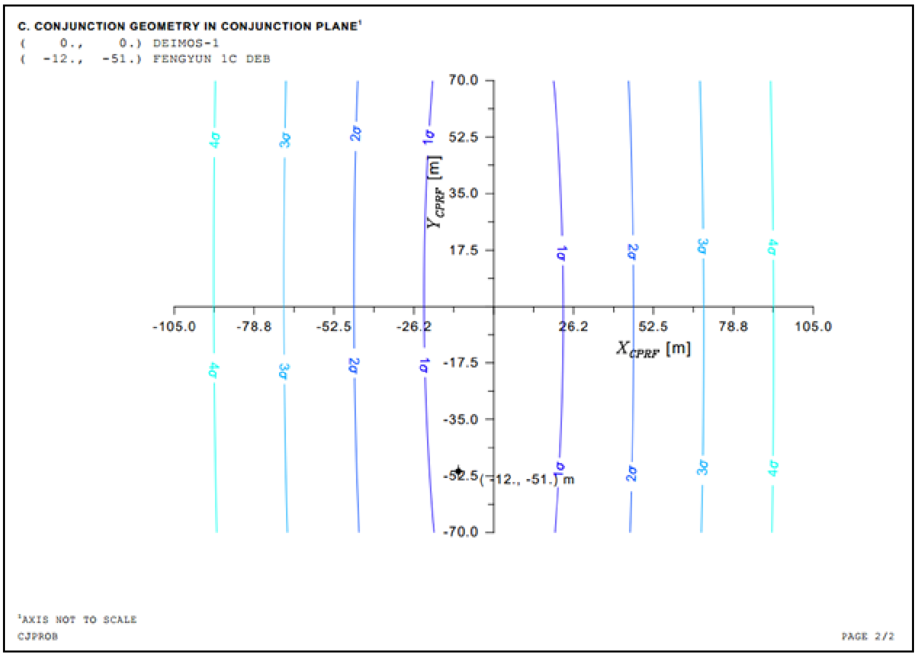


Figure 5: Bi-dimensional analysis in conjunction plane of CSM #1 for FENGYUN-1C.

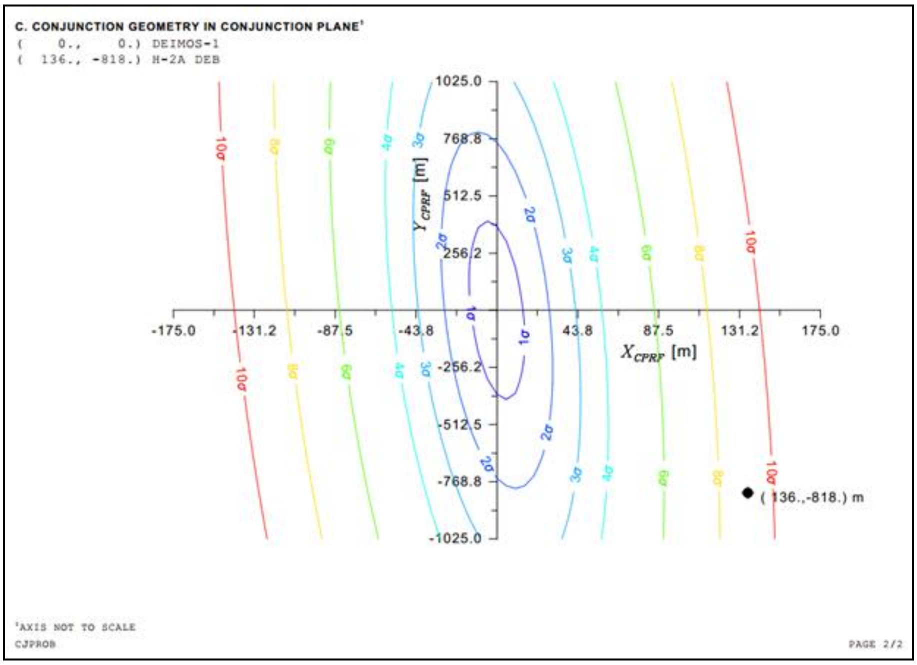


Figure 6: Bi-dimensional analysis in conjunction plane of CSM #1 for H-2A.

This data show that the collision probability with H-2A was quite low, being over 8σ. The problem was that this situation could worsen in case a collision avoidance manoeuvre was done to avoid FENGYUN-1C. This could lead to a very threatening situation, as there would have been no time to perform a second manoeuvre.

Considering all the information available, a simulation of a manoeuvre was done. It was decided that a 60s +DV manoeuvre would have been done 20 hours before the first close approach. The reasons why this manoeuvre was selected can be summarized as follows:

1. As the radial miss distance was negative with respect to FENGYUN-1C, i.e., the object approached from below, a +DV manoeuvre was needed in order to increment that distance.
2. A 60 seconds +DV manoeuvre was calibrated to elevate the semi-major axis about 70 meters.
3. The phase-time shift effect would be high enough to rise the overall miss distance up to 10 km approximately.
4. The combination of radial increment and phase shifting would cancel the Close Approach with object H-2A.

As JSpOC did not reply on time with the prediction of this simulated manoeuvre, another 60s +DV manoeuvre was planned four hours later (that is, only 16 hours before the first TCA), propagated and sent to JSpOC. Their reply to this last manoeuvre was that the collision with object H-2A was avoided, and that the effect over the geometry with FENGYUN-1C was as expected: an increase in radial separation with along/cross separation as well.

Bi-dimensional analysis in conjunction plane:

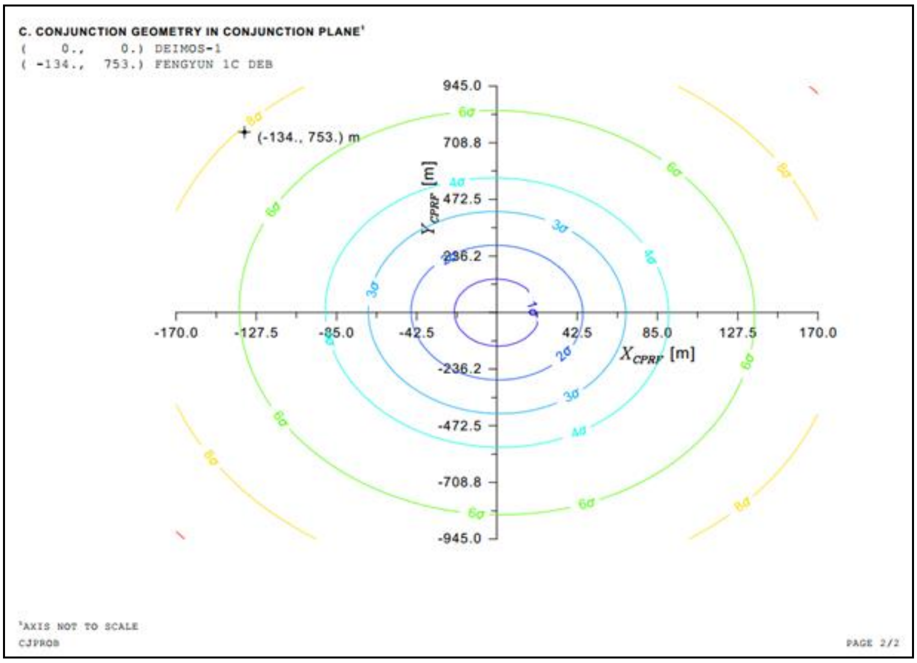


Figure 7: Bi-dimensional analysis in conjunction plane of CSM #2 for FENGYUN-1C (simulated).

The manoeuvre was positive tangential as the secondary approached from below (relative radial distance less than zero), so an increase in SMA would lead to bigger relative radial distances. In addition, the overall miss distance will also increase due to the phase-time shift effect. Both objects were successfully avoided.

3.2. DEIMOS-2 Operational Experience

Since the launch of DEIMOS-2, around 20 CDMs/CANs have been received, considering two of them as risky, but no collision avoidance manoeuvre has been performed until the current date.

One interesting event happened only one month after DEIMOS-2 launch. A manoeuvring campaign composed of around one thousand manoeuvres was performed at the beginning of the mission in order to move the satellite from the injection orbit to the desired one. Right after starting the campaign, the first conjunction warning was received just two days before the TCA and the event involved DEIMOS-2 and RapidEye 1 satellites.

At that moment, DEIMOS-2 had on-board a set of planned manoeuvres to be performed. Right after receiving the CAN, a continuous communication with JSpOC followed, in order to inform them of the manoeuvres already performed, and to provide them with the predicted orbit, considering the manoeuvres already scheduled.

On-board uploaded manoeuvres were a set of combined out-of-plane and in-plane manoeuvres, with the objective of decreasing the inclination and increasing the semi-major axis. The uncertainties related to the already ordered manoeuvres (e.g. confirmation of the successful firing, thruster misalignment…) were considered to analyse the collision risk.

Both satellites were flying in similar co-planarian orbits with opposite velocity vectors

Additionally, it is worth to mention that, as the secondary object was an operational satellite, the engineers in charge of the collision avoidance of the secondary object contacted with DEIMOS-2 operations team in order to exchange the JSpOC information regarding the conjunction.

As lesson learned of this close approach notification was that the exchange of information between JSpOC and the operations teams is vital for assure the integrity of the satellite. Moreover, a protocol of providing JSpOC with updated ephemeris twice per day during the manoeuvring campaign was set up.

4. Future work

The plan for future developments related with operational collision avoidance issues is twofold: on one side, an objective is to integrate the operational tools available for both DEIMOS-1 and DEIMOS-2 missions, simplifying the interfaces and easing the distribution of relevant information to the key actors involved.

On the other side, since over the last years improvements within the DEIMOS-1 internal software, aimed at finding the possible collision events and their conjunction probability, have been made, an in-depth analysis is scheduled to demonstrate its reliability level against the JSpOC solution.

The DEIMOS-2 flight dynamics software has also a direct interface with two other tools: CORCOS (COllision Risk COmputation Software) devoted to the computation of collision risk between two objects, and CAMOS (Collision Avoidance Manoeuvre Optimisation Software) devoted to the evaluation of different mitigation strategies through the optimisation of avoidance manoeuvre parameters (see Ref. 2). These two tools could be shortly employed once tested with operational cases.

5. Conclusions

Thanks to the technical base and specialised knowledge of Deimos in the field of Flight Dynamics, a wide set of tools related to the foreseen collision avoidance activities was already available for the Operation's Team before the launch of DEIMOS-1.
Then, thanks to the continuous effort of the team, operations since the beginning of DEIMOS-1 mission have been used as the most precious test bench to improve the experience on the available tools, to consolidate the relationship with JSpOC and to better the information flow towards each relevant stakeholder in Deimos Imaging.

The launch of DEIMOS-2 has started a new challenge, as its low-thrust thruster implies a redefinition of some of the avoidance strategy standards valid for DEIMOS-1. As a consequence, the consolidated operational procedures inherited from the DEIMOS-1 experience are going to handle collision avoidance activities not only for multiple satellites in parallel, but also for satellites with different types of thrusting capabilities.

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