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Current Status of KARI Measurement Activities on SSA

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Abstract

KARI, as a national space development agency, not only develops satellites but also operates 8 satellites as of 2022. Accordingly, KARI is performing various activities related to SSA for the safety of its own satellites. These activities can be broadly categorized as follows: Measurement, Protection, Disposal, Mitigation, Remediation and International cooperation.

Among above activities, Measurement is one of the SSA research fields that acquires orbital information about space debris using ground-based sensor such as radar, optical telescope, laser and so on, or space-based sensors. KARI is entirely dependent on CSpOC data for orbit information of space objects except for KARI's satellites in operation. However, only CDM data from CSpOC is insufficient to perform tasks, such as collision avoidance maneuvers, in terms of accuracy and timeliness of orbit information for space objects approaching the operational satellite. Therefore, KARI has been conducting studies to acquire radar observation data independently and to obtain accurate orbit parameters for objects approaching its own satellites in a timely manner since 2010: international research cooperation with FHR, tracking test using KARI's radar, development of a radar simulator, research on improving our radar maximum detection range, and planning research on new radar development and so on.

In this paper, we introduce the current status of KARI's radar related activities described above. We show overview, result and analysis of each study. In addition, we also introduce and analyze practical test results with our launch tracking radar system. Finally, we introduce the future plans of KARI related to the measurement activities.

Keywords: Measurement, SSA activities, KARI, Radar

Nomenclature

P_{fa} = Probability of false alarm
P_d = Probability of detection
R = Range
P_t = Peak power of radar
G = Antenna gain
λ = Wavelength
σ = RCS
G_p = Processing gain
P_r = Radar sensitivity
L = System loss
P_{av} = Average transmit power
A_e = Antenna aperture
Ω = Solid angle
t_S = Scan time for Ω

Acronyms/Abbreviations

Inter-Agency Space Debris Coordination Committee (IADC), United Nations (UN), Low Earth Orbit (LEO), Korea Aerospace Research Institute (KARI), Space Situation Awareness (SSA), Combined Space Operations Center (CSpOC), Conjunction Data Massage (CDM), Fraunhofer Institute for High Frequency Physics and Radar Techniques (FHR), Korea Multi-Purpose Satellite (KOMPSAT), Orbit Determination (OD), Precise Orbit Determination (POD), RIC (Radial/In-track/Cross-track), Tracking and Imaging Radar (TIRA), Inverse Synthetic Aperture Radar (ISAR), International Space Station (ISS), Radar Cross Section (RCS), Two Line Element (TLE), Least Mean Square (LMS), Fast Fourier Transform(FFT), Space Traffic Management (STM), Pulse Repetition Frequency (PRF), Korea Astronomy & Space Science Institute (KASI), Optical Wide-field patrol Network (OWL-Net), Electro Optical Satellite surveillance System (EOSS)

1. Introduction

Space debris is man-made space objects located in Earth-orbit that have ceased to useful functions and composed of derelict spacecraft, launch vehicles, satellite fragmentation from break-up of rocket bodies or spacecraft and so on. The population of space debris is rapidly increased because there have been more than 6340 rocket launches since Sputnik's launch in 1957 and 640 fragmentations resulted from break-ups, explosions, collisions, or anomalous events [1]. The future population of space debris is also instable, known as Kessler syndrome [2], despite of mitigation measures from international space communities such as IADC, UN [3].

The major concern of worldwide space agencies with space debris is collision between operational satellite and space debris. In particular for LEO region, the average collision speed is 8 to 12km/s, which can lead a variety of detrimental consequences in the event of a collision [4]. Due to the rapid increase in space debris and given hazards from debris, KARI is actively conducting studies on SSA to protect our space assets and provide service to the public.

Measurement is one of the SSA research fields that acquires orbital information about space debris using ground-based sensor such as radar, optical telescope, laser and so on, or space-based sensors. KARI is entirely dependent on CSpOC data for orbit information of space objects except for our satellites in operation. However, only CDM data from CSpOC is insufficient to perform tasks, such as collision avoidance maneuver, in terms of accuracy and timeliness of orbit information for space objects approaching the operational satellite. Therefore, KARI has been conducting studies to acquire radar observation data independently and to obtain accurate orbit parameters for objects approaching its own satellites in a timely manner since 2010.

In this paper, due to the lack of introduction to the studies of KARI, we briefly introduce the measurement activities, especially related to radar. We introduce overview, result, analysis of each study. In addition, we also show test results and explain the research conducted with the goal of detecting space object with our launch tracking radar system. Finally, we introduce the future plans of KARI related to the measurement activities

2. Studies

KARI has been conducting studies to acquire radar observation data and to obtain accurate orbit information for objects approaching its own satellites. In this chapter, we show the overview and result of each study briefly.

2.1 International research cooperation with FHR

KARI and FHR concluded a research contract for mission support and monitoring by ground-based radar observation in 2012. The work packages include space object tracking for conjunction assessment, high-resolution radar imaging of LEO space object, especially KOMPSAT-2, -3, -5 and so on. KARI received TIRA tracking data, i.e. observation vectors, orbital parameters for KOMPSAT-5, conduct the orbit determination with received tracking data and analyze OD quality using POD. In Fig. 1, we compare the KOMPSAT 5 RIC difference between tracking OD and POD by presenting the POD with red line and the tracking OD with blue line. In analysis, we consider POD as true since POD is calculated from GPS data of KOMPSAT 5. The tracking OD from TIRA data shows accuracy with in several hundred meters in radial, in-track, cross-track and 3D range compared to POD. Fig. 2 shows the ISAR post-processing images for KOMPSAT 2, 3.

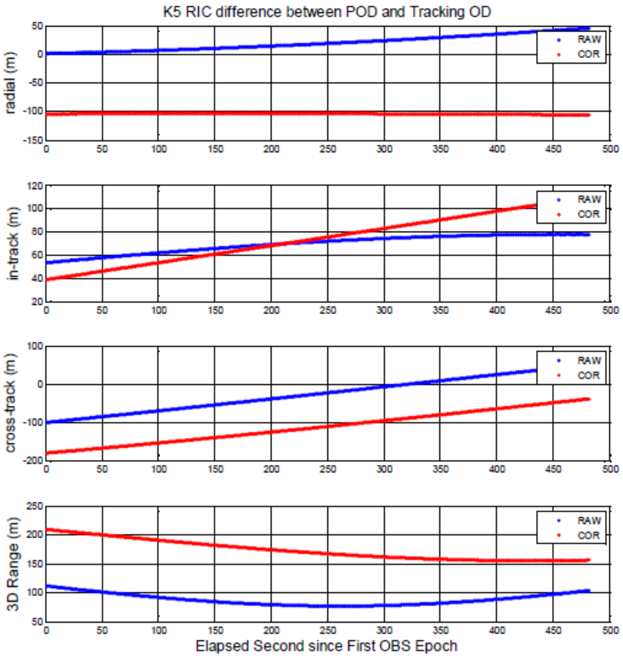
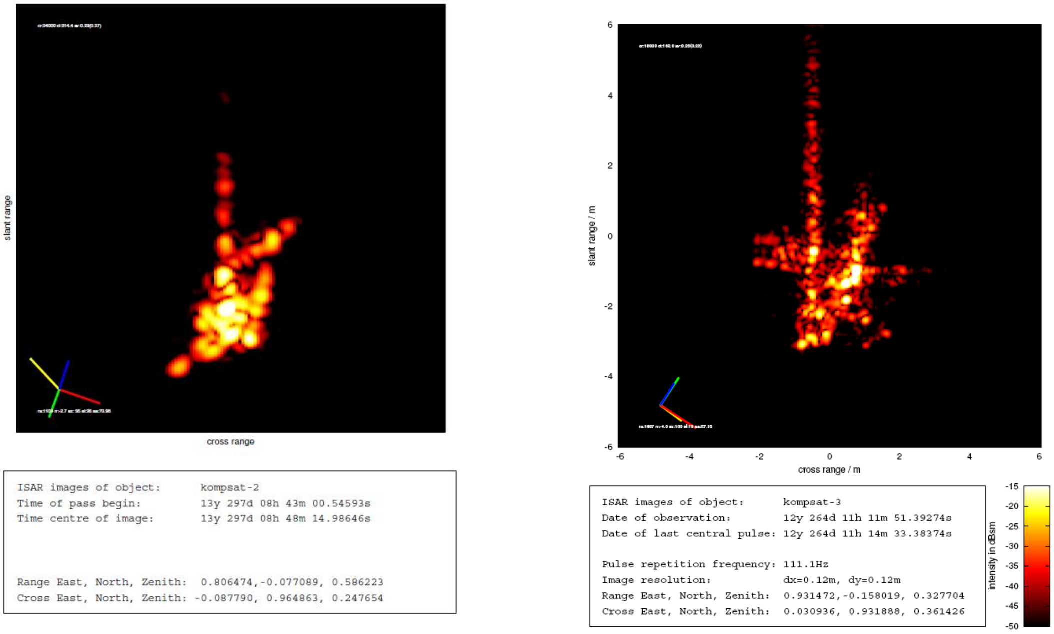


Fig. 1. K5 RIC difference between POD and Tracking OD from TIRA data



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ISAR images of object:      kompsat-2
Time of pass begin:         13y 297d 08h 43m 00.54593s
Time centre of image:       13y 297d 08h 48m 14.98646s



Range East, North, Zenith:  0.806474,-0.077089, 0.586223
Cross East, North, Zenith: -0.087790, 0.964863, 0.247654
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ISAR images of object:      kompsat-3
Date of observation:        12y 264d 11h 11m 51.39274s
Date of last central pulse: 12y 264d 11h 14m 33.38374s

Pulse repetition frequency: 111.1Hz
Image resolution:           dx=0.12m, dy=0.12m
Range East, North, Zenith:  0.931472,-0.158019, 0.327704
Cross East, North, Zenith:  0.030936, 0.931888, 0.361426
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Fig. 2. ISAR Images for KOMPSAT-2(left), KOMPSAT-3(right)

2.2 Tracking test using NARO tracking radar

NARO space center of KARI operates launch vehicle tracking radar systems in Goheung and Jeju. KARI conducted a space objects tracking test with our tracking radar system in 2014 [5]. Tracking radars have limitations in tracking small space objects that require higher specification since tracking radars was constructed for the purpose of tracking launch vehicles. Table 1 shows a major specification for our tracking radar and the limits to tracking for LEO space objects with small RCS. Therefore, we decide to select the ISS with a relatively large RCS as the tracking target. We obtain the tracking data from NARO tracking radar and conduct orbit determination using radar tracking data and compare with TLE. The left part of Fig. 3 shows the estimated range and we figure out that tracking begins at a distance of about 1180km from the radar, ends at a distance of 1260km. The right part of Fig. 3 represents the difference between tracking OD from NARO tracking radar data and TLE. Our analysis describes the biggest difference within 1.5km in in-track, relatively small difference in cross-track and radial within 1km, 0.5km respectively.

Table 1. Major specification for tracking radar

	Spec.
Peak power	250kW
Pulse width	0.5, 1, 4 µs
Bandwidth	1.4MHz
PRF	306 ~ 3000MHz
Center Frequency	5480GHz
Antenna	4m, 43dBi
Beam width	1˚
Sensitivity	-116dBm

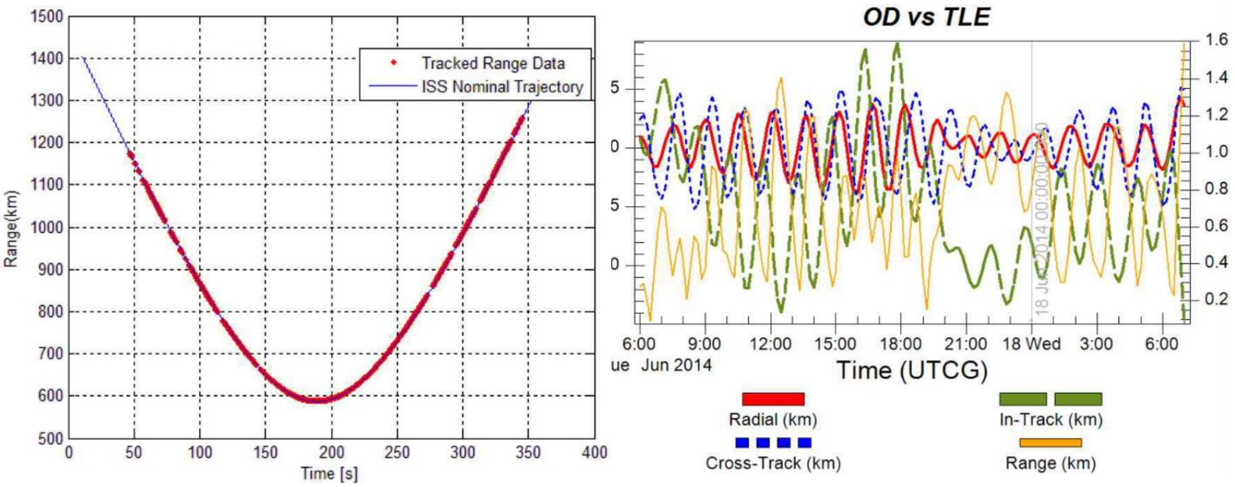


Fig. 3. ISS range measurement(left), Tracking OD vs TLE(right)

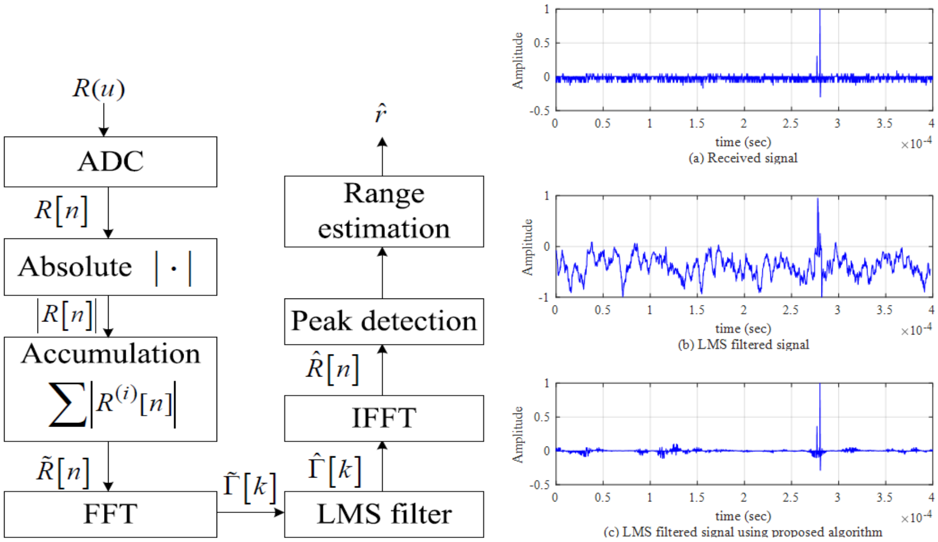
2.3 Development of a radar simulator

KARI had developed a simulator software for radar system design and performance analysis in preparation for the development for space object surveillance radar. The simulator software includes algorithms for precision tracking radar and wide-area surveillance radar. For example, the simulator includes precision trajectory estimation algorithm using dish antenna, algorithm for wide area surveillance radar using phased-array antenna. The simulator can support beam-park mode, active tracking, ISAR mode for precision tracking radar and scanning mode, detection under scan-to-scan, active tracking mode for wide area surveillance radar. The radar simulator can simulate the transmission signal and the signal reflection from space objects to generate a radar reception signal, support a function to generate a state vector by signal processing the received signal, perform a function of estimating the orbit information of space objects and creating a catalogue using correlation processing and orbit estimation. Finally, it is possible to derive radar design parameter to satisfy the tracking requirements. Fig. 4 show the GUI of developed radar simulator.

Fig. 4. Radar simulator

2.4 Research on improving our radar maximum detection range

As mentioned in section 2.2, KARI have the launch-vehicle tracking radar system with limitations to track the space objects. We conducted a study to improve the maximum tracking range of our radar with signal processing techniques. We use 2 signal processing techniques to reduce the noise: non-coherent pulse integration, LMS filter. In the proposed technique, we add a certain number of received signals, convert the accumulated signal to the frequency domain using FFT, apply the LMS filter. Using LMS filter in time domain can rather increase the noise level, since only a certain part is desired signal component, and the most of the remaining parts are noise components in the case of the received radar signal. In simulation, we consider the target object is the ISS. In Fig. 5, we describe a structure of the proposed algorithm, received and output of LMS filter using NARO tracking radar data. In the right part of Fig. 5(a) to (c), we compare the original received signal amplitude (a) and the received signal applied LMS filter in time domain (b), received signal applied LMS filter in frequency domain (c). The result show that we can obtain the gain by applying the LMS filter in frequency domain. Fig. 6 shows the results of the estimated range of ISS over two days. In Fig. 6, we can obtain the increased detection range from 300km to about 1000km against ISS using the proposed algorithms.



(a) Received signal

(b) LMS filtered signal

(c) LMS filtered signal using proposed algorithm

Fig. 5. Structure of the proposed algorithm(left), received signal and output of LMS filter(right)

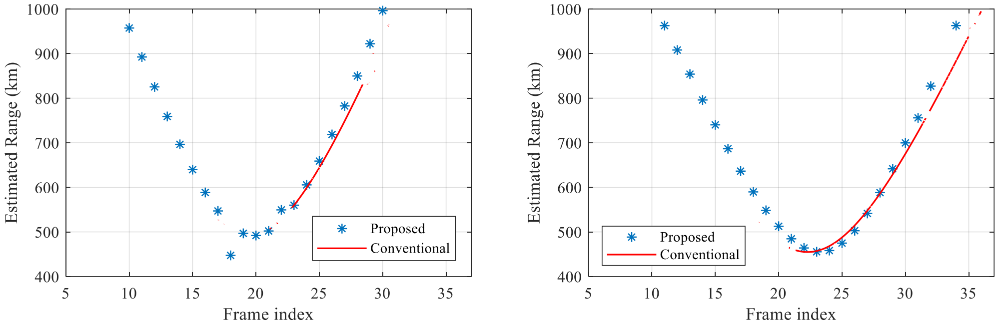


Fig. 6. Estimated range of ISS on the 1st day(left), 2nd day(right)

2.5 Planning research on New radar development

KARI conducted planning research on the advancement of technology and new radar system development, necessary for STM. In our planning research, we consider a radar capable of detecting low-earth orbit objects considering the current equipment, operational capability, and technological level. First, we derive the requirements for precision tracking and image radar using dish-reflector antenna in order to obtain precise orbit information of space objects close to our operating satellite. The minimum detectable size of planned radar is 10cm-sized space objects at 2000km range. Imaging radar is the next step of the planned radar that can produce the ISAR image with same target performance. Table 2 shows the major specification of the result for planning research.

Table 2. Major specification for tracking radar

	Spec.
Peak power	400kW
Min. detectable size	10cm@2,000km
P_{fa}	10^{-6}
P_d	98%
Frequency	X-band
Antenna	30m, 65Bi
Beam width	0.078˚

3. Detection and Tracking experiment using NARO tracking radar

KARI carried out a detection and tracking experiment on an actual low-earth orbit satellites using the Jeju tracking radar with proposed signal processing techniques in 2021. Jeju tracking radar system can detect the space objects with $\sigma = 1m^2$ in the 1000km range based on radar equation analysis using proposed signal processing algorithms. According to above result, we select 5 satellites, i.e. Woldview-4 (hereafter WV4), KOMPSAT-5, ERS-2, CAS500-1, KOMPSAT-3A as tracking target. we set the pulse width, PRF to be used in the experiment as 1 μs, 2500Hz respectively. Table 3 shows the average RCS and minimum slant range of target satellite on the experiment day. We consider the table-tracking mode based on TLE and search-and-tracking mode after detection.

Table 2. Major specification for tracking radar

Date	Satellite	Avg. RCS(m^2)	Min. slant range(km)
22 Nov 2021	WV4	6.5	299
22 Nov 2021	K5	3.46	883
23 Nov 2021	ERS-2	9.527	498
23 Nov 2021	CAS500-1	3.9	650
23 Nov 2021	K3A	5.36	551

3.1 Analysis based on the radar equation

Prior to the experiment, a preliminary analysis was performed based on the radar equation as below:

$$R^4 = \frac{P_t G^2 \lambda^2 \sigma G_p}{(4\pi)^3 P_r L}, \quad P_r = \frac{P_t G^2 \lambda^2 \sigma G_p}{(4\pi)^3 R^4 L}. \qquad (1)$$

Fig. 7 shows the radar sensitivity according to the RCS and slant range of the selected target satellite. When the target satellite is located in the boresight, it was confirmed that there is a possibility of detecting all satellites since the minimum radar sensitivity is -116dB.

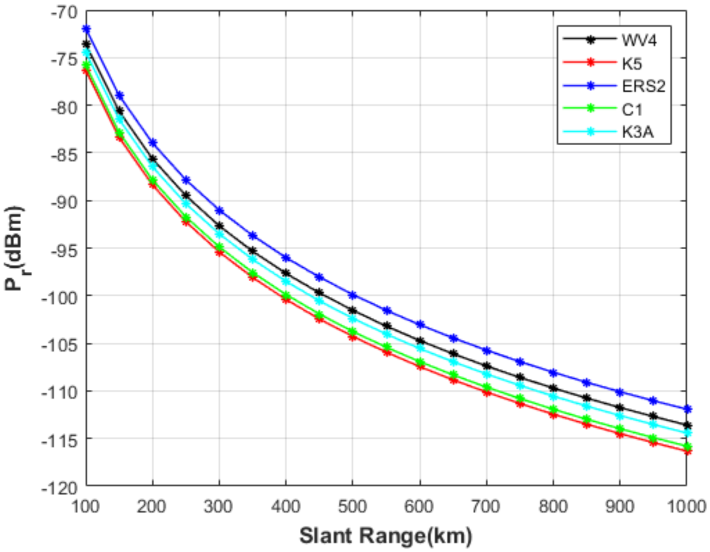


Fig. 7. Radar sensitivity versus slant range change for target satellites based on (1)

Secondly, given that the orbit accuracy of TLE is 2~3km, we analysed using the search-radar equation [2] as follow:

$$P_r = \frac{P_{av} A_e t_s \sigma G_p}{4\pi \Omega R^4 L} \qquad (2)$$

We consider the scan time and solid angle as 5 °/sec, $\Omega=\int_0^{\frac{\pi}{600}}\int_0^{\frac{\pi}{600}} \sin\phi \, d\theta d\phi$ respectively. We figure out that WV4 has the possibility of detection from Fig. 8,

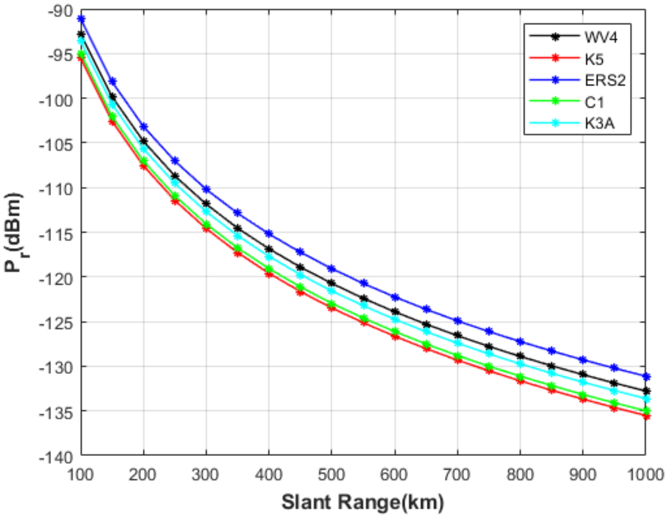


Fig. 8. Radar sensitivity versus slant range change for target satellites based on (2)

3.2 Results and analysis

We conduct the experiment over 2 days, and received the reflected radar signals for K3A, WV4. In the case of WV4, we detected for 23 frames out of a total of 62 frames, and 2 frames out of a total of 138 frames were detected for K3A. Fig. 9 shows the difference between TLE-based slant range over time and estimated range from observations. The tracking begins at a distance of about 926km from the radar, approaches to 299.4km, and then moves away to a distance of 906km.

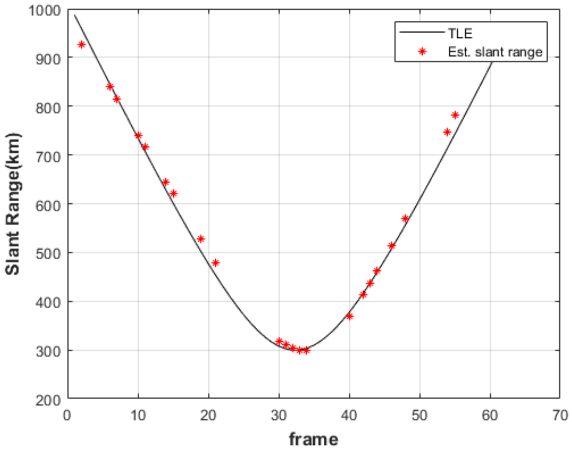


Fig. 9. Estimated range of WV4

According to the previous analysis from radar equation in section 3.1, we assume that all 5 satellites are detectable but only K3A and WV4 were detectable and K3A didn't receive most of the frames. We conducted an analysis for these results. First, there is a difference between the actual experimental environment and the ideal environment of the radar equation, and one of them is RCS fluctuation. The relative RCS can change continuously depending on the attitude, movement, azimuth, elevation of the target. We only consider the average RCS value in radar equation analysis therefore it can be inferred that the undetectable targets had a lower RCS value than the average value at that time. Secondly, radar equation does not reflect the radar performance variation resulted from the change in atmospheric refractive index [6]. In this experiment, a pointing error can be occurred since the target is located at a high altitude. As a result of the calculation, based ray tracing method [7], we figure out that an altitude error of about 0.3 degrees occurred by reflecting the atmospheric pressure, water vapor pressure and altitude of target on the day of the experiment. Third, we consider the table tracking mode based on orbit information from TLE as a tracking method before detect. The orbit information from TLE used alone cannot guarantee that the target is accurately positioned in the boresight. However, inconsistency occurs because the radar equation analysis result assumes that the target is located exactly at the boresight. Therefore, we conclude that it is necessary to design with the search radar equation or a large margin in mind, not considering only the radar equation when designing a radar system in the future.

4. Domestic/International cooperation

KARI has been carrying out domestic and international cooperation to acquire optical and radar observation data. First, a tracking request for a space objects close to the satellite in operation was requested, and the observation result was received through a collaboration with the KASI which has the OWL-Net system. In addition, the Korea Air Force's EOSS, which has recently been built, performs a tracking request for space objects of interest and receives the observation results.

In terms of international cooperation, radar observation data were received through a contract with Leolabs, and analyse the accuracy of the orbit determination results for our satellite with the POD data calculated based on out satellite's GPS data. In addition, we obtained optical observation data(FITS, IOD, OD, etc) for space objects approaching our satellites through a contract with ShareMySpace which is a French private company. The accuracy evaluation of acquired orbit determination data was also performed.

We plan to acquire observation data using laser and orbit information using passive RF in order to acquire observation data for objects in geostationary orbit. Furthermore, as a member of the IADC, KARI will continue the international cooperation and related tasks.

5. Conclusions

KARI has conducted various studies on a field of measurement in order to acquire accurate orbit information of objects approaching to our operating satellites in a timely manner. In this paper, international radar research cooperation, research conducted with our tracking radar, radar simulator development, radar performance improvement research, planning research results for new radar, and domestic/international cooperation were briefly introduced. In addition, we present implications for each study, cause analysis for the results and further study plan of KARI.

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