Mission Operations to Improve Space Mission Protection

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As the number of satellite launches increases, debris problem has become a significant issue. From universities and small companies to space agencies, operators have different strategies to deal with this problem as well as the space weather. This study reviews the current practice of satellite operators concerning security measures regarding space weather and space debris risks. The relevant background for conjunction analysis and collision avoidance is provided. Existing mission operations structures at various space agencies and operators around the world are investigated. Risks and vulnerabilities are summarized for orbits at different altitudes and improvements in operations are suggested for various scale operators.

I. Introduction

THE space environment which is composed of space weather, micrometeoroids and manmade space debris may pose significant threats to space missions. Among those, space weather may cause single event upsets on memory units, latch ups, damages on solar arrays and batteries, spacecraft charging as well as adversely effecting the communications. Collisions with debris and micrometeoroids can cause significant to catastrophic damage on spacecraft as well as increasing the amount of debris even further. In view of these hazardous effects of the space environment, satellite operators have to take actions to protect the space assets which are critical for the key segments of economy and security.

Currently, the Joint Space Operations Center (JSpOC) of the United States Strategic Command (USSTRATCOM)[17] is providing conjunction analysis services to operators worldwide to support collision avoidance operations. Based on their catalogue of objects bigger than 10 cm, standardized operations flows for collision avoidance exist for all major space agencies[8, 12-15]. In addition, Space Weather Prediction Center (SWPC) of National Oceanic and Atmospheric Administration (NOAA) is providing space weather information for satellite operators[19]. Besides these organizations, European Space Agency (ESA) has initiated the Space Situational Awareness (SSA) program to support satellite operators with Space Weather (SWE) and Space Surveillance and Tracking (SST) segments[1]. While the SWE segment provides real-time information (nowcasts) and forecasts on environmental conditions[18], the SST segment will provide a catalogue of objects and conjunction analysis services to support collision avoidance operations[2].

The satellite (and debris) population is increasing with more countries launching satellites, many without mitigation measures such as propellant for de-orbiting or collision avoidance. Therefore the number of conjunctions is likely to grow in the future, with any collision in space (such as the Cosmos-Iridium incident) significantly increasing the debris population. In addition, while big organizations with access to all sorts of data, tools and sensors to check for possible collisions and refine the data with further sensor measurements are able to implement standard procedures, most other countries and operators have varying degrees of awareness and capabilities regarding conjunction prediction, analysis and avoidance. Since the utilization of space is a global demand, the need for a coherent international cooperation is becoming more and more important.

In this paper, current practices of satellite operators concerning security measures towards predictions of space weather and space debris risks are reviewed. Existing mission operations structures at various space agencies and

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operators around the world are investigated. Relevant conditions at LEO, MEO and GEO are summarized and possible improvements to minimize the risks are suggested for the benefit of various scale operators.

II. Current Environmental Conditions and Operational Practices

Most satellites are in LEO, MEO and GEO and the relevant conditions for these specific regions in terms of space weather and space debris can be summarized in table below:

Table 1 Summary of Conditions at Different Orbital Altitudes

	LEO	**MEO**	**GEO**
Space Weather Conditions	Not so critical*	Very critical	Critical
Object Population Characteristics†	Very high density of both trackable (~5%, > 5cm.) and non trackable objects	Low density of trackable (>0.4 m.) and non trackable objects	High density of trackable (>1 m.) objects, stable regions are more populated
Conjunction Characteristics†	Impact velocities associated with conjunctions are high and collision risk is higher around polar regions	Relatively the lowest risk of conjunction with objects in space	Impact velocities associated with conjunctions are relatively lower

* However, it has to be taken into account in radiation shielding design and in the operations phase.
†Based on the analysis performed using the ESA MASTER 2009 software [30]

In view of the abovementioned environmental conditions, major satellite operators implement standard operations to protect their space assets against space weather events and collision. In this manner, the next two sections summarize the current operational frameworks, data sources and operational practices of these major organizations.

A. Operations With Respect to the Predictions of Space Weather

The effects of the space weather on a spacecraft can be categorized as long term and short term. Among these, long term effects can be handled (up to a point) through spacecraft shielding. However, shielding has little contribution to reducing the vulnerability to short term effects, or namely single event effects (SEE) [24]. In addition, radiation hardened components are costly and may not be available and not all satellite manufacturers have the expertise to incorporate effective protective measures in their software and hardware design. Therefore operations with respect to the predictions of space weather are important for reducing the adverse effects of single energetic particles.

In order to protect the systems and certain instruments on-board the spacecraft from the probable hazardous effects, the systems could be placed into safe mode and the instruments could be switched off when a strong radiation environment is predicted as in the case of MetOp-A[20]. However, it is important to have reliable estimates of the radiation environment since avoidance operations usually disrupt nominal operations and mission return.

To support operations with respect to the predictions of space weather, ESA has initiated the Space Weather Segment within the Space Situational Awareness program[1]. A precursor system within this segment called Space Environment Information System to support Operations (SEISOP) collects information from various sources and provides services through a web based client tool to support mission operations[3,4]. The majority of the space weather data that this system uses is provided by the NOAA and it is complemented by other space weather data sources worldwide through the interface called Space Weather European Network (SWENET). By having space weather and spacecraft data in one source, this system is developed to support mission operations by providing mission specific analysis, enhancing the awareness regarding space weather effects and uncovering possible cause-effect relationships to identify the interaction between a space weather event and spacecraft anomaly. However, the data are often fully available to ESA member states and possibly partners.

On the other hand, SWPC of NOAA provides real-time monitoring and forecasting of solar and geophysical events which may impact satellites, communications, navigation, and many other technological systems [19]. The data, products and services are shared with international partners and satellite operators mainly benefit from the alerts, warnings and watches on several categories that SWPC provides. Through the specific scales introduced for geomagnetic activity (K, Kp, A indices, G1 to G5), solar radiation activity (S1 to S5) and radio blackouts (R1 to R5), operators are informed about the severity of the space weather environment.

B. Collision Avoidance Operations

With the use of Space Surveillance Network of the USA (US-SSN), the JSpOC provides conjunction assessment services to the operators based on an extensive catalogue of more than 20000 objects. The service includes conjunction summary messages which are provided to operators 3 days in advance of the "time of the closest approach" (TCA)[21]. In addition, if an owner/operator provides the internally determined (most likely via Global Navigation Satellite System (GNSS) receivers) more precise orbit information to JSpOC, this assessment can be refined. However, several space agencies, such as ESA, NASA, JAXA, CNES and DLR have already developed their own operational frameworks/systems for conjunction assessment and collision avoidance operations[8,12-15]. The procedures differ slightly from each other though they are very similar in terms of operational frameworks. In this manner, a general framework for the collision avoidance operations can be seen in the flowchart below:

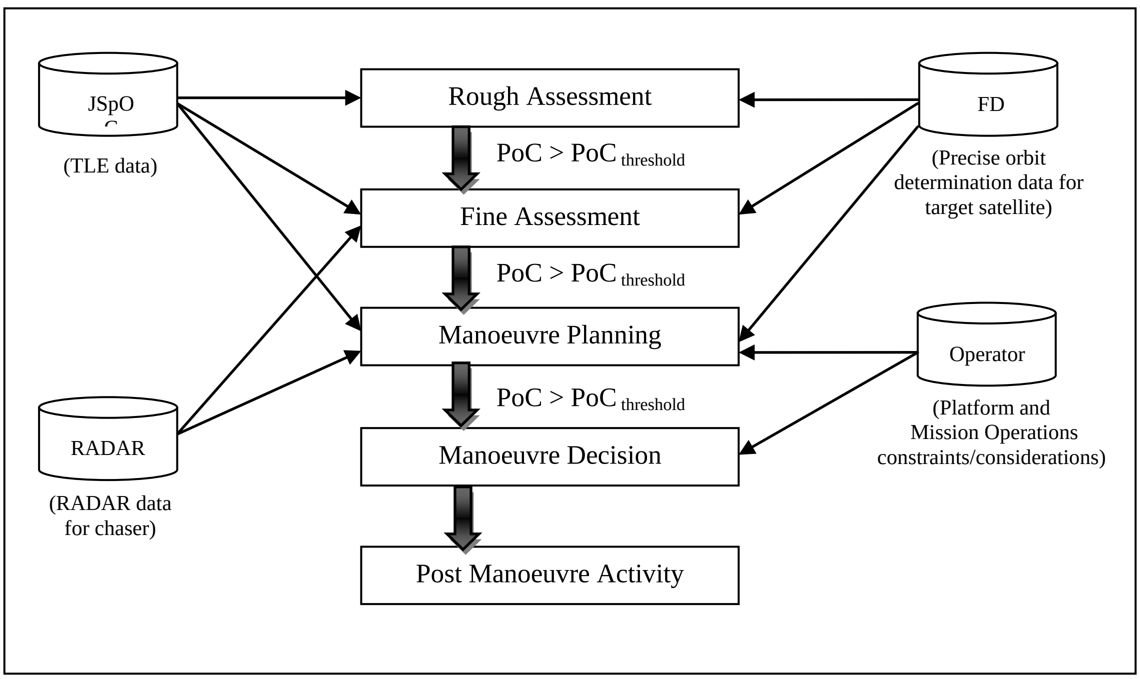

Figure 1. Standardized operational flowchart for collision avoidance.

The conjunction assessment procedures of the major agencies have many elements in common[8, 12-15] and a sample procedure will be explained here. Conjunction assessment teams of agencies make use of the in house generated precise orbit determination solution of the target satellite and Two-Line Element (TLE) data of all catalogued objects provided by the JSpOC for screening and an initial assessment of conjunctions over a time span of seven days ahead. At this point each agency has its own method to estimate the orbit uncertainty of the risk object via TLEs. Then, based on the initial conjunction assessment, the corresponding "probabilities of collision" (PoC) are calculated and checked if they are below or above a pre-defined threshold value. Usually this first step is automated. Later, if the probability of collision is higher than this threshold, a fine assessment procedure takes place by refining the orbit determination both for the target satellite and the risk object via updated measurements, most recent TLEs and, if required (and available), radar data. Considering that the updated probability of collision via precise estimations is still high, a collision avoidance maneuver (CAM) is designed based on mission and platform constraints. While the maneuver is designed, the post-maneuver orbit is also checked for potential collisions. Finally, the maneuver is executed if the trend of the evolution of collision probability is still indicating a significant risk.

The core to the above framework is the assessment of conjunctions with the objects in space. In this manner, tracking of and orbit determination for objects are the most important parts of the collision avoidance operations. Here, reliable tracking of as many objects as possible is essential to obtain a wide catalogue of objects to improve collision risk assessments. Currently, the catalogue of USSTRATCOM is the only open source to support mission operations in terms of collision avoidance[21]. On the other hand, French Air Force has a catalogue of space objects which is not public[13]. However, ESA has also initiated a Space Surveillance Tracking Segment within the Space Situational Awareness Program to provide conjunction analysis and collision avoidance services to spacecraft operators[2], though probably available to ESA member states and partners only.

The orbit estimation accuracy of the catalogue is also very important in terms of operations. The orbit prediction accuracy depends on the orbit type, the covariance (uncertainty) of the state vector determined at the initial epoch and time gap between this initial epoch and the epoch of the prediction (forecast span)[2]. Since this accuracy is a function of time, estimated conjunction geometry and probability of collision also vary over time. In this manner, it is important to have a data set which is fresh or accurate enough to support orbit propagations for the conjunction assessments.

Regarding the discussion above, using the TLE data provided by the US-SSN catalogue results in a high uncertainty for conjunction predictions which complicates the analysis further. The initial covariance of the TLE data is estimated by comparing the TLE data with a numerically propagated orbit which is then fitted to the TLE data[7,8,16]. As an example of such an analysis, estimates for the initial covariance are given by Flohrer[16] and propagation errors are provided by Wang [28]. It can be deduced from these studies that the biggest uncertainty usually occurs for along track direction and least for radial. These initial covariance values are considered to be high for conjunction analysis, or more specifically for orbit propagation from the initial epoch of the TLE data towards the TCA. Therefore, TLE data are often only used for the initial screening of the catalogue to detect a conjunction event. In this manner, the refinement of the orbit determination for the chaser (the object posing the risk) is then performed by using radar data (if available) which is comparable to GNSS data solution. If radar data are not available then the most recent TLEs are used. On the other hand, an accurate orbit determination for the target (spacecraft at risk) is performed by the flight dynamics (FD) teams using the GNSS data collected on board or by other means such as S-Band ranging. This additional information for orbit determination refinement is required well in advance to introduce a time interval for tracking data of four passages of the debris object, orbit determination, re-assessment of the collision risk and avoidance maneuver execution if necessary before the TCA.

Having the catalogue of objects as the primary data source, the first step of the conjunction analysis is filtering the huge number of objects to perform the search in a reasonable domain[7,10]. Any event passing the conjunction filtering is further investigated by considering the probability of collision. In practice, the significance of a conjunction event is mostly determined by an estimated probability of collision[9,10,11]. This probability is a function of the uncertainties in positions at the TCA, geometry of the encounter and sizes of the encountering objects [6, 10, 11, 29]. In addition to the probability of collision, the radial miss distance can also be considered as a risk indicator since uncertainty is the smallest along this component.

With the use of continuously updated orbit determination and associated covariance information, a conjunction event is analyzed throughout the previously introduced operational flowchart. At each step the collision risk is re-evaluated with respect to updated probability of collision. Since the covariance at predicted conjunction epoch is smaller for shorter time propagations of the ephemeris, it is more preferable to wait for fresh orbit determination information towards the TCA instead of executing the maneuver directly when the conjunction is detected.

Based on the continuously evaluated collision risk, the decision for executing an avoidance maneuver is decided on an accepted collision probability level (ACPL), which is defined by the spacecraft operator. Therefore ACPL value in turn indicates the threshold above which the collision avoidance maneuver is executed at a particular instant before the TCA. Here the execution time of the maneuver should be decided in such a way that the propellant consumption is minimized with respect to the platform and mission constraints. In addition, ACPL is also an important metric for mission design. Based on an annual flux of statistically distributed objects and an ACPL, some additional metrics such as annual collision probability, maneuver rate and risk reduction can be calculated and a total ΔV budget for collision avoidance and risk reduction can be estimated[11].

III. Proposed Improvements to Mission Operations

Since protective operations can only take place in response to risks that can be predicted, enhanced knowledge and understanding of the space environment and its effects on space assets are not only important for increasing the mission survivability but also to avoid unnecessary measures causing reduction in mission return. Therefore it is important to have as accurate risk information as possible for protective operations. In this manner, the room for improvement is smaller for big operators; however, there are many small scale operators with varying degrees of awareness and capabilities regarding space weather and collision avoidance. These countries and operators are becoming players in the space business and they have an increasing number of satellites. Considering various scale operators, several improvements for protective operations can be suggested.

1. Better risk analysis data

Currently the maneuver decisions are based on the limited JSpOC data and there is need for improvement of the database used for evaluating close encounters particularly for small operators. In this manner, operations companies may support relevant agencies (such as ESA and/or the JSpOC) in this respect by providing precise mission orbit data. This will especially improve near encounter alerts published by these agencies for their own missions. In addition, space observation by ground based sensors can be improved by globally interconnecting existing relevant sensor systems and establishing new sensors. This will improve the overall datasets with respect to the number of trackable objects (i.e., smaller ones will become trackable), the quality of the data and, as a consequence, the quality of the predictions. A good global distribution of the ground based debris tracking stations could improve the reliability of the data and thus the reliability of the predictions.

Another critical point is to make these collision prediction (and possibly avoidance maneuver suggestion) tools publicly available through a common access point so that operators can make an informed decision as to whether they should make a firing and, if required, regarding the time, extent and direction of the firing in a standardized manner. Some examples of such conjunction analysis tools are provided in a comparison study by George[27]. Public risk evaluation tools are also necessary in terms of estimating the impacts of the space weather.

Finally, there are also studies to improve the quality of conjunction analysis such as improvement of the risk indicators by Berend[25] and the predictions using TLE data by Levit[26]. While the former discusses a new risk indicating parameter based on radius and phasing conditions at the intersection of orbital planes, the latter contributes to achieving a requisite increase in orbit prediction accuracy for objects in the publicly available TLE catalog. Evaluating and implementing such methods could further increase the reliability of conjunction analysis procedures.

2. Better and standardized maneuver planning practices

In terms of maneuver planning, satellite operators perform maneuver design and post analysis themselves. Maneuver planning in response to an externally generated risk warning (e.g. from JSPoC) must be based on a thorough understanding of the data contained in the warning as well as well-established methods, which include tested and optimal algorithms. Furthermore, the input data should suit the propagators used (e.g. averaged TLE vs. osculating elements and forces to be taken into account, e.g. non-conservative forces). In addition, standard conjunction analysis tools must be available during the maneuver planning stage since it is necessary to check if the maneuver would increase the collision risk with another object. To summarize, the operations planning team must be armed with enough awareness, knowledge and analysis tools to execute a minimum of safe firings so that enough propellant is left for a maximum number of future avoidance maneuvers.

3. Collision avoidance as a routine part of the operations schedule

Since a collision in the space creates a global problem, the operators should make collision avoidance a routine part of their schedule. Currently, as far as the authors are aware, there is no study on how small satellite operators handle collision avoidance operations. An operational procedure for collision avoidance focusing on minimizing risk should be established by operators. A clear, realistic and well-thought-out decision-making tree should be set up and it must include all information to support fast and clear decision-making and to consider all relevant constraints such as restrictions of the mission and platform, station keeping, the performance and accuracy of the propulsion system and, most importantly, available propellant.

Establishing procedures alone is not enough. Necessary measures should be initiated as early as possible to reduce the risk of problematic progress of a near encounter situation by having time-overheads for all foreseen measures. Also heart of a CAM is the orbit data of both counterparts, and this data should be as up to date as possible and (as far as possible) be supported with information on the quality and robustness of that data (e.g.

covariances). Finally, it must be noted that, if the operations phase is performed by small scale operators (provided the SC has got an active orbit control system), special conditions have to be considered, such as limited human and ground station capabilities/coverage, platform constraints etc. In this case, early initiation of measures is even more important, implicating that automated early warning notification services should be used (e.g. as provided by the JSpOC).

Further, the state of such an event should be well documented to make sure that no information is lost through temporary staff changes or shift changeovers. Also, a well documented decision process can help if such situations reoccur later during the mission, maybe with a slightly changed and thus partly inexperienced team. Finally, if the near encounter situation is reasonably clear and stable, it is preferred to have an early CAM that is big enough under controlled circumstances compared to trying to avoid a CAM hoping that the situation will clear up itself (although radial separation will in most cases be more important than in-track, an early maneuver will also increase the in-track separation or decrease the ΔV demand). If a hasty action will have to take place shortly before the near encounter (e.g. during a night shift), this is especially error-prone. However, it is important to have enough ΔV and mission non-availability budget foreseen for that purpose.

4. Collision avoidance as a part of design

Although strictly not an operators' issue, collision avoidance operations should be evaluated from the design stage onwards with an allocated propellant budget. The ΔV budget and/or the mission concept must foresee CAMs and proper de-orbiting, shift to graveyard orbits or comparable actions (e.g. drag enhancing mechanisms for mini satellites without active orbit control), in order to keep man-used space as clean as possible. In addition, the mission concept has to foresee a budget of non-availability of the payload due to occasional CAMs, in order to make sure that safety of the mission (and cleanliness of space) has priority over availability of the payload also in practical operations life. Finally, an analysis of telemetry which is dedicated to identify and quantify degeneration of subsystems or parts, and an appropriate treatment during the operations phase of such subsystems or parts most likely to be threatened by micro-debris or –meteorites (e.g. recalibration or switch to redundant systems) should be established. In this manner, together with a functionality tree of subsystems (a comprehensive system diagram) including troubleshooting and problem indicators, critical situations can either be avoided, or rapidly be identified and overcome.

IV. Summary and Conclusion

Space weather, space debris and consequent collision risk have been a part of routine spacecraft operations. While bigger operators have the knowledge, means and methods to avoid these problems as much as possible, smaller operators rarely have access to such tools. However, a spacecraft failure or a collision creates problems for the whole orbit region and causes an even higher collision probability.

This paper studied the existing operations workflow for an "ideal" operations case, as practiced by bigger operators and tried to identify key problems, particularly for smaller operators. Improvements are proposed regarding higher awareness of collision issues leading to better procedures, availability of better orbit estimations and more reliable conjunction data, availability of tools to assist collision prediction and avoidance planning and incorporating collision avoidance and de-orbiting a part of the satellite design. The importance of acting early, along clear guidelines and with the help of reliable data is emphasized, particularly for smaller operators.

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