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Statistical Analysis on Conjunction Events for Satellites in LEO and Recommendation for Future SSA and STM

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Abstract

In this paper, statistics of conjunction events for recent year regarding KARI LEO satellites are thoroughly analyzed and reviewed. The satellite operation team is able to easily access the precise orbit ephemeris of their own satellite, that is primary object, at all times. However, the information of secondary object, which is approaching to the primary one, is very limited. In this case, one can rely on historical data and experience from statistical data as a reference. It is similar to the data-driven approach in artificial intelligence. The key parameter for statistical analysis includes type(debris, rocket body, and satellite), size, orbital characteristics (altitude, eccentricity, and inclination) of the secondary object, and allowable time to respond against collision risk from initial identification or notification. The minimum distance, covariance, collision probability, and the time of closest approach should be covered in the analysis by using historical real-flight conjunction events. In addition, information about operator in terms of country is also valuable to examine a feasibility of future interface for communicating each other if needed. The size of secondary object, RCS(radar cross section), is also meaningful to get some insight for requirement of ground-based tracking system such as radar, laser, and so on. This study aims at minimizing the false alarm, providing more reliable conjunction assessment, and generating operationally applicable procedure for future SSA and STM, based on statistical results.

Keywords: Conjunction Event, Low Earth Orbit, Space Situational Awareness, Space Traffic Management

1. Introduction

With ever-increasing number of space object, collision risk of space system with space debris or other satellites is getting higher and higher. In addition, recent deployment of mega constellations makes our space environment more complex and congested. In order to cope with this, SSA(space situational awareness) and STM(space traffic management) are essential to ensure safe and sustainable use of outer space for future generation. The primary objective of SSA and STM research is to ensure flight safety and mitigate collision risk for the full cycle of space systems including on-orbit collision avoidance and end of mission disposal. While SSA is to discover, monitor, characterize, and provide warning for a conjunction event, STM focuses on operations with an interaction and coordination between operational entities. The first step is to identify, analyze, and evaluate the collision risk completely. And then, some appropriate mitigation actions should be taken in advance to avoid catastrophic consequences. These activities should be done in an accurate and timely manner.

2. Satellite Operations in KARI

As of 2022, five(5) satellites in low Earth orbit and three(3) satellites in geostationary orbit are being operated and controlled by KARI (Korea Aerospace Research Institute) in Daejeon, Republic of Korea, as shown in the Table 1. Moreover, 15 satellites will be placed into LEO in the next few years. This means that more frequent conjunction events are expected without doubt and an operation team should prepare their action plan according to the procedures in a guideline and/or manual.

For the routine operations, CA-FAST (Conjunction Assessment - Flow Automation Support Tool) is a main in-house software for risk mitigation against conjunction events. It is able to automatically generate the conjunction analysis report between KARI satellites and other space objects including space debris, without any human intervention. The first step of the work flow is to digest the various input data from internal and/or external entities. And, then it synthesizes and visualize the data depending on the minimum distance, covariance, collision probability, and the time of closest approach. If an event violates the pre-defined yellow limit, the tool investigates the event in more detail. In some cases, the precise ephemeris for KARI satellites is uploaded to the CSpOC server for a subsequent re-evaluation against the close approach. At each step, the initial/intermediate/final reports are distributed to the flight dynamics engineers and the mission operation manager via messages as well as e-mail. These results are essential for the effective decision-making process, which includes gathering information, identifying the action plan, and assessing alternative measures. The mitigation maneuver planning and its re-assessment are also supported. Moreover, all actions regarding conjunction assessment are readily configurable by user. With this tool, the event is easily shared to the relevant parties anytime, anywhere. The earlier identification and more timely action with high reliability ensure operational safety of valuable space assets against high-risk events, in order to keep the sustainable and peaceful space mission operations.

Table 1 KARI Satellite Program

Orbit Type	Satellite	Altitude (LTAN)	Payload	Ground Resolution	Launch Date	Operational
LEO	KOMPSAT-2	685km (10:50)	Optical (M/S)	1m (PAN)	Jul. 2006	Operational
	KOMPSAT-3	685km (13:30)	Optical (M/S)	0.7m (PAN)	May 2012	Operational
	KOMPSAT-3A	528km (13:30)	Optical (M/S) /IR	0.55m (PAN) 5.5m (IR)	Mar. 2015	Operational
	KOMPSAT-5	550km (06:00)	SAR/AOPOD	1m (HR)	Aug. 2013	Operational
	CAS500-1	498km (11:00)	Optical (M/S)	0.5m (PAN)	Mar. 2021	Operational
GEO	COMS	35,786km	MI/GOCI COM	1km (MI) 500m (GOCI)	Jun. 2010	Operational
	GEO-KOMPSAT-2A	35,786km	MI	0.5km (MI)	Dec. 2018	Operational
	GEO-KOMPSAT-2B	35,786km	GOCI /Environment	250m (GOCI)	Feb. 2020	Operational

Figure 1 represents the number of space objects in Low Earth Orbit with respect to their altitude (as of Mar. 14, 2022). Y-axis is altitude(km), and X-axis is number of objects. Satellites from KARI are also added in the circle. The orange circle is optical payload, and the blue represents the radar mission. The future missions are also depicted in the green circles in the figure. There are already a lot of space objects in LEO. Historically, due to the Chinese anti-satellite missile test in 2007, debris population was sharply increased near 800km altitude. And, accidental collision between Iridium and Cosmos in 2009 generated more than 2,000 space debris, which is still on-orbit now. More recently, the Starlink constellation is orbiting 550km altitude for their space-based internet services. And, the number of satellites is expected to be exploded with mega-constellations by many actors around the world.

The problem is space debris, more than 60%, they are not controlled at all. In case of conjunction events with space debris, a satellite with maneuver capability has to take an action to mitigate collision risk. However, the ephemeris and prediction of a small-sized space debris is uncertain or even unknown. This makes it difficult to deal with the conjunction event in a safe manner. On the other hand, in case of close approach with operational satellite, operators should communicate each other for data/information sharing for their analysis and any upcoming plan. This is a coordination between operators for their safe operations in order to deal with collision events. The situation of space objects in geosynchronous orbit is relatively better than low earth orbit thanks to the ITU(International Telecommunication Union) regulation and its limited resources on longitude and RF frequency. The objective of SSA & STM research is to ensure flight safety and mitigate collision risk for the full cycle of space systems including on-orbit collision avoidance and end of mission disposal.

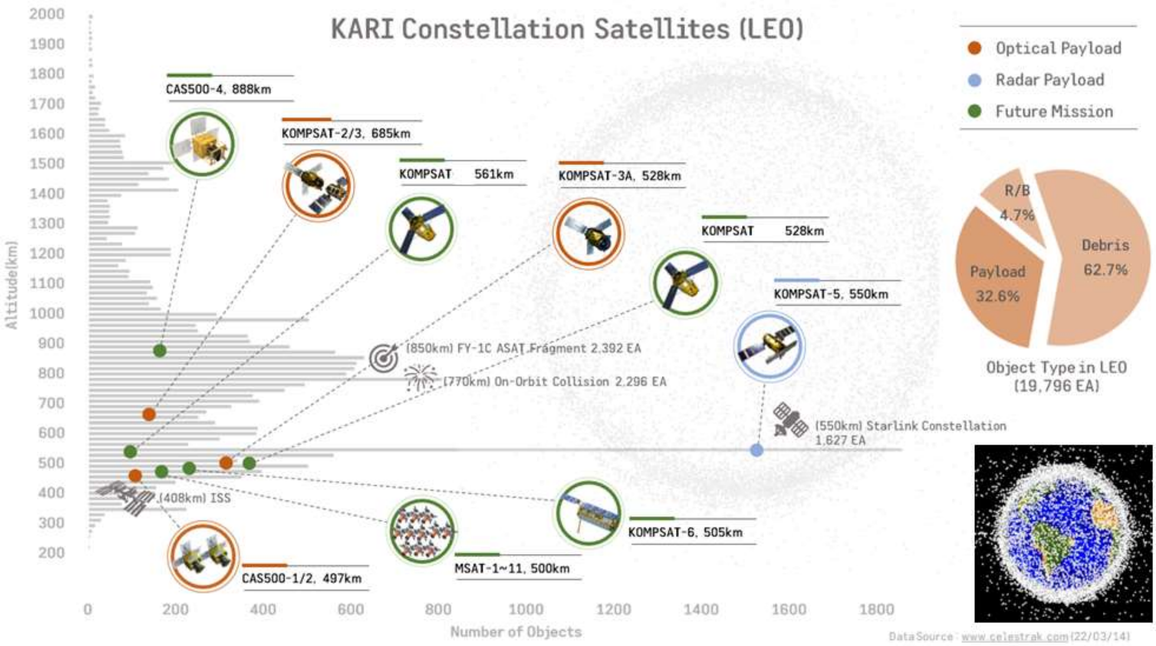

Figure 1 KARI Satellites and Space Object Population in LEO

3. Statistical Analysis

In order to get more reliable and applicable procedure, statistical analysis for conjunction event in the past is to be reviewed in more detail. KARI is mainly relying on the conjunction data services from the 18th Space Control Squadron (18 SPCS) in United States under the signed SSA Sharing Agreements with USSPACECOM. The 18 SPCS Conjunction Assessment (CA) process identifies close approaches between all resident space objects (RSOs) in the 18 SPCS catalog by using satellite observations from the U.S. Space Surveillance Network (SSN), which includes a variety of sensors throughout the world that detect, track, catalog, and identify man-made objects orbiting Earth. The screening volumes of 18 SPCS for LEO objects related with the KARI's satellites are as follows:

Table 2 Screening Volumes from 18 SPCS

Type	Orbit Regime Definition	Propagation	Radial	In-Track	Cross-Track
LEO 2 Covariance	500 km < Perigee ≤ 750 km Eccentricity < 0.25	5 days	0.4 km	25 km	25 km
LEO 1 Covariance	Perigee ≤ 500 km Eccentricity < 0.25	5 days	0.4 km	44 km	51 km

KARI's CA-FAST checks and downloads the newly created conjunction data message from the CSpOC(space-track.org) server. And, the three(3) different internal steps are applied with following criteria:

- Step (1). Monitoring the Event of Interest
  - minimum range(3-dimensional distance) between the KARI's satellites and any space objects < 1 km
- Step (2). In-depth Analysis (prediction window: 3 days)
  - minimum range < 1km
  - radial distance < 300m
  - probability of collision > 1.0E-04
- Step (3). Collision Avoidance Maneuver (prediction window: 2 days)
  - minimum range < 100m
  - probability of collision > 1.0E-03

Figure 2 and 3 represent the Number of Conjunction Events and Corresponding Actions in 2021 and 2022. The green bar is the number of step (1) which monitors the event of interest. And the blue one depicts the Step (2), number of in-depth analysis with 3-day prediction window. The red bar indicates the number of collision avoidance maneuvers for risk mitigation. In 2021, KARI had more than 100 conjunction events of high-interest, and 52 fine assessment reports were issued accordingly in 2021. There were 2 orbit maneuvers to mitigate high collision risk. However the number of conjunction events and corresponding actions has been sharply increased in 2022, which results in 253 high-interest events, 163 in-depth analysis, 1 COLA maneuver.

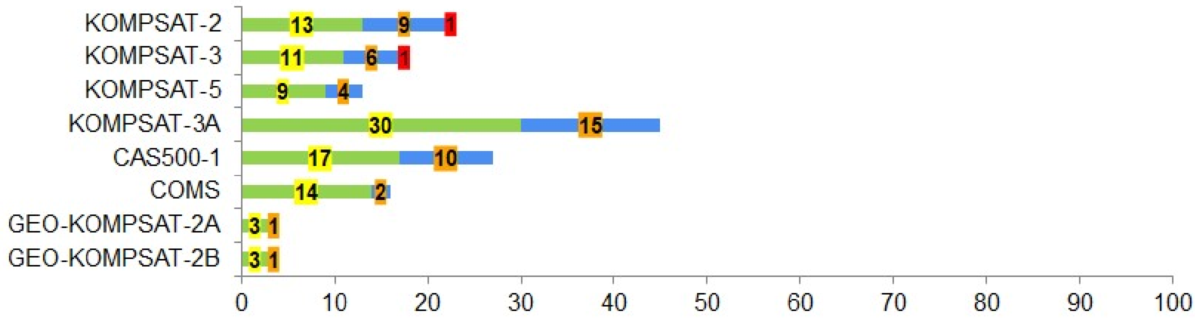

Figure 2 Number of Conjunction Events and Corresponding Actions in 2021

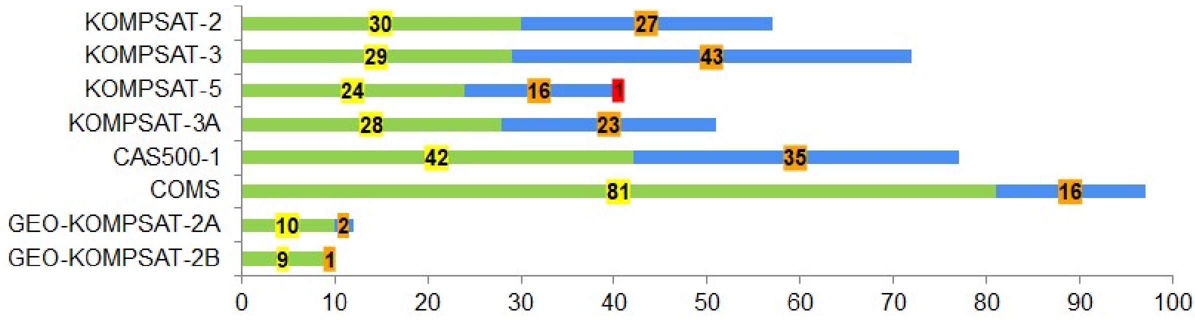

Figure 3 Number of Conjunction Events and Corresponding Actions in 2022

Table 3 summarizes the conjunction events of interest belong to step (1), from 2017 to 2022. As the number of space objects increased, the close approach between satellite and others is expected to be frequent.

Table 3 Statistics: Conjunction Events of Interest (step (1), from 2017 to 2022)

Satellites	2017	2018	2019	2020	2021	2022
KOMPSAT-2	22	18	6	8	13	30
KOMPSAT-3	37	15	14	8	11	29
KOMPSAT-5	20	26	4	8	9	24
KOMPSAT-3A	18	20	9	8	30	28
CAS500-1	Before Launch	Before Launch	Before Launch	Before Launch	17	42
COMS	9	24	10	22	14	81
GEO-KOMPSAT-2A	Before Launch	Before Launch	0	0	3	10
GEO-KOMPSAT-2B	Before Launch	Before Launch	Before Launch	2	3	9
SUM	106	103	43	56	100	253

4. Event Analysis from CDMs

The key parameter for statistical analysis includes type(debris, rocket body, and satellite), size, orbital characteristics (altitude, eccentricity, and inclination) of the secondary object, and allowable time to respond against collision risk from initial identification or notification. The minimum distance, covariance, collision probability, and the time of closest approach should be covered in the analysis by using historical real-flight conjunction events. In addition, information about operator in terms of country is also valuable to examine a feasibility of future interface for communicating each other if needed. The size of secondary object, RCS(radar cross section), is also meaningful to get some insight for requirement of ground-based tracking system such as radar, laser, and so on.

In 2022, KARI identified 6211 LEO conjunction events by using CDMs from CSpOC. Depending on the event, the number of CDM for each events is up to 15, which means that new CDM can be released 3 times a day. Table 4 summarized the number of conjunction events from CDM. The CAS500-1 in the lowest altitude has a large amount of events due to different screening volume with respect to the low perigee altitude. Table 4 also indicates the type of secondary objects against each satellite. The lower the operating altitude, the larger the proportion of payload. On the other hand, the higher operational altitude, the larger the proportion of space debris. Figure 4 depicts the area of secondary object with three(3) ranges: small(less than $0.25m^2$), medium(between $0.25m^2$ and $1m^2$), and large (greater than $1m^2$). For example, CAS500-1 had many conjunction events with small payloads such as CubeSat, which is 811 events(51.5%) out of 1574 in total.

Table 4 CDM Statistics: Type of Secondary Objects

Satellite (mean altitude in km)	Debris	Payload	Rocket Body	TBA	Unknown	SUM
KOMPSAT-3 (685km)	436	87	13	0	89	625
KOMPSAT-2 (682km)	534	118	19	0	136	807
KOMPSAT-5 (550km)	457	242	33	5	98	835
KOMPSAT-3A (528km)	265	810	35	29	143	1282
CAS-500 (498km)	633	1760	48	58	163	2662

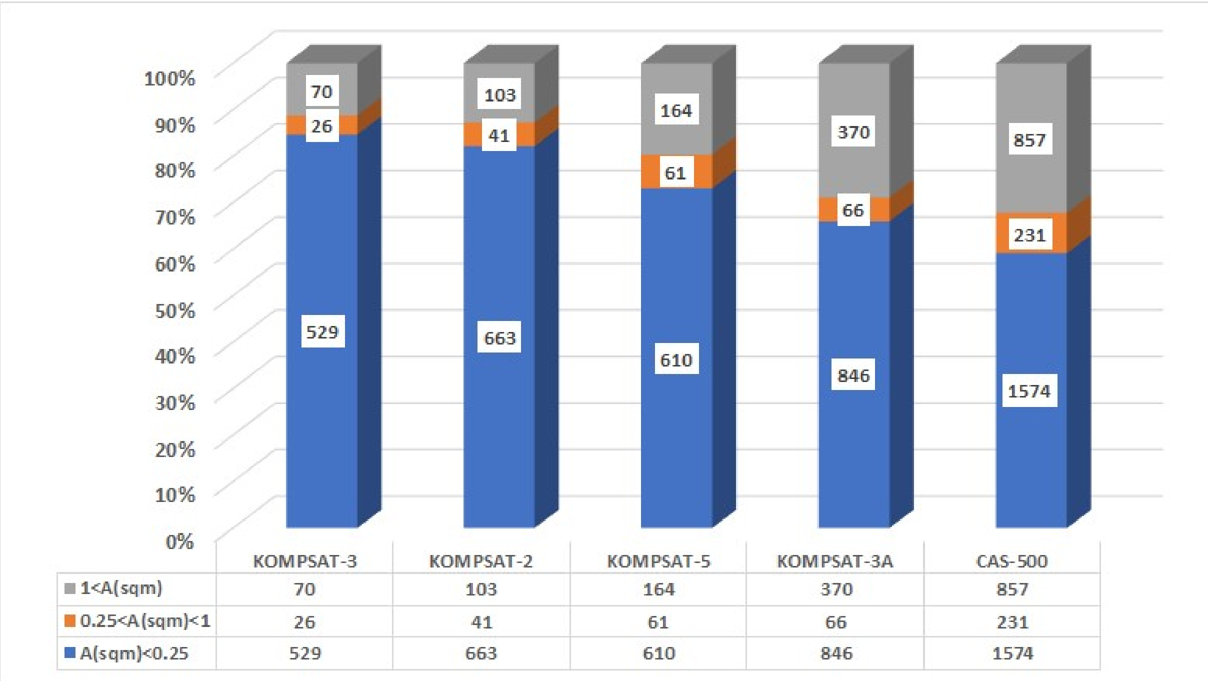

Figure 4 CDM Statistics: Area of Secondary Objects

If we have conjunction events with payload(that is operational satellite), sharing of data and information is possible to take action for risk mitigation. Therefore, this study with historical dataset can aim at optimizing the analysis, minimizing the false alarm, providing more reliable conjunction assessment, and generating operationally applicable procedure for future SSA and STM, based on statistical results.

5. Future Works and Recommendations

STM is protection to safeguard operating satellites from collisions, through capabilities to detect and evaluate collision risk and procedures to respond. And it is also prevention to creation of debris throughout the space system lifecycle from launch to re-entry. Similar to the road traffic management and air traffic management, here in this slide, we are familiar with, space traffic management, space situational awareness, and on-orbit service are expected to be realized in our daily life very soon. STM encompasses the means and the rules to access to space, conduct activities in space, and return from outer space as well, safely, sustainably and securely. It can be realized through, a combination of best practices, guidelines, technical capability, and operational synchronization with data and information.

There are major two key technologies for space traffic management. At first, it is meaningful to have an automatic process of massive data, which includes data statistics, analytics, from the operation of space assets. We need a study for space environment and break-up modelling about future evolution of space populations. Data analysis deals with ground-based and space-based tracking system, conjunction geometry and collision probability. In parallel, with the consolidated data server, we can have lots of data: raw measurement, conjunction data message, two line element, ephemeris, and any relevant evaluation reports. And, characteristics of space object, for example its size, mass, mission orbit, and operational status, should be available for a meaningful data processing. Secondly, it is impossible for any single entity to gather SSA/STM information in near real-time. So, we need all-in-one platform for data sharing, which includes ephemeris, flight plans, planed maneuvers, predictions for close approach, and so on. And, data should be combined and synchronized. For this, we need,

- Protocols for collection and exchange of data
- Protocols for creating, populating and operating open architecture data repository
- Data integrity measures and standards to ensure quality from diverse data sources

And, infrastructure for data server, network, and security should be prepared with inter-operability. Using this technology, global STM stakeholders can share 'Data' and 'Information' in the platform. This can cover all space entities: industry, academia, space agency, even military as well.

6. Conclusions

In this paper, statistics of conjunction events for recent year regarding KARI LEO satellites are thoroughly analyzed and reviewed. The satellite operation team is able to easily access the precise orbit ephemeris of their own satellite, that is primary object, at all times. However, the information of secondary object, which is approaching to the primary one, is very limited. In this case, one can rely on historical data and experience from statistical data as a reference. The statistics in this paper shows the a lot of operational experiences from the different altitude in low earth orbit. For long-term sustainability, space traffic should be well-controlled and coordinated by sharing data and information.

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