GENERAL COLLISION AVOIDANCE MANEUVER DECISION ALGORITHM

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ABSTRACT

Recent advances in Space technologies will cause significant increase in satellite launches in next decade. One of the major problem of satellite operation teams are to keep their satellites free of collision risks. In near future, the number of Collision Avoidance maneuvers will be increased significantly as a result of increase in satellite launches. Conjunction messages provided by Combined Space Operations Center (CSpOC) notifies satellite operators about the possible risks of collisions for the space debris or other satellites. Satellite operators perform their own way of evaluating significance of the Conjunction Data Messages (CDM). There is no common evaluation method in the industry. Collision Avoidance Maneuver Execution causes significant loss of effort, source and service. Therefore, it is important to execute a maneuver if the CDM is evaluated as risky. In this study, new way of evaluating CDM messages by taken into account not only the CDM parameters but the mission specific parameters are proposed.

1 INTRODUCTION

It is expected that hundreds of satellites to be launched into orbit every year [1]. As a consequence, CDM messages issued in CCSDS format [2] will increase dramatically, causing satellite operation teams to be alerted to the new messages 24/7. Current debris tracking systems does not track space debris smaller than 10 cm in Low Earth Orbit (LEO) [1], it is estimated that there are more than 500,00 objects big enough to cause damage on spacecraft of satellites. Currently the CDMs for the objects bigger than 10 cm have CDM parameters consistent internally (for example, probability of collision (PoC) increases as the Miss Distance decreases). Although, some of the CDM parameters are interrelated to each other this study takes their effect on GO, NO-GO decision separately, the main reason is to generalize the decision algorithm without defining additional constraints for the CDM messages. In near future, tracking objects smaller than 10 cm can be possible which has independent and unreliable characteristics for each parameter, such as PoC, the Miss Distance and Covariance of objects can be computed with different certainty, in that case the General Collision Avoidance Maneuver Decision Algorithm will still be applicable.

CDM is generally issued 72 hours before the Time of Closest Approach (TCA). The subsequent CDM messages are broadcasted in every 6 to 8 hours, which makes around 9 CDM messages to be issued before the closest approach starting from the first CDM. However, total time needed to plan, prepare and execute Collision Avoidance Maneuvers (CAM) can be time consuming. The CAMs are performed to decrease collision risks; further analysis may be needed to guarantee that the planned maneuver does not increase PoC.

CAMs cause satellite services to be interrupted for a period of time. Therefore, deciding a collision avoidance maneuver is a trade-off between "interruption of service and resource usage" versus "risk of collision". CDMs include probability of collision (PoC) for a specific object (Obj2) with the operational satellite (Obj1). Most of the time the Obj2 is a space debris, with no possibility for maneuver. Therefore, all the actions should be taken by Obj1 responsible entity to prevent collision. CDMs are issued in every 6 to 8 hours. In every CDM, the miss distance and PoC changes, normally the changes are minor, but sometimes dramatic changes in the CDMs are also observed, sudden changes in PoC of CDM may cause operations team to miss the uplink of maneuver commands into satellite if initial risks are evaluated as LOW. This can jeopardize satellite operations and cause permanent loss of functionality. Sometimes it is crucial to plan a maneuver even if the PoC is not high (less than 5.0E-5), taking into account the possibility for an increase of PoC in subsequent CDMs. In those cases, the reliability of measurements or covariance against miss distance of Obj2 should be taken into account. This study defines, explains and evaluates mission parameters and CDM parameters to facilitate GO/NO GO decision for the Collision Avoidance Maneuvers.

2 CAM PROCESS

Generally, the process of CAM analysis, preparation planning and execution can be divided into the following phases.

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1.) Monitoring and analysis phase
2.) CAM Preparation, Planning and Validation (PP&V)
3.) CAM execution and post maneuver operations.

2.1 Monitoring and Analysis Phase

Satellite operations team should continuously monitor the CDM messages. Once received, initially the miss distance and PoC values of each CDM messages are analyzed, then the observation times and relative position and velocity of the objects should be analyzed, characteristic of the Obj2 should be checked to see if it is a maneuverable object or not.

If miss distance and/or PoC exceeds threshold values (both of them or PoC), then preparation and planning of CAM phase starts with determination of maneuver epoch which is computed by taking into account:

- the TCA,
- last pass to be used as uplink of maneuver commands,
- satellite routine and maintenance operations,
- and separation between objects needed to minimize the collision risks.

For LEO satellites the maneuver execution should be done multiple orbit before the TCA to guarantee separation between objects are high enough to mitigate collision risk.

The Monitoring and Analysis Phase yields three key outputs for the CAM, which are:

- the orbit (start and end of orbit) where the maneuvers should be performed,
- delta velocities,
- direction of thrust

The collision risk should be analyzed very carefully, executing a maneuver while it is not needed causes loss of services, effort and valuable resources; not executing a maneuver while it is needed is also significant problem, not only for the satellites own mission but also can put other missions' life at risk. Section 4 of this study focuses to provide a guideline to mission coordinators and/or mission managers for deciding GO or NO GO for a maneuver based on parameters extracted from CDM and some of the key characteristics of the mission.

2.2 CAM Preparation, Planning and Validation Phase

This is the phase Flight Dynamics responsible notifies mission coordinator about the CDM message with some of the key parameter of the CDM (time of closest approach, PoC). Mission Coordinator and Flight Dynamics responsible coordinate the activities related to the CAM. CDM message has data for two objects, called Obj1 and Obj2. Generally, the Obj2 is a space debris, which is unable to make maneuvers. Therefore, the only way to decrease collision risk is to plan and execute the maneuver for Obj1. In case the Obj2 is also a maneuverable object, coordination and communication with Obj2 controllers and owners should be done before taking maneuver decision.

The preparation part of this phase includes determining type of the maneuver, such as the direction of thrust and argument of latitude at the orbit specified during the Monitoring and Analysis Phase. These two values, together with delta velocity magnitude applied to satellite during the maneuver, causes collision risks to be decreased. In some missions maneuvering in a specific argument of latitude with certain thrust direction may not be possible because of the mission constraints (payload or sensor constraints). Preparation phase tries to find an optimum solution for the CAM. It could be difficult to find the best solution, in those cases repetitive computations are done to find a solution which does not risk satellite and mission. Having very detailed procedures, automated tools and experienced team is crucial for this phase.

The planning part of this phase includes, determining the pass to be used for the uplink of the commands (general approach is to reserve at least two passes for the uplink, one pass as a backup), generation of maneuver commands, generation of post maneuver ephemeris file, post maneuver contact table and generation of post maneuver orbital events should also be planned and performed. Distribution of orbital elements into ground systems should be performed after a GO decision. If there are more than one maneuver, then post maneuver products should be generated for each maneuver with an assumption that the previous maneuvers are performed successfully.

Multiple CAMs can be performed by taking into account satellite passes such that a satellite contact should exist between maneuvers. In that case, result of each maneuver can be evaluated with the telemetries downloaded during the pass.

The maneuver commands are generated and kept ready for the uplink, in some missions, simulation of maneuvers should be performed to validate maneuver commands. The simulation should be completed before the commands are uplinked into satellite.

The overall computations explained in this section should be completed before the satellite pass which is reserved for the uplink of maneuver commands. Appropriate time should be reserved for decision authority to give GO/NO-GO decision.

2.3 CAM Execution and Post Maneuver Computations

Post maneuver computations include maneuver efficiency computations and post maneuver orbit determination activities. These computations are performed using the telemetries collected after the CAM. After the post maneuver ephemeris is generated, new ephemeris file, new orbital event file, and satellite contact tables are prepared and distributed into other ground segment modules. Maneuver report is written to summarize all of the activities performed with in the scope of CAM.

3 ALGORITHM PARAMETERS

The General CAM Decision Algorithm uses two types of parameter set, one set of parameter set is extracted from incoming CDMs, the other set is generated from mission characteristics.

3.1 Parameters extracted from CDM

Table 1 CDM Parameters

Name of the Parameter	Unit
TIME OF CLOSEST APPROACH	YYYY-MM-DDTHH:MM:SS
MISS DISTANCE	meter
COLLISION PROBABILITY	-
RELATIVE POSITION	meter
RELATIVE VELOCITY	meter/second
RELATIVE SPEED	meter/second
Covariance Matrix of Obj1	
Covariance Matrix of Obj2	
TIME_LASTOB_START of Obj1	YYYY-MM-DDTHH:MM:SS
TIME_LASTOB_START of Obj2	YYYY-MM-DDTHH:MM:SS
TIME_LASTOB_END of Obj1	YYYY-MM-DDTHH:MM:SS
TIME_LASTOB_END of Obj2	YYYY-MM-DDTHH:MM:SS
MANEUVERABLE of Obj1	boolean
MANEUVERABLE of Obj2	boolean

The parameters listed in table Table 1 are the ones extracted from CDM messages, some of the parameters are updated in subsequent CDM messages. They should be tracked during the Preparation, Planning and Validation Phase to be sure if there is a significant change which could affect CAM preparation.

3.2 Mission Parameters

Table 2 Mission Parameters

Name	Description
Loss of Service Ratio	[Loss of service duration in case the maneuver is executed] / [Remaining Lifetime of the mission]
Fuel Factor	[Expected fuel consumption] / [Fuel remained on board]
Mission Criticality	Determined by Mission Coordinator or Operations Responsible, if there is an ongoing critical maintenance activity and/or critical mission is planning to be done during the time of CAM

Mission constraints are only taken into account while the CDM constraints are evaluated as LOW or MEDIUM.

Table 3 Time definitions used in algorithm

Name	Description
ΔT_{Prep}	Time needed for maneuver preparation
ΔT_1	Time between CAM epoch and TCA
ΔT_2	Time between Command Uplink pass time and CAM epoch
T3	Start of time where nominal operations of satellite should be stopped or degraded because of CAM computation and execution
T4	End of time where satellite operations are resumed

4 ALGORITHM

Algorithm below describes how to collect CDM and mission related score points.

Maneuver preparation can be started as long as MOPT (Minimum Operational Preparation Time) in Eq. 1 and PoC in Eq.2 are satisfied:

$$MOPT > \Delta T_{Prep} + \Delta T_1 + \Delta T_2 \quad (1)$$

$$PoC < 5.0E-5 \quad (2)$$

$$5.0E-5 < PoC < 5.0E-4 \quad (3)$$

$$5.0E-4 < PoC \quad (4)$$

If Eqn. (2) is satisfied, then the collision risk is considered as LOW;

If Eqn. (3) is satisfied, then the collision risk is considered as MEDIUM;

If Eqn. (4) is satisfied, then the collision risk is considered as HIGH;

Figure 1 shows CAM Algorithm starting from first CDM notification, subsequent CDM updates are shown as "New CDM" in the figure, once a CDM message is evaluated as HIGH, the CAM commands should be generated and kept ready for possible GO decision.

General CAM Decision Algorithm is based on a maneuver score which is composed of sum score points of CDM and mission characteristics.

The maneuver score should be increased 70 points if the collision risk is HIGH.

The maneuver score should be increased by 10 points if Eq. (5) is satisfied and decreased 5 points if Eq. (6) is satisfied.

$$(MissDistance < 1\ km) \quad (5)$$

$$(MissDistance \geq 1\ km) \quad (6)$$

Where, the $MissDistance$ and PoC are the values of parameters from the latest CDM message close to $MOPT$.

The maneuver score should be decreased by 5 points if Eq. (7) is satisfied and increase by 5 points if Eq. (8) is satisfied.

$$(T_{LastObservation}\ of\ Obj2 \geq Older\ than\ a\ month) \quad (7)$$

$$(T_{LastObservation} of\ Obj2 \leftrightarrow within\ 3\ days) \quad (8)$$

The covariance of obj1 and obj2 are provided at TCA with respect to an object reference frame in the CDM. The CR_R, CT_T and CN_N elements of covariance matrix for both objects are analysed to determine the covariance contribution into Total CAM score. Generally, the covariance of obj2 is higher than that of the obj1. The higher covariance of objects given in CDM used in the analysis. Initially the relative position and velocity of the objects are analysed to understand possible collision geometry. If the objects are crossing each other in velocity vector direction (in that case the relative velocity in tangential component is higher), in that case the $\sqrt{CT\_T}$ should be used to evaluate the risk. Likewise, if the relative velocity vector in Radial component is higher, then $\sqrt{CR\_R}$ should be used to evaluate the risk.

The maneuver score should be decreased by 10 points if Eq. (10) is satisfied and increased by 5 points if Eq. (11) is satisfied.

$$Cov\_Obj = MAX(COV\_Obj1, COV\_Obj2) \quad (9)$$

$$[(\sqrt{Cov\_Obj.CT\_T}) or (\sqrt{Cov\_Obj.CR\_R}) \geq CovarianceThreshold \quad (10)$$

$$[(\sqrt{Cov\_Obj.CT\_T}) or (\sqrt{Cov\_Obj.CR\_R})] < CovarianceThreshold \quad (11)$$

Where, the $CovarianceThreshold$ is 1 km it is the same value used in Eq. (5) and Eq. (6)

Mission related score points are described below;

The maneuver score should be decreased by 5 points if there is no Mission critical operation or maintenance activity planned to be executed at $T_{ServiceInterruption}$ defined in Eq. (12). Likewise, it should be increased by 5 points otherwise.

$$(T4 \geq T_{ServiceInterruption} \geq T3) \quad (12)$$

The maneuver score should be increased by 5 points if the $Fuel\_Factor$, defined in Eq. (13) is more than 5 percent Eq. (14). Fuel factor is an indication whether the remaining fuel on board is above the fuel budget of the mission or not. In another words, it is a percentage value shows the deviation from planned fuel consumption.

$$Fuel\_Factor = \frac{[PFC] - [AFC]}{Total\ Fuel} \quad (13)$$

$$Fuel\_Factor \geq 5\% \quad (14)$$

$$Fuel\_Factor \leq 0\% \quad (15)$$

Likewise, the maneuver score should be decreased by 5 points if the $Fuel\_Factor$ is less than 0 percent Eq. (15).

Where, PFC is Planned Fuel Consumption since the beginning of the mission and AFC is Actual Fuel Consumption.

4.1 Computation of Total Maneuver Score

Total CAM score is a varies between 0 to 100, where;

- Values between 0 to 60 means, NO GO
- Values between 61 to 70 means, Mission Manager Decision
- Values between 71 to 100 means GO

$Total\ CAM\ score$ is computed by accumulating all of the CDM and Mission scores given in the Table 4 below.

The weight of each score is mission dependent. For example, in some missions, the weight of Fuel consumption could be higher (more critical) than Service interruption.

Table 4 Maximum and Minimum values of CDM and Mission Scores

Name	Range	Coefficient
PoC	Max: 70; Min: 0	A_0
Miss Distance	Max: 10; Min: -5	B_0
Last Observation time of Obj2	Max: 5; Min: -5	B_1
Covariance of Objects	Max:5; Min -10	B_2
Service Interruption	Max: 5; Min -5	B_3
Fuel Factor	Max: 5; Min: -5	B_4

If CDM is evaluated as HIGH, then the Eq. (16) is used for computing $Total\ CAM\ Score$.

$$Total\ CAM\ Score = A_0 + \sum_{i=0}^{4} \mathcal{R}(B_i) \quad (16)$$

Where, $\mathcal{R}()$ is a function defined in Eq. (17):

$$\mathcal{R}(X) = \frac{|X| + X}{2} \quad (17)$$

The $\mathcal{R}()$ function returns itself if the parameter value is positive, and returns 0 otherwise.

If the CDM is evaluated as MEDIUM, then Eq. (18) is used for computing $Total\ CAM\ Score$.

$$Total\ CAM\ Score = A_0 + \sum_{i=0}^{4} B_i \quad (18)$$

5 CONCLUSION

General Collision Avoidance Maneuver Decision Algorithm is proposed in this study. The main idea is to provide a general understanding of a CDM message, to provide more tangible value for a specific CDM about how critical is it for the mission.

Total CAM score gives an indication that how important is the CDM message for the mission. Performing a CAM with the score value of 71 vs 99 can have different meaning for the upper management, or customers who get service from the satellite. It gives more tangible indication for all parties involved in the process. Recording maneuver score for each CDM message is statistically important to evaluate total effort spent on monitoring, analysis and preparation of the CAMs and to predict danger of Collision Risks in near future.

The algorithm proposed in this study assumes all of the CDM parameters to be mutually independent from each other. This makes the CAM Decision Algorithm to be applied to any CDM, even if the parameters included in CDM are mutually dependent (e.g. the reliability of an Miss Distance is higher than that of PoC, and receiving higher PoC may not change Miss Distance and/or object co-variances in subsequent CDM messages).

The parameters used in this study does not address all mission specific constraints, but the components contained in this study contributing to total scores can be extended to suit the requirements of any mission by taking into account needs of other entities involved in the overall process, such as end users and agencies.

6 REFERENCES

1. Final Report-IG-21-011 - NASA's Effort to Mitigate the Risks Posed by Orbital Debris
2. CCSDS Conjunction Data Message Recommended Standard Blue Book June 2013 508.0b1e2

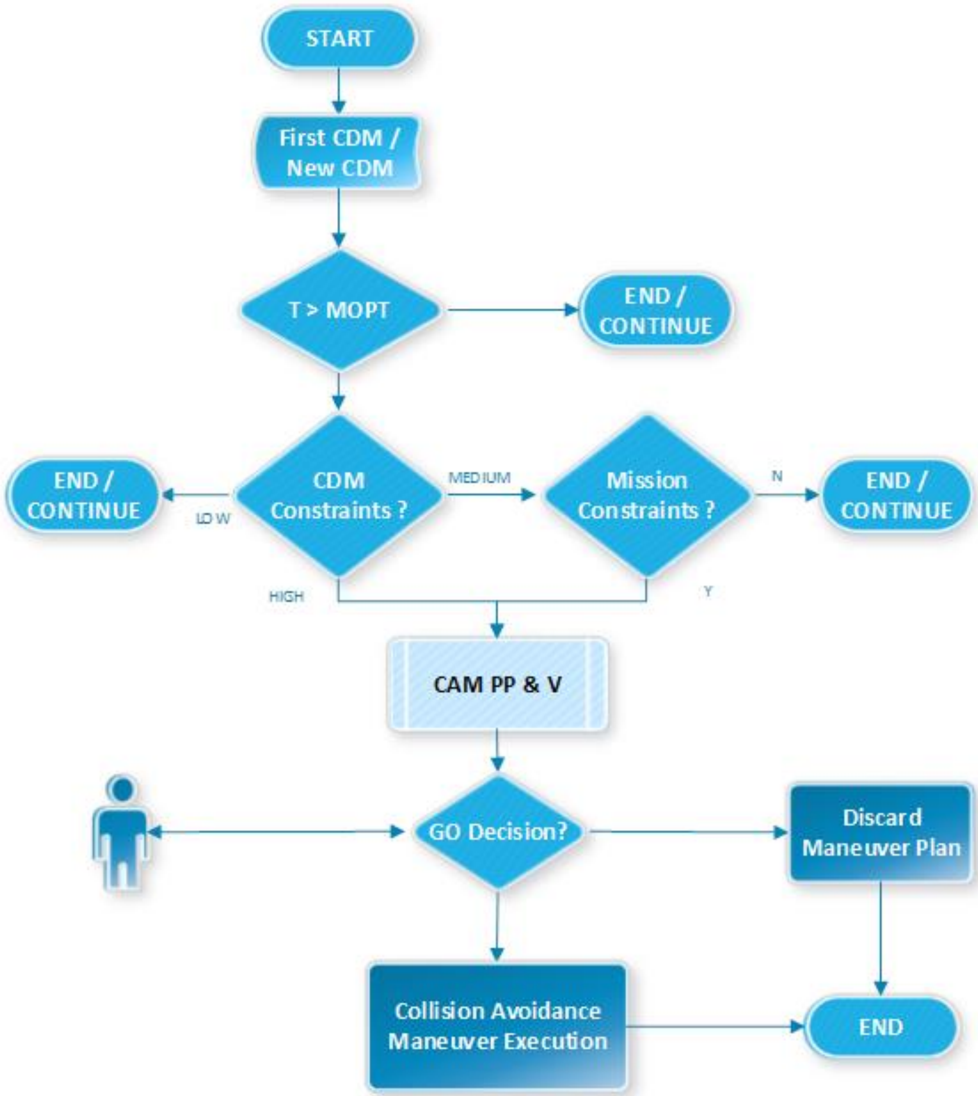

Figure 1 General Collision Avoidance Maneuver Decision Algorithm

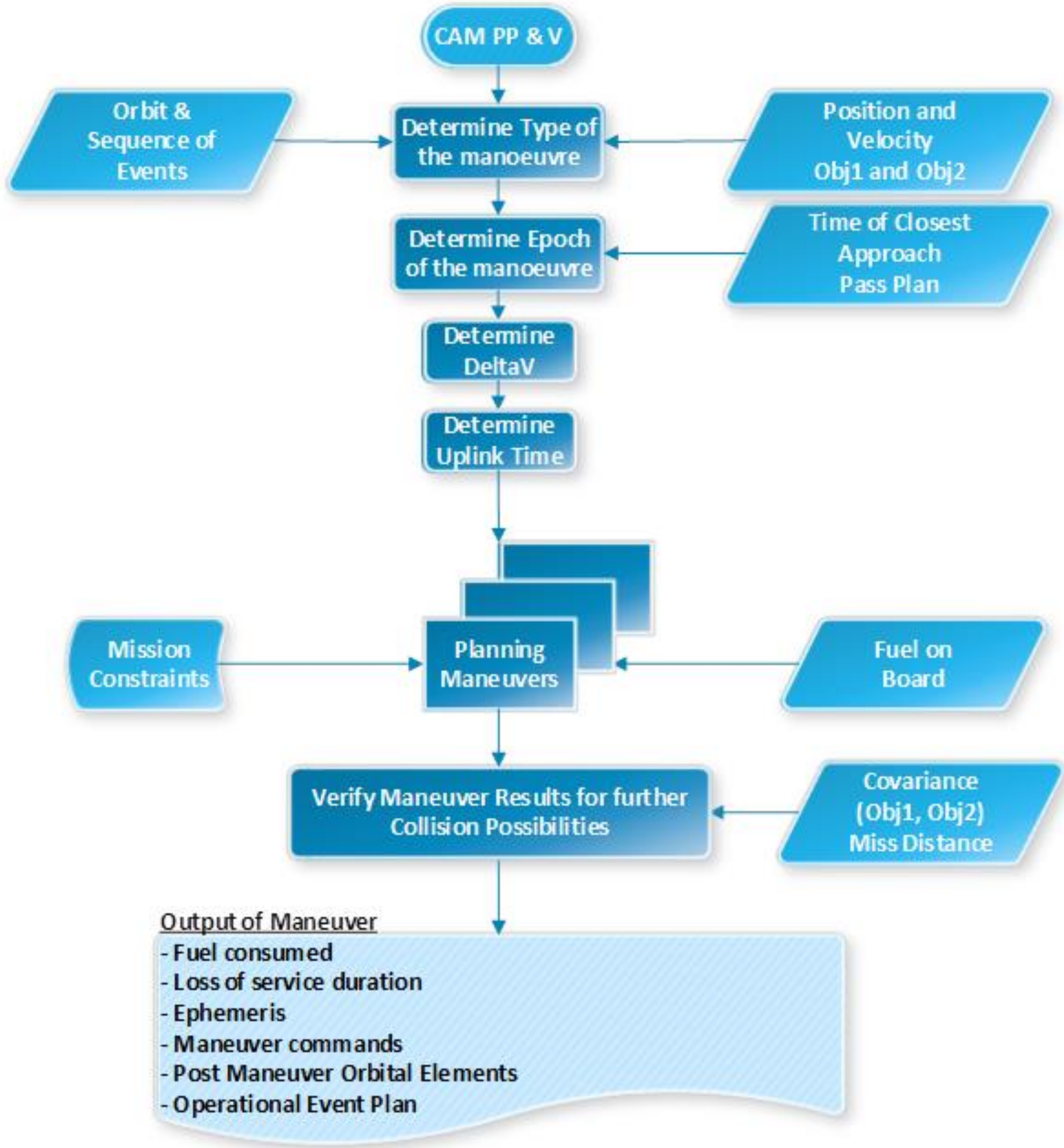

Figure 2 Collision Avoidance Maneuver Planning, Preparation and Validation