Development of The First Japanese Space Debris Observation Radar

Katsuhiro Ono(1), Toru Tajima(2), Akio Mizutani(3), Yoshitaka Taromaru(2),
Shuzo Isobe(4), Tadashi Takano(5), and Toru Sato(6)

(1) NEC Corporation, 1-10 Nisshin-cho, Fuchu, 183-8501 Japan, k-ono@db.jp.nec.com:
(2) National Space Development Agency, 2-4-1 Hamamatsu-cho, Minato-ku, Tokyo, 105-8060 Japan:
(3) Japan Space Forum, 1-29-6 Hamamatsu-cho, Minato-ku, Tokyo, 105-0013 Japan:
(4) National Astronautical Observatory, 2-21-1 Osawa, Mitaka, Tokyo, 181 Japan:
(5) Institute of Space and Astronautical Science, 3-1-1 Yoshino-dai, Sagamihara, 229-8510 Japan:
(6) Kyoto University, Yoshida-honmachi, Sakyo-ku, Kyoto, 606-8501 Japan:

ABSTRACT

The National Space Development Agency (NASDA) started conceptual study of a space debris observation system in 1994. The project indicates Japan's intention to equip its own debris observation system as inevitable infrastructure assuming the debris problem to be serious in manned space activities in 21st century. Since 1996, NASDA has focused on a pilot radar observation system and has made a basic design of an active phased array (APA) radar to observe debris 50cm in diameter in LEO orbit. Subsequently, the space guard center project for observing space debris and near earth objects (NEO) has been promoted by the Japan Space Forum (JSF). The Japan Space Guard Association (JSGA) and NASDA have been supporting JSF to proceed with the project. The space guard center consists of Kamisaibara Space Guard Center (KSGC), which has a radar sensor, and Bisei Space Guard Center (BSGC), which has optical sensors.

This paper describes overview, technologies and future concept of the radar system in KSGC.

1. INTRODUCTION

NASDA initiated study of debris observation system in 1994. The USA's Two Line Element (TLE) has been the only source of debris orbital elements. We consider that debris observation will be essential infrastructure for supporting manned space missions. Therefore, the study intends to achieve the observation with independent technologies.

Several experimental observation of debris have been performed [1] by using Middle and Upper atmosphere (MU) radar [2,3], the bistatic radar of the Institute of Space and Astronautical Science (ISAS), and optical telescopes of the National Astronomical Observatory (NAO) and the Communication Research Laboratory (CRL). NASDA made the conceptual design of an ideal system for observing several centimeter-size debris in the first stage of the study, and the design was based on the accomplishments of experimental and operational observation results in Japan and other nations. In addition, we determined the orbit of an unknown object with one visible pass (the duration of the visible arc is approximately 100 seconds) data. The experiment proved the feasibility of the ideal system. The NASDA preliminary study is presented in section 2, and the system design approach derived from the study is described in section 3. This debris observation radar introduced in this paper is positioned as a pilot system. The radar system for an order of centimeter-diameter debris will be developed in the next phase based on this achievement. The overview of the system is described in section 4. The experimental operation mode is specially incorporated in the system for the further development of radar technologies. The routine observation modes and the experimental mode of the system are presented in Table 2. Several significant technologies on signal processing and tracking beam scheduling can be improved and evaluated in the experimental mode. The technologies applied in the system are presented in section 5. The concept of future operation is presented in section 6.

The detailed design of the system was completed in 1999. The component or subsystem manufacturing and radar site construction are scheduled to be completed by the end of 2002. The system installation work and integration test will be performed by 2003. The regular operation of the system is scheduled to start in April, 2004.

2. NASDA PRELIMINARY STUDY

NASDA conducted a study of a space debris measurement radar system between 1994 and 1997. Initial conceptual work consisted of an international survey of current debris observation activities and a feasibility study

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for detecting debris smaller than one meter. Subsequently, the study was focused on beam agility to observe as much debris as possible.

The major accomplishments of the preliminary study were:

a) Determined system size for observing small debris

Various antenna sizes and transmission power levels were studied for observing object smaller than one meter in the L-, S- and C-frequency bands. Then, we focused on a 3 GHz APA system, and the elements for APA in the S-band in terms of the diameter of detectable object were estimated.

b) Determined the number of debris pieces that can be observed simultaneously

In this study, one meter was assumed as the minimum detectable debris size in a 300 km orbit at 30 degree elevation. A comparison of 1997 TLE data with September, 1998 Radar Cross Section (RCS) data taken from the Monthly Satellite Situation Report produced 6,338 debris matches. A subsequent orbit analysis resulted in 1,003 targets determined to be observable. The six orbital elements of these debris pieces were identified and the position of each target at the certain time plotted within topocentric-horizon coordinate system was simulated. Fig. 1 shows the result of this simulation. The maximum number of targets visible simultaneously is seven among 1,003 of candidate debris on Mar. 1st, 1998, for example.

c) Determined the elevation of initial acquisition

The narrower the elevation area of debris observation, the shorter its range for observation. Therefore, if the higher elevation of initial acquisition is chosen, the size of system can be very small. On the other hand, the high elevation decreases the arc length of the debris pass. We made a trade-off of these two factors, and determined 30 degrees elevation for the initial acquisition.

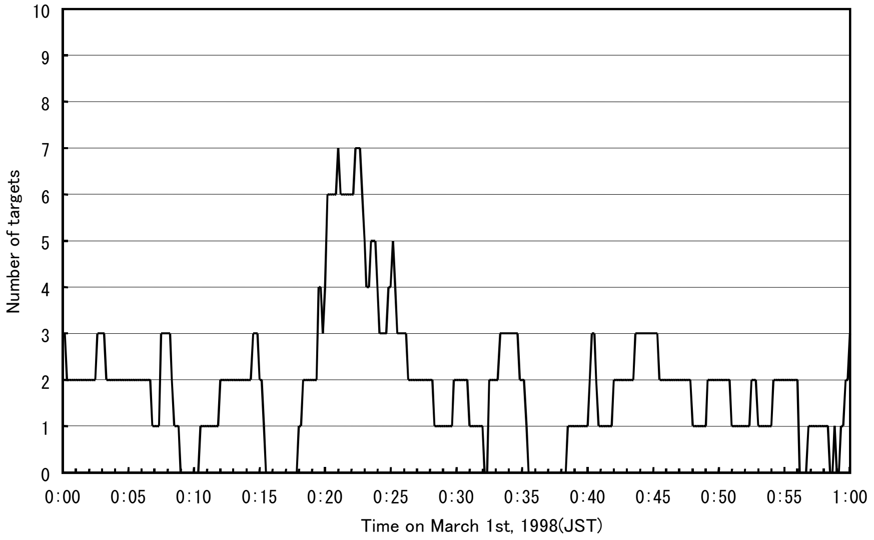


Figure 1. Number of targets visible simultaneously.

3. SYSTEM DESIGN APPROACH

Examining the results of the NASDA study, the following system particulars were specified.

a) Multiple tracking capability

According to the simulation described in section 2, paragraph b), the maximum number of simultaneous tracks is seven. However, the steady increase in debris that is currently taking place dictates that an ultimate goal of 10 debris pieces should be established. To achieve the capability, an APA system is desirable.

b) Minimum detectable target in size

The preliminary study identified several vital barriers (such as budgets, infrastructure, technologies). To deal with this subject, a minimum size of one meter was targeted for this initial stage. From the simulation in section 2, paragraph b), we set the target as 300 km LEO, and the elevation over 30 degrees. As a result, one meter-diameter debris at 577 km slant range is specified for the radar detection capability of this pilot system in the initial stage. The next system will focus on the debris of the order of centimeter in diameter.

c) Maximum beam scanning area

Based on the initial acquisition elevation described in section 2, paragraph c), the lower edge of elevation scanning angle is 30 degrees. Considering the skyline of KSGC site and other observation applications, elevation scanning area from 15 to 75 degrees is adopted. Regarding the azimuth scanning area, to attain longer arc length of debris pass, 360 degrees coverage is the best possible. To cope with this azimuth beam positioning capability, electrical beam scanning and mechanical azimuth rotation, both are provided.

4. SYSTEM OVERVIEW

Based on the research findings, a S-band planar APA antenna mounted on the mechanical rotated turret system is adopted to cover 360 degree in azimuth. As shown in Fig. 2, the total system consists of a radar system in KSGC and the central processing system in the NASDA space center; the two are connected by high speed digital communication lines. Fig. 3 presents an external view of the radar system; its major function and performance are shown in Table 1. The KSGC is located in Kamisaibara, Okayama (western Japan), and the NASDA space center is in Tsukuba, Ibaraki (eastern Japan).

The descriptions of components and sub-system are as follows:

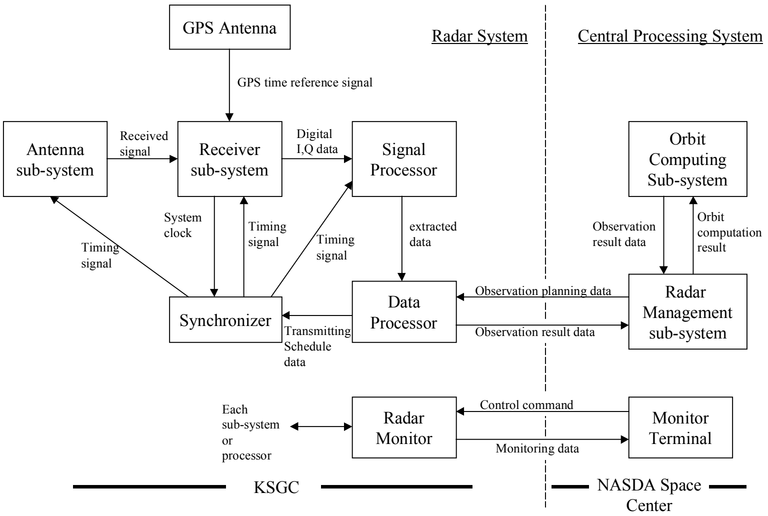


Figure 2. System diagram.

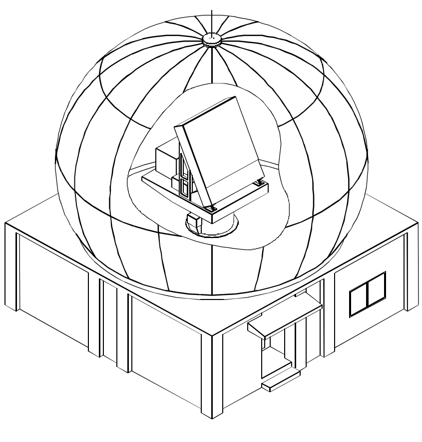


Figure 3. External view of radar Site.

Table 1. Major function and performance of the System

Item	Function and performance
Frequency	S-Band
Transmitting Peak power	70 kW, nominal
Pulse width	300 μ sec (compressed to 1.5 μ sec)
Beam width	2 degree in azimuth and elevation
Beam Scanning Electrical Mechanical	 ± 45 degree azimuth and 15-75 degree elevation ±270 degree, maximum 10 degree/sec
Acquisition	Azimuthal scanning
Tracking	Automatic, time-shared tracking up to 10 targets
Integration	1, 2, 4, 8, and 16 pulses, selectable
Number of data to process	At least 1,000 passes/day
Data Storage capacity	8 GB or more

a) Antenna sub-system

This sub-system consists of a planar APA and control units; the aperture of APA is approximately 2.8 m by 2.8 m square. The APA has 72 column with each column containing dipole antennas and transceiver modules (TRM)—approximately 1,400 TRM in the entire APA. To prevent grading lobes, a scanning area is limited to 15 to 75 degrees in elevation and ±45 degrees in azimuth. The turret activated by servo controlled motor turns the APA ±270 degree from the azimuth home position in order to achieve 360 degree beam positioning. This APA uses the COTS technology of NEC's cylindrical APA system [4] and microwave TRM (Fig. 4).

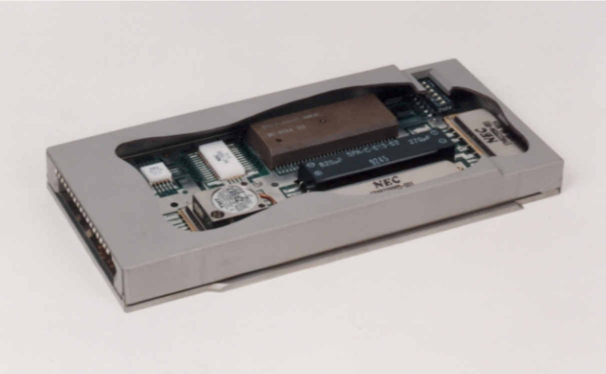


Figure 4. Transceiver module.

b) Receiver sub-system

This sub-system consists of Intermediate Frequency (IF) amplifier, Analogue to Digital (A/D) converter, digital phase detector, signal recording system, and Global Positioning System (GPS) receiver. Incoming signals from antenna sub-system are processed by the IF amplifier and A/D converter. Digitized data (6 MHz-sampled clock and 14 bit word) is processed with the digital phase detector and an I/Q signal is produced.

The digitized I/Q signal can be recorded in the signal recording system. The recording system is equipped with high capacity media to bring the recorded data for off-line analysis. The GPS receiver supplies the time reference signal with precise 10 MHz and 1pps clocks for the system synchronization and time stamping on the received target.

c) Signal Processor

This processor has two versatile Digital Signal Processor (DSP) units that process the incoming radar information in real time. The processor sends the extracted data (debris ID, stamped time, measured range and angles) directly to the data processor described below. The major functions of the signal processor are: 1) doppler shift effect compensation, 2) pulse compression, 3) hit by hit range walk compensation, 4) coherent/incoherent integration, 5) target detection, 6) range/angle measurement.

d) Data Processor

The data processor (DP) consists of a high performance Unix-based workstation. The major functions of the DP are: 1) producing transmitting schedule data from the observation planning data; 2) tracking the target; and 3) observed data transmission to radar management sub-system.

e) Synchronizer

This unit generates all necessary timing signals for synchronizing all the real-time aspects of the system by using a 10 MHz reference signal from the receiver sub-system and transmitting schedule data from the DP.

f) Radar Management sub-system

Using TLE or its own debris catalogue data, this sub-system creates optimized observation planning data automatically. The priority, frequency of appearance in sight of debris and property of the radar system are taken into the sub-system and evaluated intelligently to produce the observation plan. The operator confirms the observation plan and can edit if needed. The system has six observation modes as shown in Table 2. The choice of the mode is also included in the observation plan.

Table 2. Observation modes

Mode	Description
Catalogue maintenance (primary purpose)	Update the orbital elements of the debris catalogue.
Event observation	Observations of special event. Processing is same as the catalogue maintenance mode, but designed for predictions with large errors.
Modeling	Beam parked at 65 degree elevation; debris crossing the beam is counted and its range is estimated.
Unknown debris	A mode for finding unknown, unlisted debris.
Optical Telescope collaboration	Simultaneous observation of debris with a telescope system in Bisei Space Guard Center (BSGC). Following two modes are available; telescope master mode and radar master mode.
Experiment	A mode for applying a new processing program and technologies, and analyzing its performance.

g) Orbit Computing sub-system

This sub-system receives observation result data from the radar system via the radar management sub-system. The orbital elements are determined by special perturbation method and are preserved in debris catalogue of the system. The sub-system helps the radar management sub-system to create the observation planning data by calculating the position of debris.

5. TECHNICAL FEATURES

The following unique technologies especially for the debris observation application shall be applied into the system.

a) Initial Acquisition.

Observation planning data generated by the radar management sub-system is sent to the radar system. An example observation diagram is given in Fig. 5. This diagram consists of selected debris for observation and mechanical azimuth direction (center of the colored belt in Fig. 5, the colored belt represents the electrical scanning area). A red (or dark) belt marks a transition area that is not available for observation.

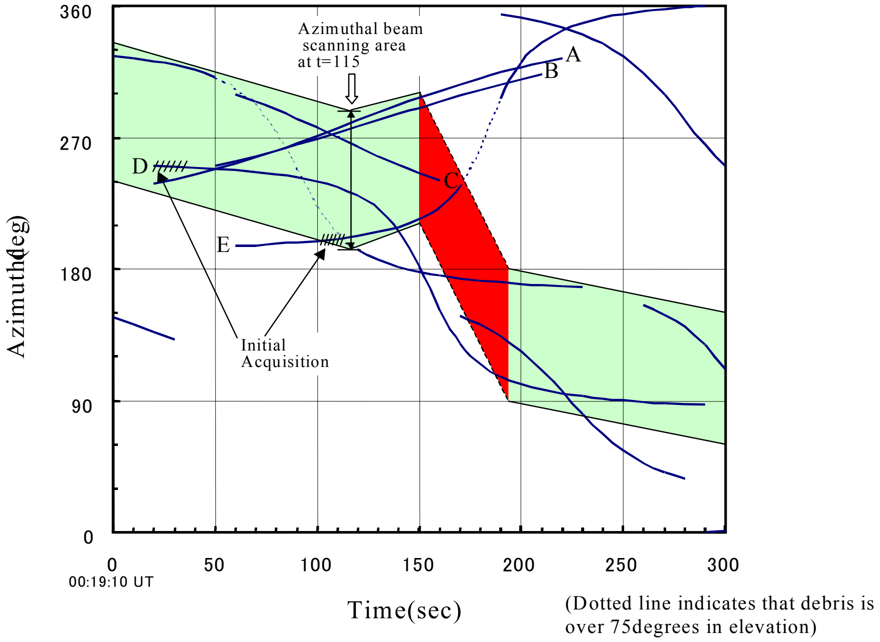
In the case of D debris in Fig.5, initial acquisition starts as soon as debris is sighted; in the case of E debris, initial acquisition starts when the debris enters the electrical scanning area.

b) Tracking

When the initial acquisition is completed successfully, the time difference to nominal predicted time calculated from the data of catalogued debris is determined and the nominal prediction will be compensated for by the time difference. From initial acquisition, the observation phase is transferred to the tracking phase. The acquired debris is tracked using the compensated nominal prediction data. Also, the earth's rotation should be compensated for by applying transformation of coordinate systems for whenever the time difference is larger than 30 seconds.

c) Multiple debris observation

The example in Fig. 5 shows a single piece of debris (C debris) at 0 second and three debris (C, D and A) will be observable at 20 seconds moment. In this example, the maximum number of visible debris is 5 (at 115 seconds). In this case the system assigns five beam slots for five beam positioning within one second. When the detection slant range of debris is 1,200 km, the time duration of each time slot becomes 160 milliseconds as 16-pulse integration mode is assigned. Total length of time slots would be 800 milliseconds (160 milliseconds × 5). Therefore, this case keeps the tracking rate of once a second. If the total length is over one second, the DP optimizes the tracking rate.



(Dotted line indicates that debris is over 75degrees in elevation)

Figure 5. Scheme for observing multiple debris.

d) Hit by hit range walk compensation

This system uses multiple pulse integration (1, 2, 4, 8 or 16 pulses) to increase the detection capability. Since the velocity of debris is very high, the detected slant range shifts hit by hit. The shift reduces the integration gain. Therefore, the digital processor compensates the shift by using the compensated nominal prediction data.

6. OPERATIONAL CONCEPT AND FUTURE TRENDS

As described in section 3, the system has six observation modes for various purposes. In optical telescope collaboration mode, the system and the BSGC telescope system [5] collaborate in observation of same debris. Two observation sites are connected via the central processing system. Each system sends the observation result data as quickly as possible. Subsequently, the central processing system produces the prediction data for the other system and sends the data immediately for the detection in the other system. Since at least 30,000 pieces of debris are estimated to be larger than centimeter orders, collaboration manner with different observation systems or data exchange internationally is indispensable. The scheme of this mode will be positioned as a prototype of the next generation system.

Using experimental mode, we can estimate the validity of new technologies such as transmitting scheduling scheme, collaboration interface, and compensation method of prediction data. These technologies will improve the ability of the next generation system for detecting the order of centimeter-diameter debris.

The future trends in concept of debris observation radar system have been discussed in a space debris committee in Japan. There are several different ideas, but the most likely system will be APA with electrical scanning antennas covering 360 degrees in azimuth, longer pulsed, and higher peak power transceiver modules.

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