SYSTEM PERFORMANCE EVALUATION AND IMPROVEMENT BY USING KSGC RADAR DATA OF SPACE DEBRIS OBSERVATIONS

Shinichi Nakamura[1], Toru Tajima[1], Nobuo Kudoh[1], Jyunya Abe[1], Kazunori Someya[1],

Katsuhiro Ono[2], Masaya Kameyama[3], Gaku Adachi[3], Sadao Aoki[4]

[1] JAXA, JAPAN [2] NEC, JAPAN [3] FUJITSU Ltd., JAPAN [4] JSF, JAPAN

ABSTRACT

Since 2003, an active phased array radar at Kamisaibara Space Guard Centre (KSGC) has been used for LEO debris observation in Japan.

JAXA evaluated the performance of the KSGC radar at its 10-year anniversary of debris observation.

This paper presents the evaluation of detection ability, measurement accuracy and tracking ability, and the improvement of tracking ability of the KSGC radar by tuning parameters.

It is well known that the evaluation of the abilities and accuracy are comparatively simple. However, improvement of tracking ability requires know-how that can only be attained through accumulation of observation facts and their analytical results.

For example, there are some non-negligible differences between debris tracking and usual flying objects (i.e. airplanes) tracking. Namely, debris tracking can be characterized by the fact that its detective distance is extremely long, velocity is extremely high, fluctuation of relative attitude is unstable, etc.

This paper describes the above points, and more specifically, the evaluation method and logic for improving system performance of the KSGC radar by using debris observation data.

1 INTRODUCTION

Japan Aerospace Exploration Agency (JAXA) is observing space debris using the Kamisaibara radar, which is a small sized phased-array radar developed by Japan Space Forum (JSF) and installed at Kamisaibara Space Guard Centre (KSGC). Observation target is the objects of which data is published by the U.S. Space Surveillance Network (SSN).

Observation purpose is to obtain highly accurate orbit information which is used for calculations in the debris reentry predictions and in the conjunction analysis between JAXA satellites and debris while aiming at obtaining the basic technic of debris observation using the phased-array radar.

2 OUTLINE OF RADAR SYSTEM

Kamisaibara radar is an active phased array radar with S-band capability.

Figure 1: KSGC and Kamisaibara Radar

Fig.1 shows pictures of KSGC and Kamisaibara radar. This radar has a radiation plane of about 3 m square with 1395 TR-modules (Transmit/Receive), with transmission power of 70 kW.

Beam control in the azimuth direction is performed by electronic beam scanning in combination with mechanical axis drive, which enables scanning within ±45 degrees to the radiation plane. Beam elevation is controlled by electronic beam scanning up to 75 degrees from 15 degrees to the fixed radiation plane inclined at 54 degrees.

The detection capability requirement was the ability to track an object of 1 m in diameter at the altitude of 300 km. According to the concept described below, desirable elevation and observation arc length necessary for orbit determination were specified and reflected in the radar system design.

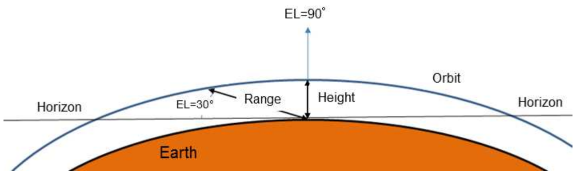
Prior to the development of the radar, JAXA had experimented debris observation using MU radar (Middle and Upper atmosphere radar) with Kyoto University.

The knowledge obtained through this experiment showed that, when the observation data was obtained only from one visible path, the required minimum arc length was achieved with 7-8 degrees of geocentric angle while satisfying orbit determination accuracy.

However, the above mentioned knowledge was obtained from a higher altitude debris observation experiment, which was approximately 900 km. The system design

Proc. '6th European Conference on Space Debris'
Darmstadt, Germany, 22–25 April 2013 (ESA SP-723, August 2013)

therefore had to include more effect of air drag perturbation as a margin of the minimum arc length, because the targeted observation altitude of Kamisaibara radar was 300km on the system design. Therefore, the detection ability was defined for debris sized 1 m in diameter at the elevation of 30 degrees with the slant range of approximately 600 km so that the minimum arc length ensures 9 degrees of geocentric angle after adding 1 degree as a margin. (Fig. 2)



Range: 600km, Height: 300km, Elevation: 30°

Figure 2: Orbit Altitude and Slant Range

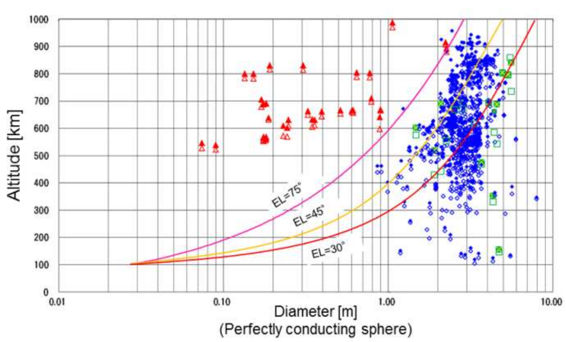
3 EVALUATION OF DETECTION ABILITY AND MEASUREMENT ACCURACY

3.1 Detection Ability

As mentioned above, practical detection ability of the radar is defined in terms of slant range at 30 degrees of elevation when a trajectory altitude is 300 km.

Therefore, on selecting an object to be observed by the radar, it was extracted by referring to observability in terms of the object’s slant range at 30 degrees of elevation and RCS published by the SpaceTrack.

Fig. 3 shows a comparison between the radar detection ability curves derived from radar equations (theoretical value) and the objects’ diameters (derived from RCSs).



(Observation Good)
■: Ha, □: Hp (Japan origin) ◆: Ha, ◇: Hp (Others)
(Observation NG)
▲: Ha, △: Hp (Japan origin)

Figure 3: Detection Ability Curves vs. KSGC Results

As can be seen from Fig. 3, a large part of the objects which can be observed by the Kamisaibara radar are distributed within the detection ability curves of 30 degrees and 75 degrees of elevations. Large objects or objects in a lower altitude than 300 km were detectable, as shown by the dispersed plots in the region below the detection ability curve of 30 degrees.

3.2 Ranging Accuracy

Since Kamisaibara radar is targeted at objects sized a few meters in diameter at a very long distance, it is necessary to transmit beams which has a very strong energy. For the above purpose, the radar employs two signal processing techniques to earn more gain of the received echo, which are pulse compression and signal integration.

Pulse compression is a technique that the energy per unit time of the pulse is strengthened 200 times, that the radar transmits the long-pulse (300 μs) to the object and reflected echo is compressed to very short pulse (1.5 μs) through the arithmetic processing. In addition, 16 echo-pulses are stacked through the integration processor.

With the above processed data, slant range is obtained from the round-trip time of the pulse. Angles are measured by two methods. Azimuth angle is measured by typical mono-pulse measurement. Elevation angle is measured by sequential roving method taking advantage of the active phased array radar, which adopts two beams to scan up and down electronically.

Normally, in the actual operation of orbit determination, only ranging data is used to determine the orbit because angle measuring accuracy (0.3 deg.) is extremely lower when compared to ranging accuracy (30 m). Angle data is therefore used only for the initial acquisition of a target in the radar beam control system.

The evaluation results of ranging accuracy based on orbit determinations are described below.

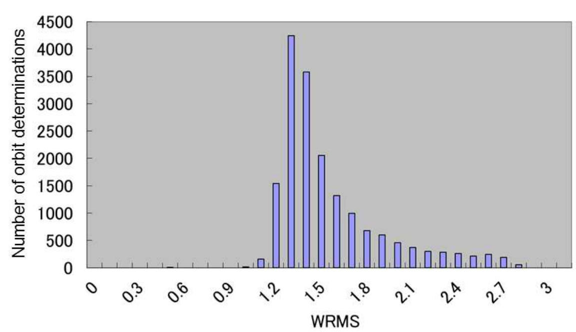


Figure 4: Distribution of Orbit Determination WRMSs

Fig. 4 is a histogram of WRMSs (Weighted Root Mean Square) that was obtained from 17545 orbit determinations in 2012. A WRMS is a value which is derived from RMS divided by the value σ of data used, where RMS is derived from the least square method.

WRMS is one of the criteria for judging the quality of orbit determinations because, when the measuring errors of the observation system are normally distributed, value σ almost uniquely means the measuring error of the observation system.

When a WRMS is closer to "1," the error can be considered to have been caused by the error in the observation system. The residuals by orbit determinations almost coincide with the radar measurement errors, because the mode of the WRMSs is 1.3 while the average value is 1.5.

It is possible that the reason for a WRMS being not equal to "1" is remaining error in the atmospheric model used in the orbit determination.

4 EVALUATION OF SYSTEM PERFORMANCE

A sequence of space debris acquisition and tracking by Kamisaibara radar consists of two phases. The first one is "initial acquisition phase" in which the radar receives some echoes coming from the beam pointing direction and determines whether the radio wave reflection is coming from the same target object. The second one is "tracking phase" in which the radar acquires observation data by beam transmission in accordance with the movement of the target following the initial acquisition.

This chapter describes the evaluation of technical factors for debris acquisition and tracking as well as the improvement of system performance by tuning parameters.

4.1 Gate Size of Initial Acquisition

A gate size of initial acquisition is one of the criteria used in determining whether multiple echoes are returning from the same target object. To describe in more detail, a gate size is an indicator to distinguish the echo returned off of the same object from other data (ex. false echo) by applying threshold ranges of certain sizes to both ranging and angle data. By evaluating the validity of the gate size, the initial acquisition performance of the radar can be indirectly evaluated.

(a) Algorithm for Initial Acquisition Judgement

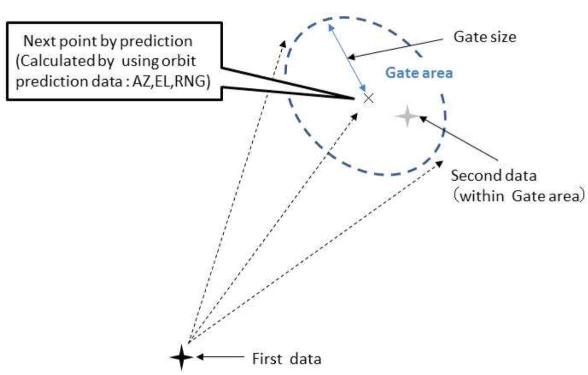


Figure 5: Gate Size of Initial Acquisition

Fig. 5 illustrates the concept for determining whether echoes are returned from the same object in the initial acquisition. The second point is estimated by using the first data, then the gate area is derived by applying the gate size to this estimated data.

The logic is, if the second echo fits within the gate, the radar system judges that this echo has been reflected from the same object. The second point prediction is caluclated by change quantity per second of orbit prediction data as a priori information.

When correlated data is accumulated to a total of 4 data according to this logic, time-offset (Δt) of is calculated by comparing the predicted data and observed data. After correcting Δt, initial acquisition completes. The radar system then transits from initial acquisition mode to automatic tracking mode by being slaved to the Δt-corrected predicted data.

Thus, although the probability of judging as a false data is reduced when the gate size is smaller, the number of valid data is also reduced, which would result in, in principle, less probability of transition to the automatic tracking.

When the gate size is much bigger, the probability of transition to automatic tracking increases. However, due to an increase of error in Δt, more false data are likely to be erroneously validated, thus potentially leading to loss of target during automatic tracking. Therefore, the gate size tuning is very important for improvement of the radar system performance.

(b) Evaluation Method

According to the settings in Tab. 1, transition probabilities from initial acquisition to automatic tracking were compared by changing the gate size at real radar observations.

Table 1:Gate Size Parameters by *Each Case*

	RNG(km)	AZ(deg)	EL(deg)
Case1	0.1	0.7	1.0
Case2	0.2	1.3	1.9
Case3	4.0	10.0	15.2
Case4	10.0	25.0	38.0

(c) Evaluation Results

From the observation results according to Tab. 1 settings, the rates of transition to tracking for each gate size were obtained as shown in Tab. 2.

Table 2:Ratio of Acquisition Success By Each Case

	Case1	Case2	Case3	Case4
Num.of paths(Planed)	63	172	41	53
Acq. success ratio	3(5%)	45(26%)	33(80%)	37(70%)

As can be seen from Tab. 2, the transition probability of Case 3 was the highest while the probability declined significantly in Case 1 and Case 2 with narrower gate sizes. Case 4, where the gate size was 2.5 times larger than that of Case 3, showed a tendency of reduced transition probability.

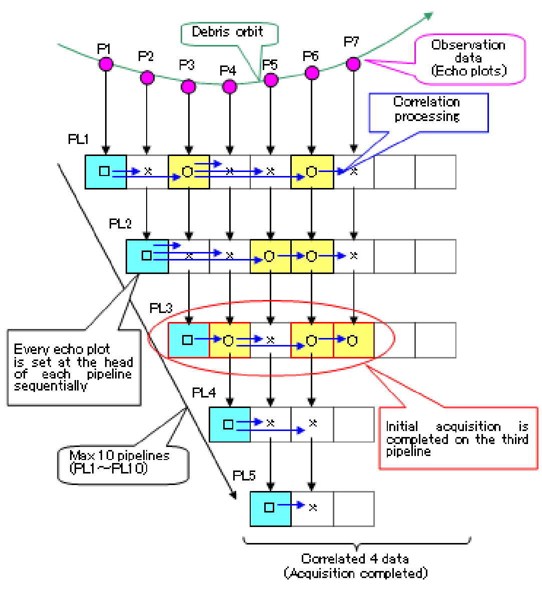
It is considered that a significant error in the Δt correction factor due to excessively large gate size resulted in the transition probability showing a declining trend after reaching its peak.

Although Case 3 showed the highest transition probability, the number of samples was small. Therefore, by including a margin for unknown factors causing tracking failures such as an error in the Δt correction factor, a half the value of Case 3 was adopted as the operational gate size.

Thus, the rate of transition to tracking is stable being approximately 75% in the actual operations, and also, most of tracking failures caused by errors in Δt-corrected orbit predictions are suppressed.

4.2 Optimization of Pipeline Processing of Initial Acquisition

(a) **Pipeline Processing Algorithm on Initial Acquisition**



□:Data head of pipeline ○:Correlated ×:Uncorrelated

Figure 6: Concept of Pipeline Processing

Initial acquisition pipeline refers to the memory used for parallel processing of the initial acquisition gate sizes. When echoes come back continuously from a target object, pipelines are used for the gate size processing where correlation between a data and the previous data is checked in sequence for each data in each pipeline to determine whether a set of data is returned from the same object.

In this correlation processing, based on the criteria of the initial acquisition gate size, ranging and angle data are compared to determine whether the echoes are considered to have been returned from the same object. Only those satisfy the criteria are stored in a single pipeline as a set of observation data.

In a pipeline, when four correlated observation data are accumulated, the process of identification initiates and then pipeline processing completes.

(b) Problem of Insufficient Number of Pipelines

Specific weakness of this radar system is a shortage in the number of the pipelines. Specific weakness means that if echoes (from 1st to 10th data) are stored in each pipeline sequentially, the pipelines will soon be full because the total pipeline number is only 10. Therefore, the 11th and subsequent data can not be correlated with their following data.

This means that, when all the data through to the 10th data are false data and stable echo can only be obtained from the 11th or later data, the initial acquisition in this case can not be achieved in principal.

Therefore, in order to prevent the initial acquisition failure, it is necessary to simply increase the number of pipelines.

(c) Evaluation Method

Using a test fixture, the number of pipelines were extended to 100 and 18 debris were observed experimentally. From this experiment, the acquisition time, the Δt correction factor, and the number of pipelines used for each debris observation were evaluated.

(d) Evaluation Result

In Tab. 3, it should be noted that observation cases where the initial acquisition was successful totalled 10 cases out of 18 cases with less than or equal to 10 pipelines, while in the remaining 8 cases the initial acquisition was successful with more than or equal to 11 pipelines.

From these results, it is clear that in order to improve the success rate of the initial acquisition of the KSGC radar, to increase the number of pipelines is very effective.

According to this experimental observation, although the maximum number of pipelines required for initial acquisition was 31, the required number of pipelines is considered to be about 60 (doubled the value of 31), because the Δt corrections were biased to the negative side in this observation while they can be shifted to the positive side at other times.

Table 3: The Number of Pipelines Required for Acquisition

Debris ID	Acq. time(s)	Δ t(s)	Pipeline number
6155	8	−14.033	6
28470	1	−16.799	2
4394	10	−12.307	10
13271	9	−14.801	2
11849	9	−12.335	11
22626	10	−13.796	11
27422	12	−7.781	8
27551	14	+3.043	20
27601	16	−1.542	31
14819	6	−15.324	4
20299	6	−15.297	10
13770	9	−0.122	14
13552	11	−8.082	13
10973	9	−10.281	9
22274	10	−10.407	21
22830	8	−12.372	6
24277	9	−13.722	5
11933	17	−6.706	24

In addition, although the number of plots (echoes) that can be stored in one pipeline is 16 data maximum, initial acquisition maximum number of plots that can be stored in one pipeline should also be doubled (32 data).

4.3 Autonomous Tracking Without Orbit Prediction Data

Kamisaibara radar has a function to acquire debris without using orbit prediction data and to track it autonomously.

A functional evaluation was conducted about whether a debris can be autonomously acquired and tracked by assuming the debris, which can be captured by Kamisaibara radar with its own capability, as a debris of unknown orbit.

(a) Autonomous Tracking Algorithm for Unknown Orbit Object

In the initial acquisition of unknown orbit debris, antenna aperture plane can be directed in any azimuth direction, where electronic scanning is performed in azimuth and elevation directions.

In the initial acquisition, the radar correlates a plurality of echoes from unknown debris passing through the beam according to the initial acquisition gate size logic.

In the initial acquisition of unknown orbit objects, we required 6 plots to have correlation confirmed, which is 2 larger than in the tracking case with predicted data (4 plots).

In the initial acquisition of unknown orbit objects, when correlated echoes are obtained in 6 points, the object's mean velocity vector (assuming linear motion in the fixed coordinate system with their origin at the observation station) is estimated by linear approximation using these 6 echo data (AZ, EL, and Range). After this processing, the system transits from initial acquisition phase to autonomous tracking phase.

In the autonomous tracking phase, radar system predicts 7th beam direction from estimated velocity vector derived from the correlated 6 echo plots, and transmits tracking beam to the estimated direction (7th beam).

If the 7th echo is returned from the object, velocity vector is estimated by interpolation of the 6th and 7th echoes. For convenience of explanation, this estimated velocity vector is referred to as "Velocity vector (New)" while velocity vector which is calculated by the 6 points in the initial acquisition is referred to as "Velocity vector (Old)."

In order to modify the velocity vector (Old) sequentially, the velocity vector (New) of the latest tracking data is reflected to the velocity vector (Old) by "αβ tracker" processing.

The "αβ tracker" is a real-time correction processing logic for debris tracking. It is a kind of weighting processing that modifies a known state quantity by using a new knowledge information. The value α is a weighting factor for position data and β is a weighting factor for velocity. Known data will be modified by the weighted amount derived from the new knowledge data.

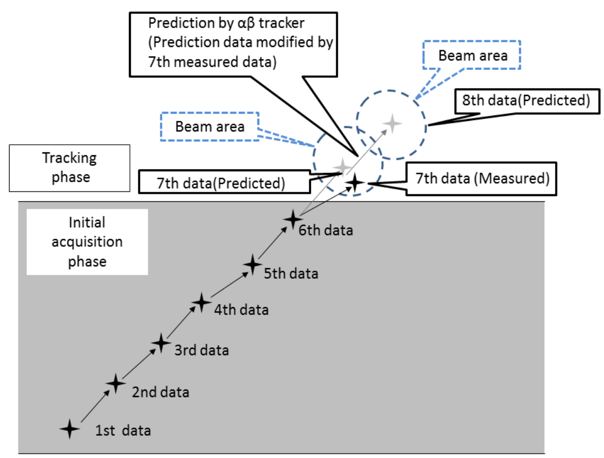


Figure 7: Beam Prediction Method on Autonomous Tracking

(b) Tracking Parameter Modification After Preliminary Study

Although we had a preliminary autonomous tracking test prior to this evaluation study, result of this test was not successful in tracking. Therefore, we modified signal processing parameters based on the analysis of results of the preliminary test.

➢ **Threshold level of signal processing**

In order to suppress the detection rate of false echoes, Pfa (Probability of false alert) was set to one-twentieth of the former value (to Pfa=7.2e^{-7}). This value corresponds to the receiving sensitivity of 1.09 m^2 for 1 m^2.

➢ **Number of pipelines**

In the cause analysis of initial acquisition failure, it can be seen that insufficient number of pipelines is one of the reasons. We therefore increased the number of pipelines from 10 to 40 by test jig to facilitate processing for initial acquisition.

(c) Evaluation Method

Considering the detection ability of Kamisaibara radar, in this tracking test, we assumed ALOS (Advanced Land Observing Satellite: ALOS's size is detectable size by Kamisaibara radar) as an unknown orbit object (hypothetical debris), and we validated the function of acquisition and tracking of hypothetical unknown debris by repeating the acquisition beam scanning ± 2° from the predicted direction.

In the electronic scanning in AZ direction for initial acquisition, the first stage scanning is run for 40 seconds. If a total of 6 echoes are not correlated, the second stage scanning is run for another 10 seconds by increasing the elevation corresponding to time elapsed. If a total of 6 echoes are not correlated also in the second stage, the same process for initial acquisition will be repeated up to the fifth stage.

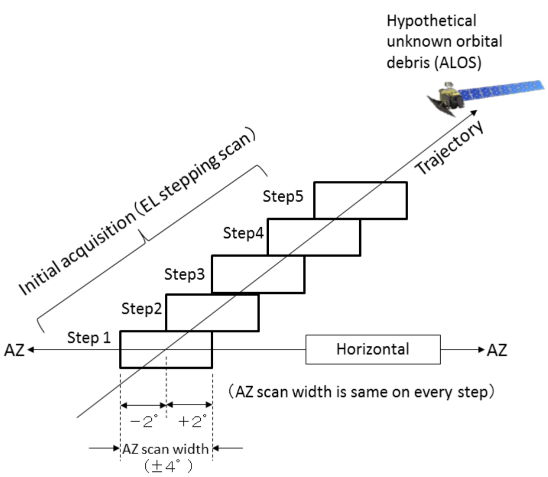


Figure 8: Initial Acquisition of Hypothetical Unknown Orbital Debris

Regardless of the number of steps, if the initial acquisition completes, the radar transfers from initial acquisition mode to tracking phase mode and autonomously tracks the hypothetical unknown debris for 30 seconds. In the 30 seconds' autonomous tracking, the radar tracks debris with correcting the beam irradiation direction by αβ tracker sequentially.

(d) Evaluation Results

In accordance with the above-mentioned test condition, we succeeded in the unknown debris autonomous tracking experiment, where transition from initial acquisition to autonomous tracking was completed. From the evaluation results, we also obtained significant studys that should be reflected for further improvements.

In the evaluation of the observed data, we calculated σ-value by using the residual between observation data and a calculated value (O-C), where the calculated value is derived from ALOS's precise orbit ephemeris by GPS carrier phase positioning method.

Table 4 Observation Data Error of Autonomous Tracking

Paths (UT)	Range(m)	AZ(deg)	EL(deg)
15 Nov. 01:53	2377.4	0.64	0.52
15 Nov. 12:54	2357.8	0.94	0.29
16 Nov. 02:23	613.5	0.77	0,26
17 Nov. 12:37	944.2	0.64	0.33
18 Nov. 02:36	598.6	0.57	0.34

➢ **Causes for ranging error increase**

From Tab. 4, residuals of the angle data are roughly the same as measurement error of the angles (0.3 deg. rms) which is attributable to radar ability, however, the difference is significant between residuals of ranging and measurement error of ranging (30 m rms).

The cause with highest contribution to the error is the fact that because the tracking object moves with ultra-high-speed (about 7 km/s), the radar system is not able to remove the Doppler shift component (Doppler-correction) on the chirp signal which is used for the signal processing upon pulse compression. If there are some Doppler shift on the chirp signal in the processing of pulse compression, it is likely that the ranging error is caused by compressed pulse not being accumulated in the correct position.

If it is a tracking case with orbit prediction data, the Doppler shift compensation value is known. In the case of autonomous tracking, however, Doppler shift compensation value is unknown and a velocity vector estimated by αβ tracker is used instead of predicted Doppler shift compensation.

The Doppler shift compensation derived through autonomous tracking is not considered to be correct because the debris velocity vector estimated by αβ tracker is based on the assumption of linear motion.

- **Improvement of ranging accuracy**

·Review of the assumption of object motion

As mentioned above, in the autonomous tracking mode, Kamisaibara system assumes object motion as a linear motion in the coordinate with their origin at the radar station for estimating an object's trajectory. So, it is desired that the radar system assumes object motion as a quadratic curve in the earth centered coordinate, and that techniques for correcting the beam direction prediction by methods including use of αβ tracker or any numerical filters (ex. Kalman filter) would be introduced. It is possible that not only improvement of ranging accuracy but also improvement of tracking success rate would be achieved.

·Improvement of real-time successive correction

The values α and β (defined by αβ tracker) are weighted for the correction of the velocity vector each in a constant ratio. However, in the real-motion, this definition has a limited representativeness. For example, it might be able to improve the accuracy of the compensation value very much by considering the change of weighting parameters for real-time processing, such as Kalman filter.

·Introduction of parallel processing of mass data with coherent integration

Kamisaibara system adopts non-coherent integration which does not require Doppler shift compensation between some echoes in the autonomous tracking because it is impossible for the radar to estimate correct Doppler shift compensation by integration processing of many hits with no orbit information of an unknown object.

However, due to dramatically faster CPU processing speed in recent years, by using parallel processing of large amounts of Doppler shift values and phase rotation values, an optimal solution that realizes the highest level of receiving can be obtained and utilized it as observation data for orbit determination.

By adopting this hi-speed processing, it is possible that, in principle, receiving level of autonomous tracking will be dramatically improved only by revising signal processing system without changing radar capabilities.

5 Conclusions

This paper described distinctive matters of Kamisaibara radar system performance evaluation results.

The radar has been developed as an experimental radar system to obtain knowledge on observing the debris by active phased array radar. In our debris observation, we accumulated practical achievements in many re-entry observations, observations of the debris of Japan origin, and maintenance of the catalogue of debris orbit elements.

Some of the evaluation results described in this paper shows that the radar can be refurbished to acquire higher performance only by revising signal processing software without revising radar hardware due to dramatically improved computer ability when compared to the time when the radar was developed.

Acknowledgment

We send special thanks to Ms. Hitomi Wada for linguistical support to making this paper.

References

[1] Ono, K., et al. "Development of the First Japanese Space Debris Observation Radar", Proceedings of the Third European Conference on Space Debris, ESOC, Darmstadt, ESA SP-473, Vol. 1, 2001, p. 73 - 78.

[2] Hirose, C., et al. "Observation of Space Debris by the Kamisaibara Radar System", Proceedings of the Fourth European Conference on Space Debris, ESOC, Darmstadt, ESA SP-587, 2005, p. 73.