Accuracy Analysis of CDM for KOMPSAT Series Satellites

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ABSTRACT

Now KARI is operating 4 LEO satellites (KOMPSAT series satellite) and 2 GEO satellites and preparing operation plan for several new satellites. To operate these satellites safely, SSA & STM activities are essential and thus KARI has performed various SSA & STM activities including collision risk mitigation (i.e., conjunction assessment and collision avoidance maneuver).

In the collision risk mitigation activities, the CDM is main information with precise orbit information of KARI satellites and external tracking measurements for secondary objects. In this paper, we analyzed the accuracy of CDM (Conjunction Data Message), which is provided from CSpOC for KARI constellation satellites. Around 40,000 CDM data in 2019 were analyzed for 4 LEO satellites by two strategies.

First, CDM accuracy for primary object was analyzed. Primary object means KARI constellation satellite and KARI has the most accurate orbit information from precise orbit determination using onboard GPS raw measurements of satellites. The CDM accuracy for primary object can be determined from difference between KARI orbit and CDM data. Next, secondary object accuracy was analyzed. Reference orbit information of secondary object are hard to obtain without world-wide space surveillance network. Thus, we assumed that last CDM is true data because CDM revised almost every 8 hours for same conjunction event and the orbit uncertainty is getting smaller with new measurement data.

We analyzed the CDM accuracy with respect to prediction duration, object type and altitude (i.e., primary satellite orbit). In case of payload, CDM orbit accuracy was 200~300m for 7 days prediction, 100m for 3 days prediction and 50m for 1day prediction. Rocket body represented similar results with payload. But debris and unknown, which are small objects, represented 1~4km difference for 7 days prediction, 1~3km difference for 3 days prediction and 0.6~1.2km difference for 1day prediction. This analysis result can be useful for decision-making process of collision avoidance maneuver and risk identification for the close approach events.

1. Introduction

The data distributed by CSpOC is typical of TLE and CDM data. Two Line Element (TLE) is a two-line text format data that can be obtained by anyone and contains orbital information for about 15,000 objects, requiring procedures such as orbital propagation, proximity, and collision probability calculations to identify objects close to an operational satellite. Although the difference varies greatly depending on the size or orbit of the object, it is known that low-orbit objects have an accuracy of approximately 1km in the 24-hour prediction, and are distributed twice a day. A Simplified General Perturbation (SGP4) orbital propagator is required to calculate the position and velocity of a particular object at a given time using the data.

The CDM is data distributed only to satellite operators and officials registered with the CSpOC and contains both orbital information and collision risk analysis of target satellites and approach objects within one data. Unlike TLE data, CDM is distributed three times a day by the number of operating satellites or close-up events according to their orbit in the form of summarizing and distributing the results of the overall analysis by CSpOC. For orbital information contained in CDM data, it has higher accuracy than TLE data. Unlike TLE data, CDM data is distributed only when close events that meet specific criteria are predicted, and data is distributed according to the criteria of user type, prediction period and minimum access. Currently, KARI is an advanced user and receives LEO 2 Advanced Covariance for KOMPSAT series satellites and CDMs for close events that are included in the GEO Advanced standards for GEO satellites.

Considering the accuracy of the data, the collision risk analysis for the current KARI operation satellite is focused on the CDM data. In 2019, about 45,000 CDM data were received, which is about 120 per day. CDM data is constantly updated for a particular close-up event, resulting in as many as 20 data being distributed.

2. Accuracy analysis for KARI operating satellites

Two approaches are required to analyze the accuracy of the orbital data contained within the CDM data. In the case of CDM data accuracy of operating satellites, accuracy can be analyzed compared to the results of accuracy orbit determination of operating satellites, and in the case of CDM data accuracy of approach objects, accuracy can be analyzed indirectly through positional covariance figures in CDM data.
In this analysis, the accuracy of CDM data (a total of 39,958 CDMs) for four KOMPSAT series satellites, which are low-orbit satellites, was analyzed, and CDM data for two GEO satellites were excluded from the analysis. This is because the amount of CDM data distributed in geostationary orbit is smaller than in low orbit, and due to frequent orbit maintenances, it is difficult to generalize the accuracy.

The precise orbital data of the operating satellite is generated through accuracy orbit determination using GPS raw data obtained from GPS receivers mounted on the satellite, and is stored daily in the form of position and velocity on earth-fixed coordinate systems over time. KOMPSAT-2, -3, -3A (hereafter, K2, K3, K3A) have accuracy within 1m using a single-frequency GPS receiver, while KOMPSAT-5 (hereafter, K5) have accuracy within 20cm using a dual-frequency GPS receiver. Therefore, the analysis in this section analyzes the error of CDM data, assuming that the precise orbital data of the operating satellite is true.
For analysis, 39,958 CDMs distributed for KOMPSAT series satellites were secured and accuracy orbiting data were secured for accuracy verification. For each CDM, the process of obtaining internal data and accuracy calculation results and storing them in the database was repeated in the following order. The analysis was performed using Python version 3.7.

A. Access CDM data in XML format to obtain all the information contained
B. Conducts orbital propagation by applying information on the position and velocity of operating satellites contained in CDM data to STK/HPOP
C. Conduct orbit propagation by applying position and velocity information similar to B of the operating satellite's precise orbit data to the STK HPOP → POD (Precise Orbit Determination)
D. Calculate errors in the direction of Radial, In-track, Cross-track by comparing B and C

Figures 1, 2, 3, 4 show the distribution of position accuracy over the remaining time for the four satellites. The remaining time represents the difference between the time to closest approach and the CDM data generation time, which is the same as the orbit prediction period. The smaller the remaining time, the shorter the orbital prediction period, which reduces the uncertainty resulting from the prediction, indicating a tendency to decrease the positional error.
Of the 15,540 and 12,532 CDM data respectively for K2 and K3, 0 were data with a position error of more than 2 km, indicating that all data had an error of less than 2 km regardless of the remaining time, indicating that very stable results were provided. In addition, the accuracy within the remaining three days of the detailed analysis date was 200m or less and the accuracy within the remaining two days of the determination of the collision avoidance maneuver was 50m or less to confirm that the accuracy was sufficiently reliable.
For the K5 and K3A, out of 5,269 and 6,617 CDM data, the proportion of data with a positional error of 2 km or more was 24.65% and 4.22%, respectively. The error shown here is judged to be an error caused by the orbit maneuver of the satellite, and it has a similar level of accuracy as the CDM data of K2 and K3 within 2 km of the error.

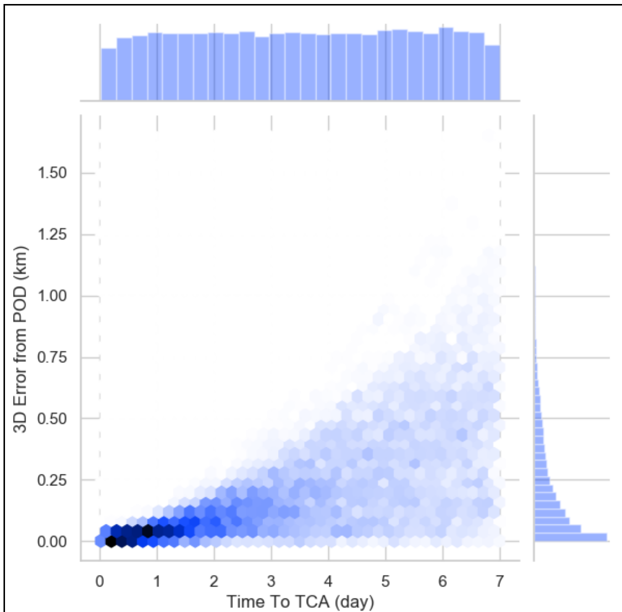

Figure 1. Accuracy Distribution over Time Remaining (K2)

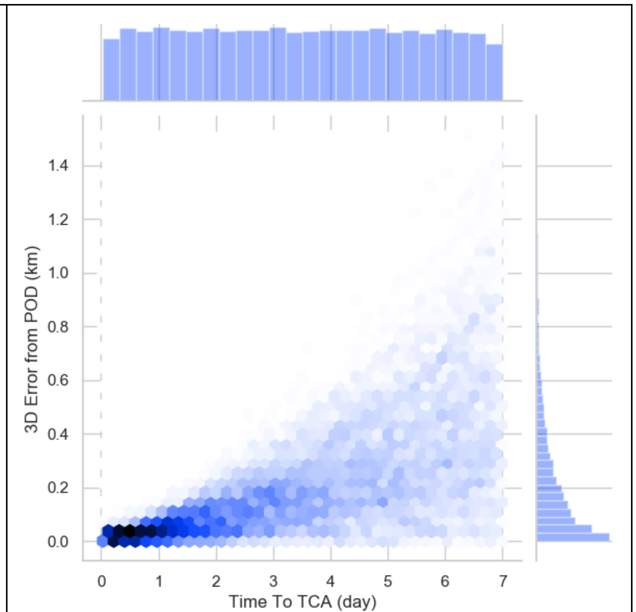

Figure 2. Accuracy Distribution over Time Remaining (K3)

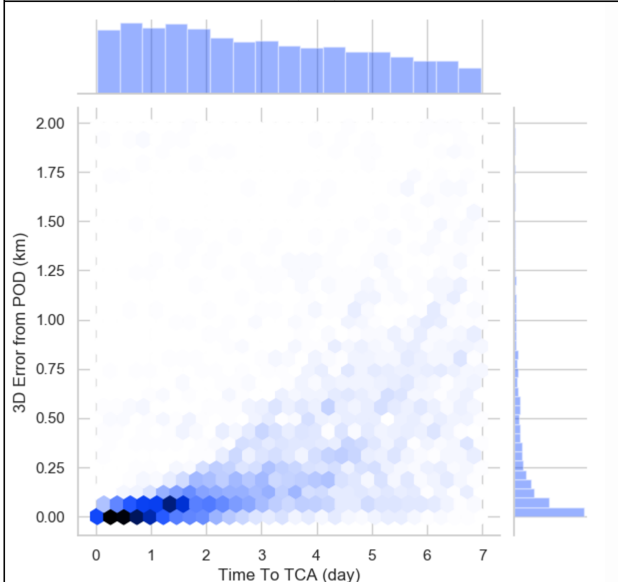

Figure 3. Accuracy Distribution over Time Remaining (K5)

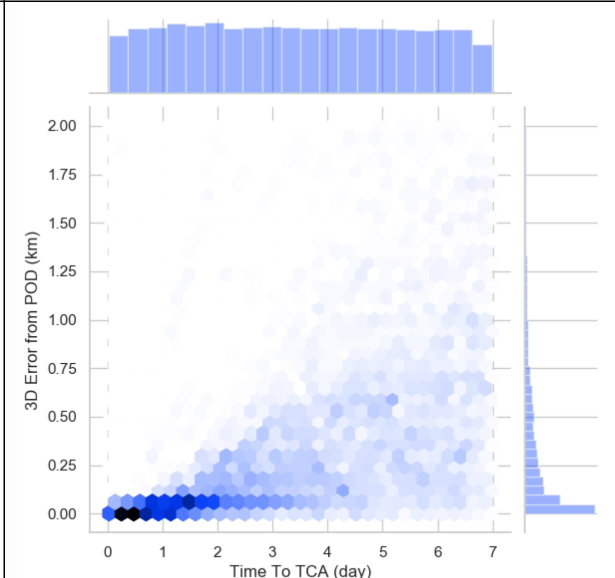

Figure 4. Accuracy Distribution over Time Remaining (K3A)

Figures 5 and 6 show the distribution of position error over the absolute time of the K5 and K3A CDMs and whether each point of distribution is near the satellite's orbit maneuver point. Both satellites can confirm that orbit maneuver have been carried out near the point where more than 2 km of error occurred. Note that since K5 performs orbit maneuver about four times a month, CDM data produced prior to orbit maneuver has frequently been shown to have large errors at minimum access points, and K3A can only show large errors around September 4th, when orbiting was performed once a year, to be judged as the position error due to orbit maneuver, except that K2 and K3 were provided with reliable data.

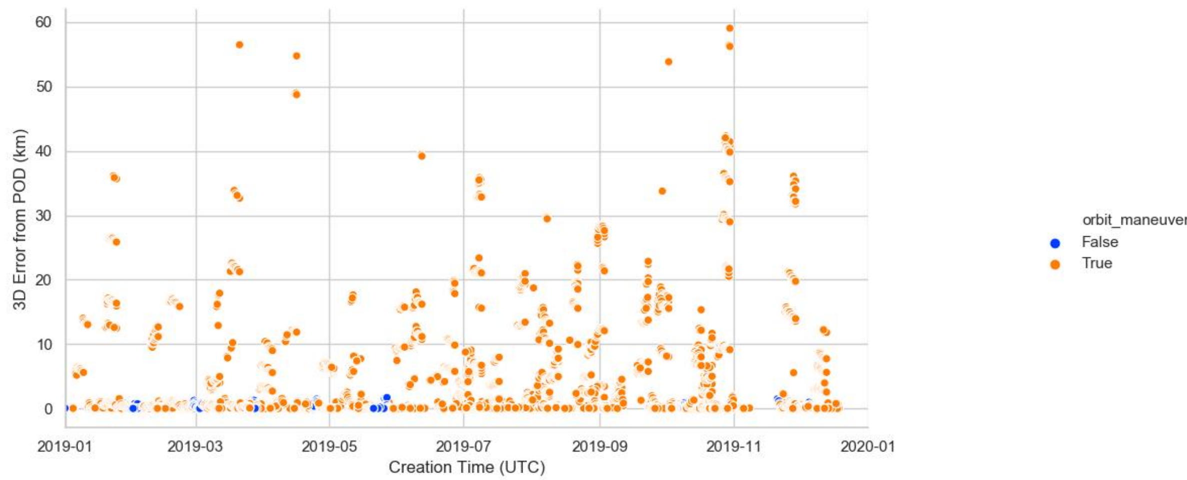

Figure 5. CDM Position Error Distribution according to time of K5

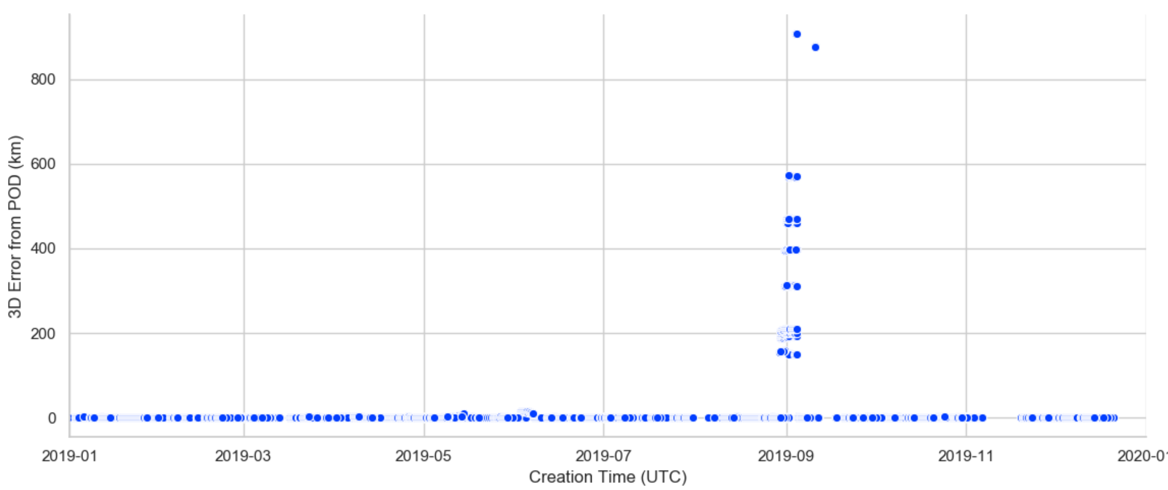

Figure 6. CDM Position Error Distribution according to time of K3A

Table 1 summarizes the accuracy and position covariance of the CDM of the KOMPSAT series satellite. The reason for the large total number of CDM data for K2 and K3 is that 685km, the mission altitude of the two satellites, is higher in space than 550km and 528km in altitude of the remaining satellites, resulting from the orbital collision of Fengyun1-C and Iridium 33-Cosmos 2251. The number of observational data used to determine the orbit of the fourth satellite averaged 400, while the K5 had a relatively small number of observational data. This is judged to be the result of frequent orbit maneuvers of the satellite. As mentioned earlier, the two-kilometer error ratio was 100 percent, 100 percent, 72.35 percent and 95.78 percent, respectively, and is judged to be the effect of the orbit maneuver.

Table 1 CDM data summary for KOMPSAT series satellite

		K2	**K3**	**K5**	**K3A**
Total number of CDM		15,540	12,532	5,269	6,617
OBS_USED Mean		459	462	384	435
AREA_PC Mean (m^2)		2.044	5.200	3.041	4.755
two-kilometer error ratio		100%	100%	72.35%	95.78%
7 day prediction	**Mean error (m)**	**215.11**	**210.61**	**289.60**	**332.53**

	STD. error (m)		212.22	211.27	366.25	381.17
	Mean error	**R (m)**	**3.87**	**5.26**	**8.35**	**5.95**
		I (m)	214.54	261.35	288.53	331.91
		C (m)	4.98	2.14	5.18	3.91
	Mean covariance (1σ)	**R (m)**	**5.18**	**4.80**	**3.89**	**5.79**
		I (m)	290.18	210.02	403.09	784.85
		C (m)	2.42	4.65	3.45	2.05
3 day prediction	**Mean error (m)**		**75.24**	**76.28**	**122.79**	**116.08**
	STD. error (m)		68.26	68.81	232.38	184.86
	Mean error	**R (m)**	**3.20**	**3.83**	**6.95**	**5.18**
		I (m)	74.28	75.35	121.34	115.02
		C (m)	4.96	4.64	4.94	3.95
	Mean covariance (1σ)	**R (m)**	**3.66**	**3.60**	**3.24**	**3.86**
		I (m)	62.22	56.12	106.93	174.20
		C (m)	2.33	2.04	3.03	1.98
1 day prediction	**Mean error (m)**		**26.14**	**29.57**	**68.61**	**30.04**
	STD. error (m)		18.77	21.17	217.90	71.87
	Mean error	**R (m)**	**2.95**	**3.38**	**6.11**	**4.15**
		I (m)	24.49	28.08	66.58	28.19
		C (m)	5.10	4.73	4.63	4.19
	Mean covariance (1σ)	**R (m)**	**3.00**	**2.84**	**2.80**	**2.93**
		I (m)	15.64	14.43	22.99	29.37
		C (m)	2.30	2.01	2.67	1.95

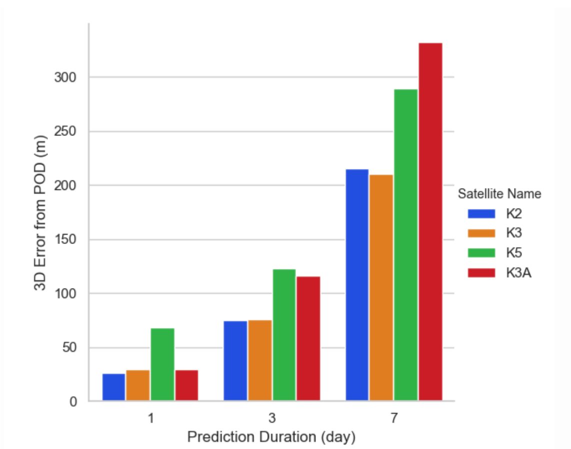

Figure 7. Mean error by satellite and prediction period

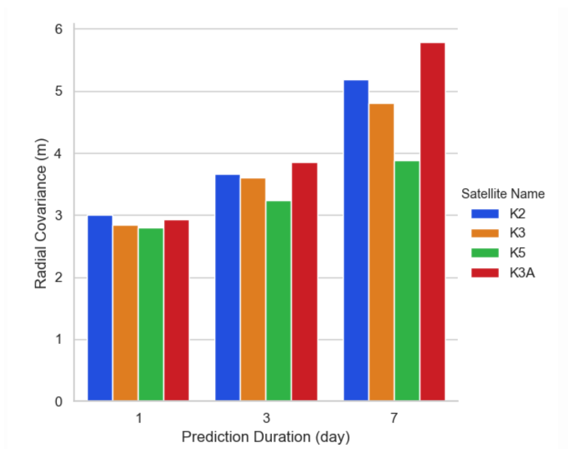

Figure 8. Mean covariance by satellite and Prediction Period in radial direction

Figures 7 and 8 show the mean covariance of the mean error and radial direction according to the satellite and prediction period shown in Table 1, with the average error of about 200 to 300 m in the forecast results for the 7 day. In detail, it can be confirmed that there is an error of about 210 meters for K2 and K3 and 300 meters for K5 and K3A. Among the three directions of Radial, In-track, and Cross-track, the error in the direction of in-track direction was shown to be the largest. In the case of the radial or cross-track, the results of the forecast on the 7 day showed an average error of 3 to 5 meters, but in the case of the direction of progress, the average error of around 200 meters shows the highest uncertainty. This is because the error caused by atmospheric resistance is the biggest among the

errors that occur when predicting orbit of low-orbit satellites, and atmospheric resistance acts in the opposite direction of satellite motion. The average covariance for the three directions was also shown to account for most of the values in the direction of progress, similar to the pattern of positional error.
The results of the 3 day forecast show that the value of position error and covariance has decreased by less than half compared to the 7 day forecast. The average error of 75 m for K2 and K3 and 120 m for K5 and K3A was shown. The trends and covariance according to direction also showed a trend similar to the results of the seven-day forecast. The results of the 1 day forecast showed a position error of 30 m for K2, K3 and K3A, showing fairly precise results from tracking without internal information of the satellite. In the case of the K5, the accuracy was relatively high at around 70 meters due to frequent track adjustments, but it was still reliable.

3. Accuracy analysis for secondary objects

A total of 39,958 CDM data were analyzed for the CDM data precision analysis of approach objects. In the case of approach objects, absolute error cannot be calculated because there is no precise orbital data unlike operating satellites. In this study, two indirect methods were used to analyze the precision of CDM data.
The first method was to use the point where more than 10 CDM data were updated for a single close-up event, which was defined as true, assuming that the last generated CDM data was the most accurate, and the remaining CDM data and positional error were calculated.
The second method is to determine the level of precision through position covariance information contained in CDM data. The position covariance information can be viewed as a concept of position uncertainty as a result of observing cosmic objects on the ground and conducting orbital determination, which can indirectly determine the level of precision.
Figure 9 shows the ratio of each satellite to a total of 39,958 CDMs. K2 had the highest ratio of 38.9%, followed by K3, K3A and K5.

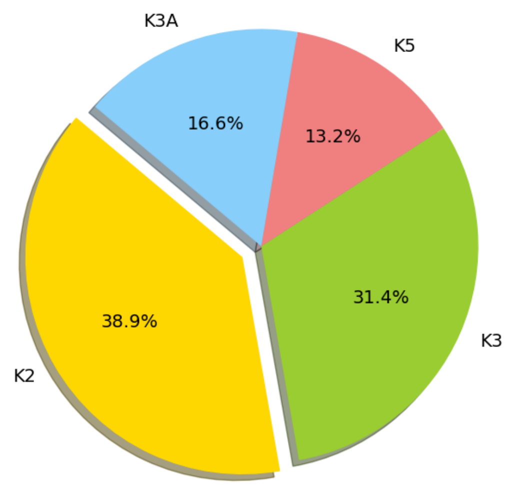

Figure 9. CDM ratio w.r.t satellites

In common with the fourth satellite, Debris was found to have the highest percentage, followed by Payload or Unknown. In the case of Rocket Body, it appears to be high in K5 and K3A, which are relatively low in altitude, but it can be confirmed that the proportion is not significant at less than 10%. Unlike other satellites, about 37 percent of K3A's approach objects are Payload, which is 1.5 to 3 times larger than other satellites.

A. Secondary type: Payload

Figure 10 and Figure 11 show the results of the accuracy analysis for the case where the approach object is Payload. First, the calculation of the positional error of the remaining CDMs, assuming that the position of the last of the many CDMs for the same access event is true. The small error means that the CDMs produced for the same access event are consistent with each other.

The average cross-sectional area of approaching Payload appears to be distributed from 1.11 to 4.12 m2 per satellite, indicating that sufficient RCS is available for ground observation, and it can be expected that levels of covariance and average error will appear similar to those of multipurpose practical satellites.

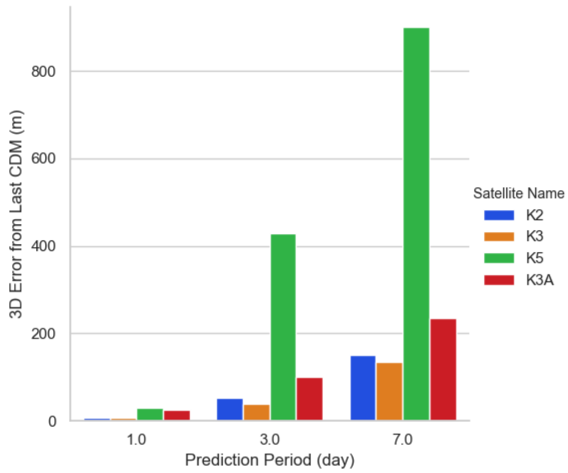

Figure 10. Mean error by satellite and prediction period

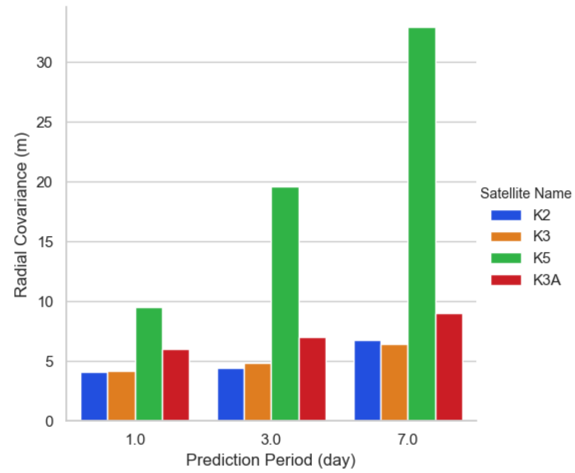

Figure 11. Mean covariance by satellite and Prediction Period in radial direction

In the case of K2 and K3, the average error was found to be within 150 meters for the 7day prediction, 50 meters for the 3day prediction, and within 10 meters for the 1day prediction, and within 250 meters for the 7day prediction, within 60 meters for the 3day prediction, and within 20 meters for the 1day prediction.

In the case of K3A, the average error was found to be within 240 m in the 7 day prediction, 100 m in the 3day prediction, and 25 m in the 1day prediction, and 1,270 m in the 7day prediction, 400 m in the 3day prediction, and 120 m in the 1day prediction, showing relatively higher average error compared to K2 and K3. The average number of observational data used to determine the orbit of Payload approaching K3A was 335, lower than K2 (413) and K3 (437), which is estimated to be due to satellite altitude differences of about 130-150 km.

Unlike the previous three satellites, the K5 showed relatively low precision in average error and average covariance. This is believed to be the main cause of frequent orbit maneuvers of the K5. In the absence of track adjustment, track adjustment may not have sufficient time for collision risk analysis, compared to continuous track determination and collision risk analysis more than 15 times over 7 days for a single close event. This can be seen in the 7day and 3day prediction, showing a similar precision to K3A if the prediction period is reduced to 1 day, while the average error and average covariance are large.

After checking the average covariance according to direction, the average covariance in the direction of Radial and Cross-track, excluding K5, remained within 10 meters regardless of the period. In the case of K5, the covariance of 30m and 20m, respectively, appears in the 7day or 3day prediction, but the results can be very stable and precise compared to the In-track direction.

B. Secondary type: Rocket body

Figure 12, and Figure 13 show the results of the accuracy analysis for when the approach object is a Rocket Body. In general, a trend similar to the Payload results can be seen. Both the magnitude of the mean error and mean covariance over time and the characteristics of each satellite were similar to the Payload result.

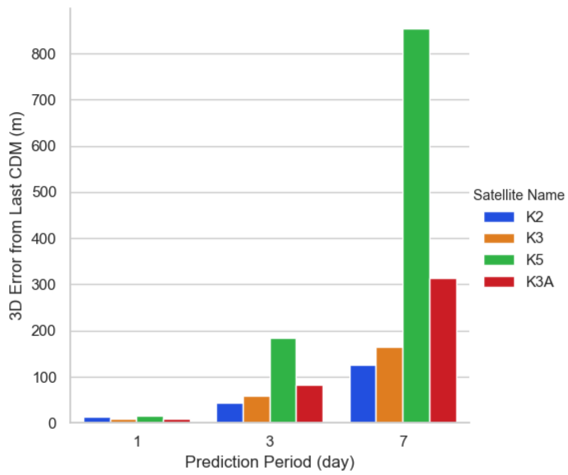

Figure 12. Mean error by satellite and prediction period

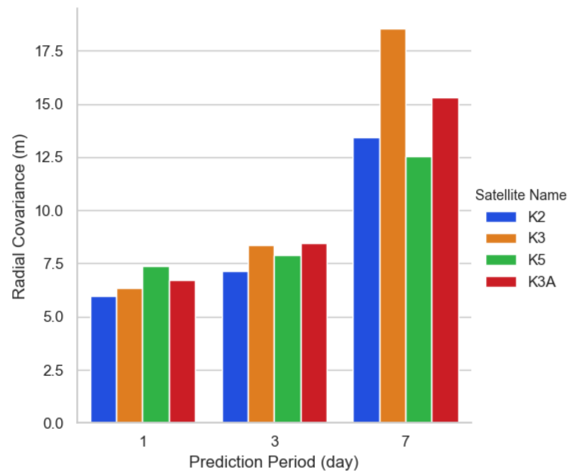

Figure 13. Mean covariance by satellite and Prediction Period in radial direction

C. Secondary type: Debris

Figure 14, and Figure 15 show the results of the accuracy analysis for cases where the approach object is Debris. Debris is the most frequently accessed object on the fourth satellite and consists of small objects 10 to 20 centimeters in diameter, as shown by the average cross-section area of Table 5. Due to the small size of the object, the number of observational data used for track determination has been reduced by one-third or one-quarter compared to the previous Payload and Rocket Body, and the resulting reduction in precision can be found in the results of average error and average covariance.

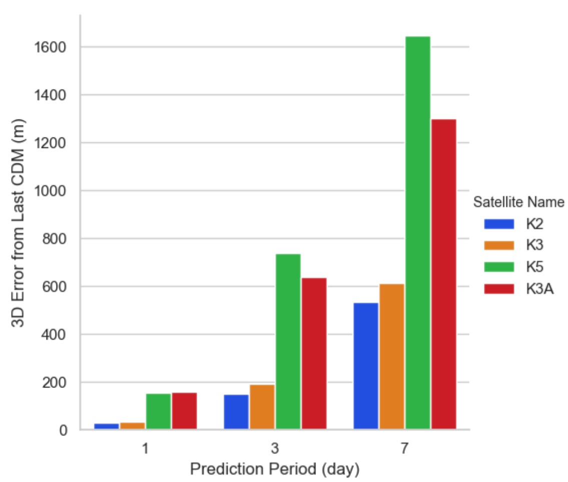

Figure 14. Mean error by satellite and prediction period

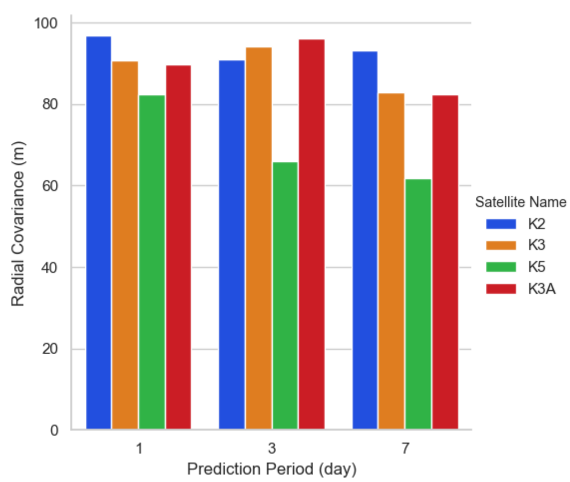

Figure 15. Mean covariance by satellite and Prediction Period in radial direction

In the case of K2 and K3, the average error was found to be within 600 m in the 7 day prediction, 200 m in the 3 day prediction, and 30 m in the 1 day prediction, 1,000 ~ 2,600 m in the 7 day prediction, 1,200 m in the 3 day prediction, and 700 m in the 1 day prediction. K5 and K3A, which are lower than K2 and K3, showed an average error of 1,500 meters in prediction on the 7 day, 700 meters in prediction on the 3 day, and 150 meters in prediction on the 1 day, 3,500 meters in prediction on the 7 day, 3,000 meters in prediction on the 3 day, and 700 meters in prediction on the 1 day.

The average covariance in the direction of Radial was shown to be about 90 m regardless of the period. This is the same feature as Payload and Rocket Body, which can be expected to be useful information, such as identifying the collision risk through the separation distance in the direction of Radial and the mean covariance, even when the average covariance is high due to the large number of covariance averages relative to the In-track direction.

D. Secondary type: Unknown

Figure 16, and Figure 17 show the results of a accuracy analysis in the case of an approach object being Unknown. The average cross-sectional area is estimated to be very small in size with all zero, and the mean error and mean covariance figures show less precision than Debris.

Unlike the preceding objects, the ratio of average covariance to within 10 km was around 80%, and the number of observational data used for orbital determination was around 30 which is one-third of Debris. In the case of K2 and K3, the average error was found to be within 1,000 m in the 7 day prediction, 300 m in the 3 day prediction, and 70 m in the 1 day prediction, 3,500 m in the 7 day prediction, 2,500 m in the 3 day prediction, and 2,000 m in the 1 day prediction. In the case of K5 and K3A, the average error was found to be 1,500 meters in prediction on the 7 day, 700 meters in prediction on the 3 day, and 200 meters in prediction on the 1 day, 3,000 to 4,000 meters in prediction on the 7 day, 2,000 to 3,700 meters in prediction on the 3 day, and 1,000 to 2,500 meters in prediction on the 1day.

The average covariance in the direction of Radial is 150 m, which is more precise than in the In-track direction, but it is considered difficult to utilize it in the 300 m radius of Radial, which is the standard for responding to the impact risk of space objects on the current antisubmarine operation satellite.

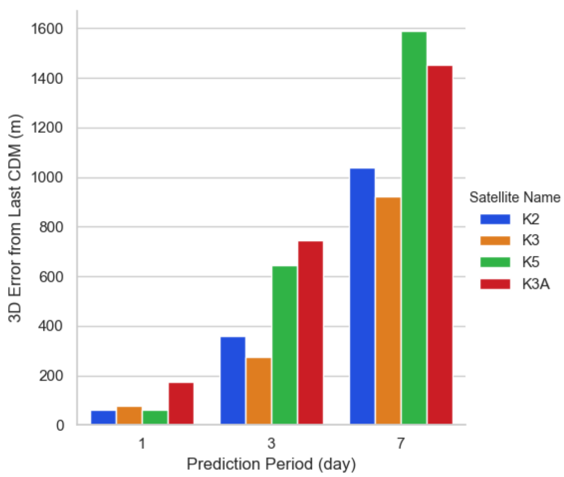

Figure 16. Mean error by satellite and prediction period

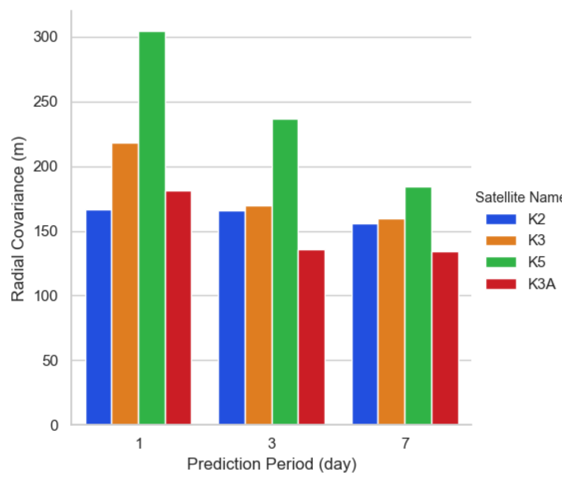

Figure 17. Mean covariance by satellite and Prediction Period in radial direction

4. CONCLUSION

CDM data plays a key role in collision risk analysis, and more data will be provided under normal operation of Space fence in the future. In this study, 40,000 CDMs were analyzed for four low-orbit satellites in 2019 to analyze the precision of CDM data currently received by the institute.

First, the precision of the 4 operating satellites was analyzed by comparing them with the CDM data. The precision of 200-300 meters for the 7th prediction, 100 meters for the 3rd prediction, and 50 meters for the 1st prediction. In some cases, the K3A and K5's orbit maneuvers showed relatively large errors, but in other cases stable and precise results could be identified. In particular, the error in the direction of Radial in the direction of the earth's center was around 5 meters, showing very precise results.

Looking at the types of objects approaching operating satellites, we found that the ratio of Debris, which is smaller than 50%, was the highest, followed by Payload, Unknown, and Rocket Body.

The accuracy of each type of object was checked and found that the relatively large Payload, Rocket Body showed a similar level of precision to the CDM of the preceding operating satellite, and the smaller Debris had a 1~4km error in the 7 day forecast, and a range of 0.6~1.2km in the 1 day forecast and 1~3km in the 3 day forecast. In the course of the collision risk analysis, reflecting all the errors that Debris has could result in a greater change in the collision risk for each analysis, resulting in less consistency and reliability in the analysis. Therefore, it is reasonable to

perform the analysis by considering the distance in the direction of Radial, which has a relatively constant degree of precision, regardless of the forecast period.
In the case of Unknown, objects smaller than Debris are expected to be identified as Debris during normal operation of Space Fence, which is expected to provide more precise data than now. Separately, it is deemed necessary to establish an independent tracking system that can exclusively track objects approaching operational satellites in the future.

5. Acknowledgement

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6. Reference

[1] JUNG, Ok-chul; SEONG, Jaedong; AHN, Sangil. Conjunction Assessment-Flow Automation Support Tool in KARI: From Design to Operations. In: 2018 SpaceOps Conference. 2018. p. 2373.
[2] SEONG, Jaedong; JUNG, Ok-chul; CHUNG, Dae-Won. Space Object Conjunction Assessment Activities for KARI Constellation Satellites in 2018. In: 2019 Korean Society for Aeronautical and Space Sciences Spring Conference. 2019.