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MU RADAR OBSERVATIONS OF SPACE DEBRIS

Toru Sato^{*}, Ken-ichiro Ikeda[†],
Toshio Wakayama[‡] and Iwane Kimura^{**}

The MU radar of Japan has the lowest frequency of 46.5 MHz among all radars used for debris observation. Despite the disadvantage of reduced radar scattering cross section (RCS) of small debris whose dimension is smaller than the radar wavelength, the radar has comparable sensitivity to those employed by US SPACECOM for routine monitoring of space debris. It is then expected to provide valuable set of information for RCS comparisons using radars with different frequencies, which is one of the most promising means of assessing the shape and mass of space debris.

The largest advantage of the MU radar is its fast beam steerability, which enabled us to observe RCS variations of unknown debris. Preliminary statistical study shows that small debris has larger RCS variations than larger debris, suggesting that they may have elongated shape rather than spherical shape as usually assumed in model calculations.

INTRODUCTION

Radar observation is the most practical way of studying the space debris environment on the low-earth orbit as far as the objects of larger than 1 cm are concerned. An extensive catalog of orbiting objects provided by the United States Space Command (US SPACECOM) has been the major source of the information, and is routinely updated based on observations made with various radars and optical devices¹. The distribution of objects obtained from this catalog has been used to assess the safety of space traffic at present and in the future combined with the results from other techniques such as optical telescope and analyses of retrieved material from the orbit^{2,3,4}. However, the main information on each cataloged object from these observations is the radar scattering cross section, which is not necessarily correlated with its mass or shape.

Although the area-to-mass ratio has been estimated by measuring perturbations of the orbit of debris due to atmospheric drag^{5,6}, apparently a more extensive study on the mass and shape of debris is needed. Radar observations at various wavelengths will provide

* Lecturer; † Undergraduate Student; ‡ Graduate Student; ** Professor; All with the Department of Electrical Engineering II, Kyoto University, Kyoto 606-01, Japan.

important information on the physical size and shape of the debris. While most of tracking radar employ UHF or higher frequencies in order to obtain sharp beam and high gain with limited antenna aperture, we demonstrate here that powerful VHF radars also can be used for debris observations.

The MU (Middle and Upper atmosphere) radar was constructed at Shigaraki, Shiga prefecture, Japan (34.85°N, 136.11°E) in 1984 mainly for the purpose of investigating atmospheric and plasma dynamics in the wide region from the troposphere to the ionosphere⁷.

The radar is a powerful monostatic pulse Doppler radar operating at 46.5 MHz with an active phased array antenna, which consists of 475 Yagi antennas and identical number of solid-state transmit/receive modules. This design realized a very fast beam steerability. The antenna beam direction can be switched to any direction within the steering range of 30° from zenith from pulse to pulse. The antenna aperture is 8,330 m² (103m in diameter), and the peak and average output power is 1 MW and 50 kW, respectively. The antenna beam has a conical shape with the round-trip (two-way) half-power beamwidth of 2.6°. The details of the system are described elsewhere^{8,9}.

Here we present the experimental setup and preliminary results of a series of observations made with the MU radar as the first attempt of measuring the distributions of orbital debris versus height and scattering cross section at the VHF band.

THE MU RADAR SYSTEM AND ITS SENSITIVITY

The MU radar operates an ionospheric sounding mode about 48 hours every month, measuring the echo power and auto-correlation functions of ionospheric scattered echoes. The same data has been utilized to pick up hard-target echoes from orbiting objects for a height range between 300 km to 1240 km and to determine their statistics¹⁰. The observations have been made for four beam directions of 20° off vertical in the east, west, north and south directions. For transmission, a 7-bit Barker code with 64 μ s subpulses has been used for the power mode of ionospheric observation. The received echo signals are sampled at 207 different range bins with 4.8-km intervals, and averaged over 25 transmitting pulses for incoherent integration. The resultant time resolution is about 1 second.

Figure 1 shows the detectability of the MU radar for a hard target with these parameters in terms of the minimum scattering cross section and corresponding radius of perfectly conducting sphere versus height. The background noise temperature is assumed to be 10,000 K, which is the mean galactic noise temperature at 46.5 MHz. Capability of the MU radar for a hard target is about 1.5×10^{-4} m² in its cross-section at an altitude of 300 km and about 3.7×10^{-2} m² at an altitude of 1240 km, which correspond to radii of conducting spheres of 13 cm and 34 cm, respectively.

As clear from this figure, most of small objects fall within the Rayleigh region of scattering, in which the scattering cross section is much smaller than the physical cross section. While this is an obvious disadvantage in terms of detectability, a large difference in the operating frequency from other radars usually chosen for this type of study will provide us with unique opportunity of obtaining the scattering cross section seen at a much lower frequency.

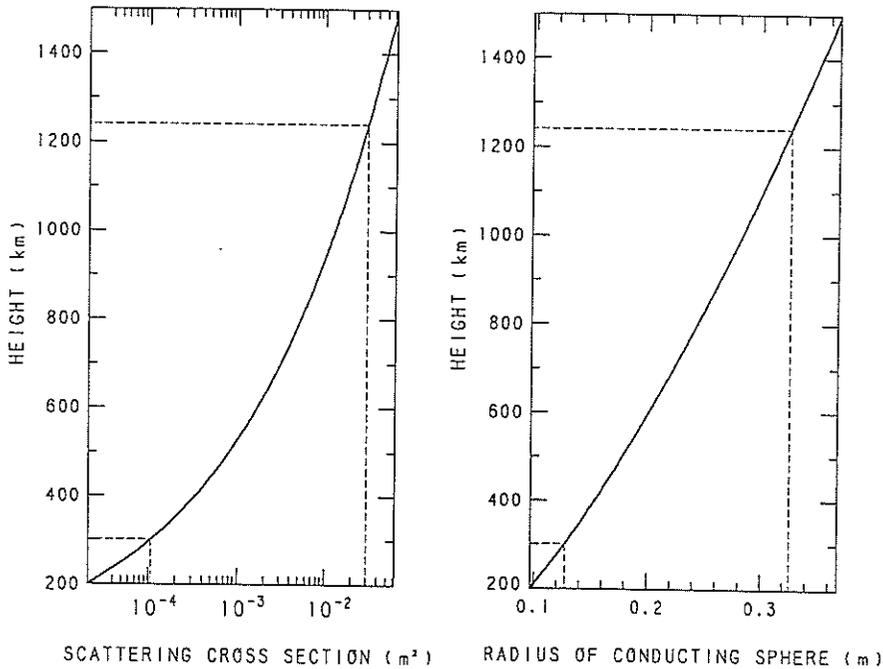


Fig. 1 Detectability of the MU radar for a hard target in terms of minimum scattering cross section and corresponding radius of perfectly conducting sphere versus height.

Figure 2 compares the height distribution of space debris observed by the MU radar with that determined from the US SPACECOM catalog. The radar data is taken during 1989, and the catalog is as of July 1989. While there is a difference between the two that the MU radar data covers only those objects that have inclination of larger than 35°, and also with different weight on the chance of observation depending the inclination, the good agreement shown in the figure confirms that the MU radar has roughly equal sensitivity in detecting space debris as the radars used for US SPACECOM catalog update.

DEBRIS OBSERVATION MODE

The major advantage of the MU radar in debris observation is in its fast beam steerability. Conventional aperture-antenna radars can track objects with known orbital elements, but can observe unknown objects only during the short time period when they pass through the fixed antenna beam. For example, the sensitive Haystack radar has been used to observe the radar scattering cross section (RCS) variations of both known and unknown objects¹¹, but the maximum duration it can observe an unknown object is limited to about 1 sec because of its very narrow antenna beamwidth.

On the other hand, the active-phased-array antenna of the MU radar can be pointed to any desired direction within the coverage of 30° from the zenith in 10 μsec. It is therefore

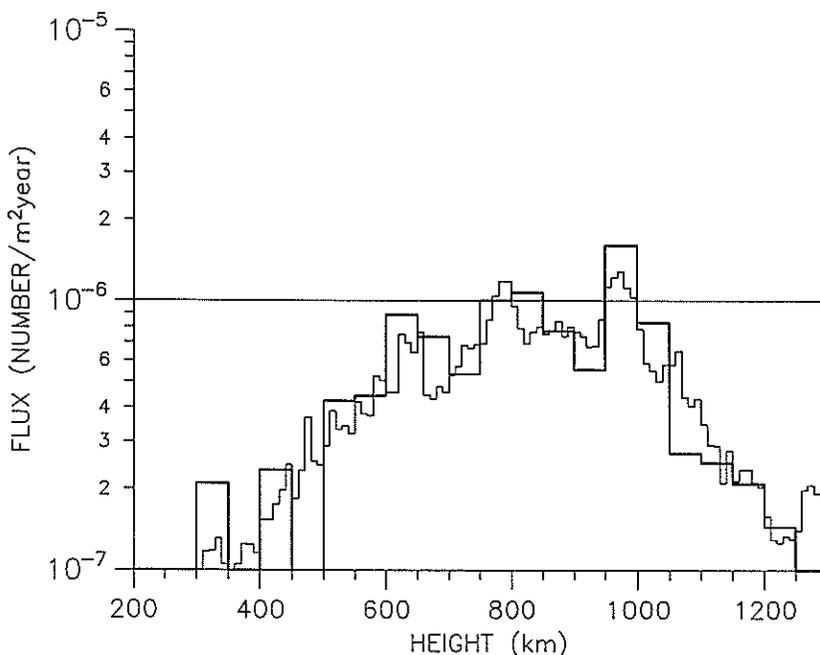


Fig. 2 Height distribution of the debris flux derived from the MU radar observations (thick line) and from the US SPACECOM catalog.

possible to observe the passage of an object with multiple beams. We developed a special debris observation mode with which the antenna beam is switched alternately from pulse to pulse among 8 directions arranged closely around the zenith. Table 1 shows the parameter of the debris mode.

Figure 3 shows the plan view of the beam arrangement together with a path of the radar calibration satellite LCS-4. This satellite is an aluminum sphere with the diameter of 1.129 m and the weight of 34 kg, launched by the MIT Lincoln Laboratory on 1971¹². It has a polar circular orbit with inclination of 87° and height of 800 km. Since the coverage of the beams are overlapped each other, it is possible to determine the instantaneous direction of the satellite seen from the radar by comparing the echo intensity of adjacent beams. It is then possible to compensate for the antenna gain reduction to get the precise RCS value at each time. The range is determined with much finer resolution than the pulse width by fitting the known time response of the pulse to the oversampled signals.

The good fit to a straight line shown in Fig. 3a and 3b suggests that the direction and the range of the satellite is determined with an accuracy of about 0.1° and 200 m, respectively. It should be noted that the beamwidth of 3.6° and the range resolution of 9.6 km of the system are several tens of times larger than these values. It is possible to roughly calculate the orbital elements of the satellite from the determined path. The obtained inclination, for example, agrees with the real value within an error of 2°.

Fig. 3c shows the RCS versus time. Since the radar did not have an accurate absolute

Table 1 Observational parameters of the MU radar for the debris mode.

Parameter	Value
Location	Shigaraki, Shiga, Japan (34.85°N, 136.10°E)
Radar system	monostatic pulse radar; active phased array system
Operational frequency	46.5 MHz
Antenna	circular array of 475 crossed Yagi's
aperture	8330 m ² (103 m in diameter)
beam width	3.6° (one way; half power for full array)
steerability	steering is completed in each IPP
beam directions	8 (vertical, 3° and 6° off-zenith)
polarization	Right-hand circular
Transmitter	475 solid state amplifiers
	(TR modules; each with output power of 2.4 kW peak and 120 W average)
peak power	1 MW
average power	45 kW (duty ratio 4.5%)
pulsewidth	448 μs (64 μs × 7 bit)
IPP	10 ms
Receiver	
IF	5 MHz
A/D converter	12 bits × 2 channels
Pulse compression	7-element Barker code
Observed range	201.46km—810.63km
Range resolution	9.6 km
Time resolution	1 s

calibration, this experiment is used to determine the system constant and the mean observed RCS value is adjusted to its theoretical value of 0.70 m². The fluctuation of RCS shown in Fig. 3c indicates the magnitude of the random errors in RCS determination. It is estimated to be 0.4 dB, which gives the lower boundary of RCS variation detectable with the MU radar. It should be noted that this technique provides RCS variation of unknown objects for a period of 10–20 sec compared to a fraction of a second available with other radars.

RCS VARIATIONS

The constant RCS shown in Fig. 3c is a rather exceptional example of purely spherical object, and most of debris should have some sort of asymmetry as well as spin motion. It is thus expected that observations of time variation of RCS will give us information concerning the shape of the object.

Bohannon and Young¹¹ examined RCS variations of known objects by tracking them using the Haystack X-band radar, and reported RCS variations which shows very high fre-

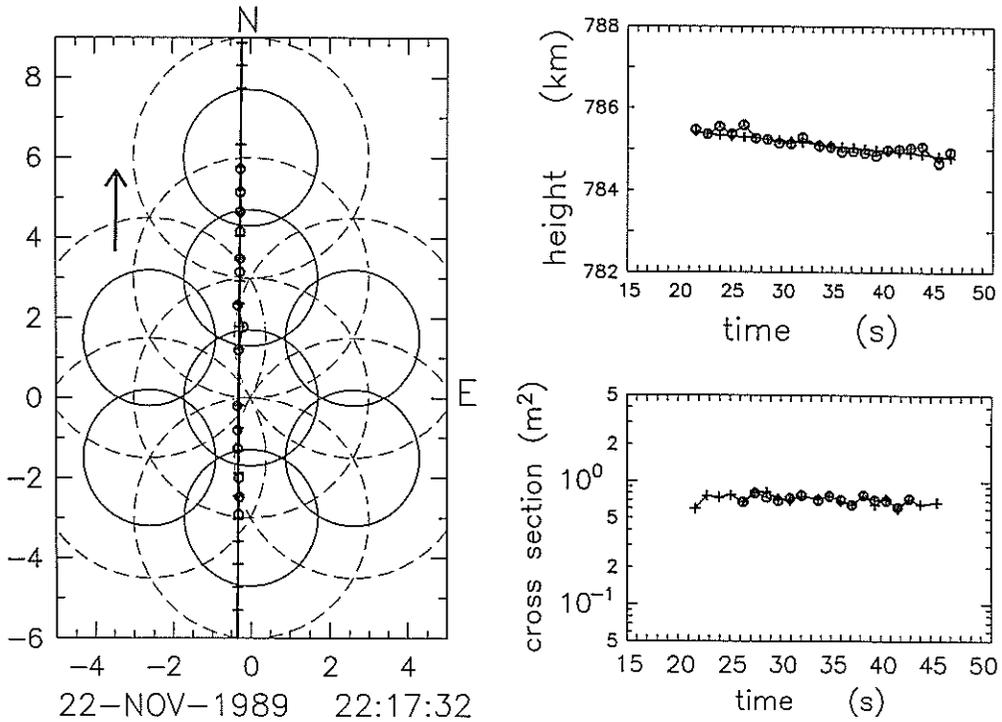


Fig. 3 Beam arrangement of the debris mode and a path of LCS-4 satellite. a) Plan view. The abscissa and the ordinate shows the east-west and the north-south angle from the zenith in degree. Solid and dashed circles denote the half-power width of the beam and its effective coverage of 3° from the center, respectively. Small circles along the path of the satellite indicates its location determined every 1 sec. The straight line and tick marks are the linear fit to these points. b) Height variation of the satellite. c) RCS variation of the satellite.

quency component extended to the order of 100 Hz. On the other hand, the RCS variation of the same object observed by ALCOR C-band radar which they cited for comparison shows similar high frequency component superimposed on the dominant periodicity of 0.1 to 1 Hz. It seems that X-band RCS variations mainly exhibit aspect sensitivity typical to objects much larger than the radar wavelength, while the lower frequency C-band variations are dominated by the spin motion of the entire body.

Although these observations with high-frequency (here used to mean that the radar wavelength is shorter than the size of the target) radars may provide detailed information on the complexity in the shape of the object, low-frequency (wavelength comparable or larger than the size of the target) observation is suitable in determining the basic shape of the object, such as the axial ratio which is important in estimating the mass of the object from the RCS.

Figure 4 shows an example of the RCS variation of COSMOS 1023 rocket booster

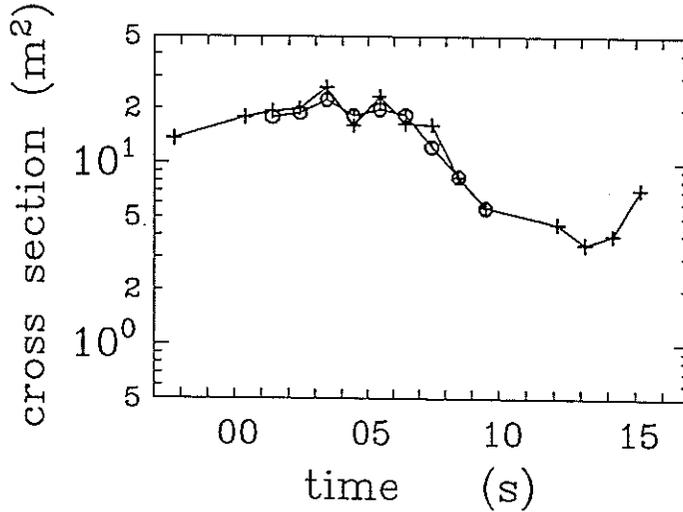


Fig. 4 RCS variation of COSMOS 1023 rocket booster.

observed by the MU radar. It is a cylindrical body of 7.4×2.4 m (maximum optical cross section 17.8 m^2). Fig. 4 clearly shows a smooth variation of the RCS, probably associated with its rotation with the maximum value of RCS which agrees well with the optical cross section. Since this is one of the largest objects in the orbit, all of debris falls in the size region where low-frequency approximation holds in computing the RCS. In such a case, the frequency of the dominant component in the RCS variation spectrum gives the spin rate, and its magnitude gives the axial ratio of the object.

Although the observation with this mode is still very limited because of the machine time restriction of the radar, we have so far made observations over 100 hours, and accumulated 136 cases of debris encounter. They are classified into four categories according to the mean RCS value in each observation. Figure 5 shows the RCS variation spectra for each category. For each observation, which consists of 10–20 samples of RCS taken at a 1-sec interval along the path of the object, relative RCS variation around its mean value is first computed on the log-scale. Then its frequency power spectrum is computed and averaged for different observations in each category. The frequency resolution of each figure is about 0.03–0.05 Hz, which is determined by the duration of each observation. Clearly, the spectra are dominated by long-period components around 0.05 Hz, showing that the RCS variations are dominated by those associated with slow spin motions.

The most important feature revealed by this analysis is the tendency that the magnitude of the relative RCS variations, which indicates the axial ratio of the objects, is larger for objects with smaller RCS values. This result suggests that the small objects with RCS of less than 1 m^2 have larger axial ratio, or in other words, more elongated shape than larger objects. A thin rod or a ribbon of length much shorter than the wavelength of 6.4 m should show large RCS variation because it can be well approximated by an electric Hertz dipole.

It is therefore likely that these small objects are lighter than the solid sphere of the same

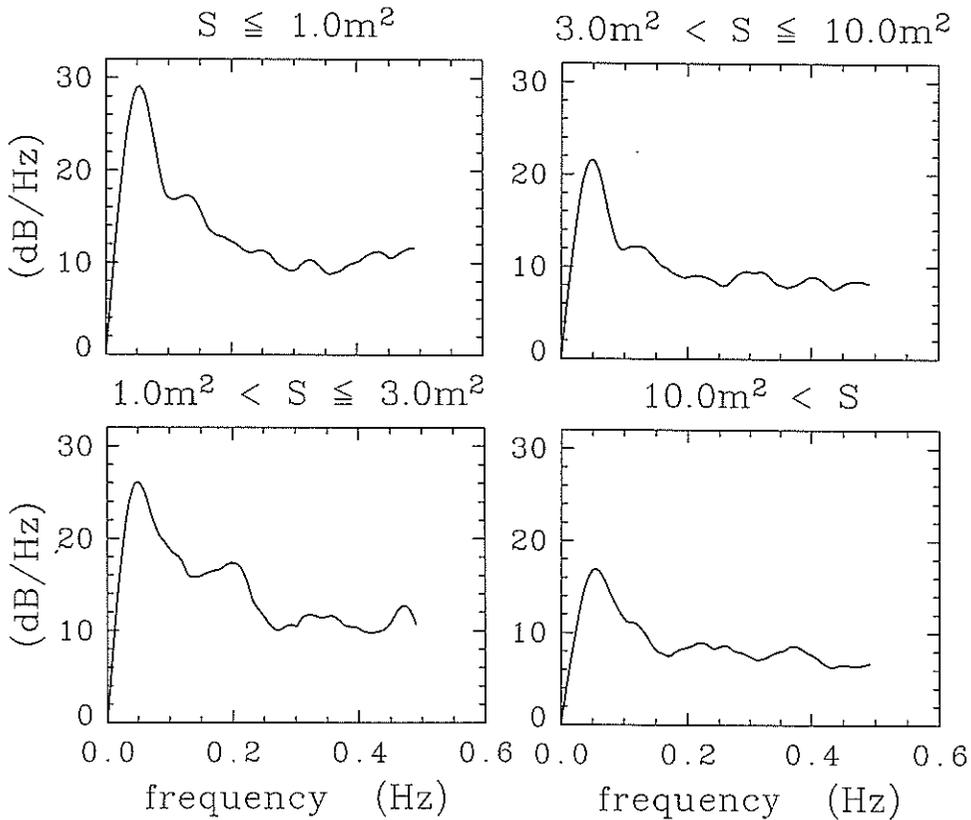


Fig. 5 Frequency power spectra of RCS variations relative to its mean value (denoted as S). 136 cases are classified into four groups according to S , and averaged in each group.

RCS as usually assumed in evaluating the effect of possible collision with debris. More detailed comparison with theoretical RCS computations as well as the more accumulation of data is necessary in order to quantitatively estimate the effective axial ratio of the objects from this type of observations.

Our major limitation is the sensitivity for small objects, which could only be solved by employing a higher frequency. If we are to extend our approach to the size region of 1–10 cm for which we have least amount of information, a frequency around 3 GHz will be appropriate so that we can still apply the low-frequency approximation. As we have seen, the multiple-beam capability is essential in studying the RCS variation of unknown targets. Since it will be very difficult to construct an active phased array radar of sufficient sensitivity at such high frequency, the practical solution to have multiple beams is to install multiple feed horns on the same aperture antenna. In order to obtain larger angular coverage, the sensitivity should be gained mainly by the high output power rather than a larger antenna aperture.

CONCLUSION

RCS variation of debris has been observed by the MU radar of Japan. It was shown that the large antenna aperture and the high output power of the radar compensated for the reduced RCS of debris at the low operating frequency of 46.5 MHz, and that the radar has similar sensitivity as radars used for US SPACECOM catalog maintenance.

We developed a special debris observation mode with the MU radar by making use of the fast beam steerability. The advantage of this mode is that we can observe RCS variation of debris with unknown orbit for a duration of 10–20 sec, which is an order longer than other radars. It was also shown that the low frequency is suitable in detecting the dominating component of the RCS variations associated with its spin motion, which will provide us information on the axial ratio of the object.

Preliminary statistical analysis showed that smaller objects have larger relative RCS variations than larger objects, suggesting that they have elongated shapes rather than spherical.

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