Debris Observation With a VHF Radar

Radar has been the most effective means of observing LEO (low earth orbit) debris of "threatening size," which is debris pieces larger than about 1 cm. All existing databases and statistics of such space debris, including the famous USSPACECOM catalogue, depend largely on observations with various radars. They usually contain an important item "size," which is determined from the strength of the received echo. In evaluating the impact of collision of debris with a shielding wall, for example, it is common to interpret it as the diameter of a sphere.

However, statistical studies showed that it is an overestimate by comparing the size estimated by radars with that calculated from the physical projected area determined from the orbital decay due to atmospheric drug (1).

WHAT DO RADARS SEE?

The size of the target is computed from the radar cross section (RCS), which is defined as the area of an isotropic scatterer whose echo power is the same as the given target. It indeed agrees with the physical cross section for large metallic spheres, but often differs largely for objects with irregular shapes, especially when observed at a high frequency band. For example, a piece of thin wire may be misinterpreted as a canon ball.

For objects smaller than the radar wavelength, RCS is proportional to the –4th power of the wavelength (or to the 4th power of the frequency). Most radars used for space debris monitoring thus employ a frequency of 5-10 GHz, or even higher, in order to obtain a high sensitivity against small debris. At such a high frequency, the RCS varies drastically as the orientation of the target relative to the radar changes. It is then hard to estimate real cross section from the observed RCS.

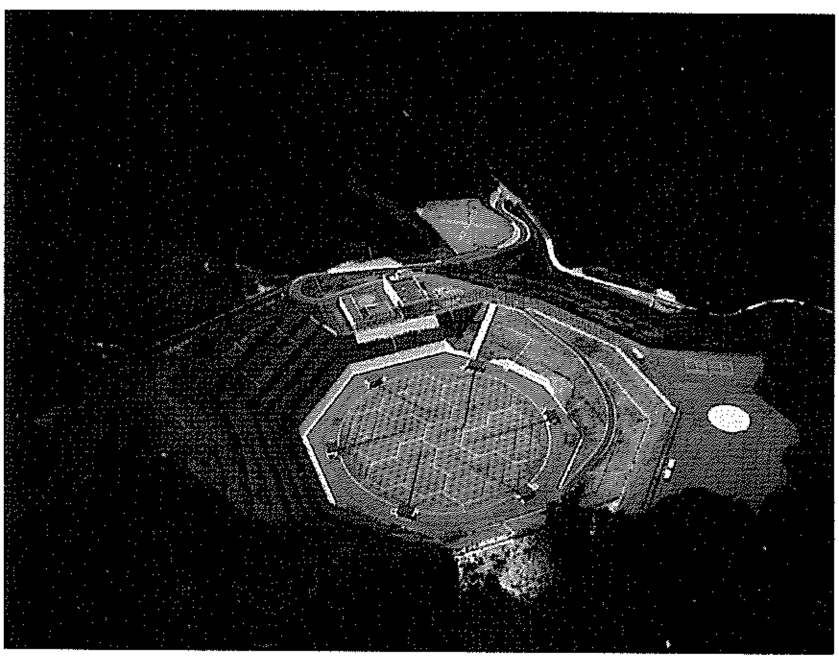

Figure 1. An aerial view of the MU radar, Shigaraki, Japan.

THE VHF MU RADAR

At a lower frequency, on the other hand, the relation between the physical cross section and the RCS becomes much simpler, although we have to pay an expensive cost in the sensitivity reduction for small targets.

The MU (Middle and Upper atmosphere) radar of Kyoto University, Japan (Figure 1) is a powerful VHF radar operating at 46.5 MHz; its 1 MW output power and the 100 m antenna size compensate for the reduced sensitivity at this frequency. It has roughly equal sensitivity to the radars used for USSPACECOM catalogue maintenance (2).

The main target of this radar is the Earth's atmosphere, or more precisely, weak backscattering from irregularities in the refractive index of the air caused by the atmospheric turbulence. Since this atmospheric echo is so weak, scientists have been bothered by contamination of strong "undesired" echoes from various objects such as space debris. We decided to make use of these previously discarded echoes and started a statistical study of space debris in 1988.

The antenna of the MU radar consists of 475 Yagi antennas constituting an active phased array. The advantage of this type of antenna is that it can observe different directions almost simultaneously by electronically switching multiple antenna beams. Figure 2 shows an example of debris observation using eight antenna beams switched sequentially from pulse to pulse around the zenith (3). The target, which turned out to be the Kosmos 1023 rocket booster, passed through these beams and the variation of RCS was tracked for about 20 sec. It is also possible to

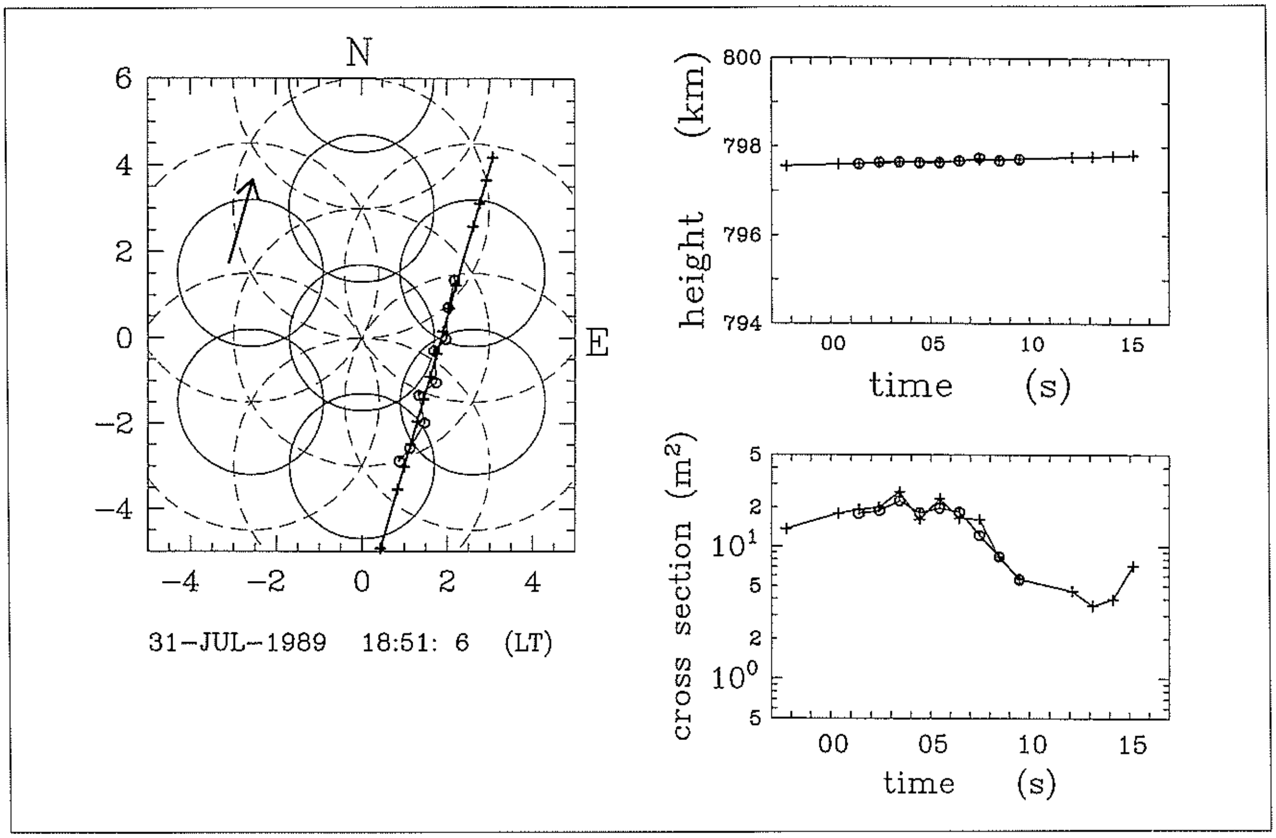

Figure 2. The angular motion (left), the height variation (upper right), and RCS variation (lower right) of Kosmos 0123 rocket booster as observed by the MU radar. The circles in the left panel show the coverage of the antenna beams.

roughly determine the orbit of the target from a single observation. Conventional radars with a large parabola antenna cannot continuously observe an orbital object more than a fraction of a second unless its orbit is given beforehand.

The large and smooth variation of RCS versus time (shown in the lower-right panel of Figure 2) indicates the rotation of the rocket booster. The maximum value roughly agrees with its maximum physical cross section.

SHAPE OF DEBRIS

The most direct way to "see" the shape of a target using a radar is to make the antenna beam sharp enough so that it can resolve the target. It is, however, impractical to get a resolution of 1 m at a distance of 100 km because the necessary diameter of the antenna is the order of 10 km. A more sensible technique is to make use of the rotation of the target. The idea is to resolve a different part of a target moving at different velocity relative to the radar by measuring the Doppler velocity spectra. This method is called ISAR (Inverse Synthetic Aperture Radar), or RDI (Range-Doppler Interferometry), and has been widely used in military radars and in radar astronomy. It was already applied to space debris by using German FGAN radar, which revealed a clear image of a Salyut-Kosmos complex (4). At the moment, the resolution is limited to about 1 m so it cannot be used to identify the shape of small targets of 1–10 cm size, which is of the largest concern.

Some statistical information on the shape of space debris is obtained by comparing the physical cross section estimated from the atmospheric drug with RCS, as shown above. The major limitation of this technique is that the same object has to be monitored for a long duration in order to detect orbital decay.

The results of our MU radar observations also provide similar information. Numerical simulations showed that the magnitude of RCS variation can be interpreted in terms of the prolateness of the object. Since a single observation gives the variation seen from one direction, we need to interpret many observations in a statistical manner. The result of such analysis indicates that the volume of relatively small debris observed with the MU radar is less than half of the sphere which has the same RCS.

FUTURE DEBRIS RADARS

In order to evaluate the actual size of space debris, shape information must be obtained. Although the first priority in designing a future debris radar is that it should have a sensitivity to detect objects of 1–10 cm, it also should have the capability to track an unknown object continuously for at least 10 sec, which is necessary to carry out both ISAR (RDI) analysis and/or the statistical analysis shown above. The phased array antenna is the essential element in realizing this capability.

REFERENCES

1. G. D. Badhwar and P. D. Anz-Meador, "Determination of the area and mass distribution of orbital debris fragments," *Earth, Moon, and Planets* 45, 29-51 (1989).
2. T. Sato, H. Kayama, A. Furusawa and I. Kimura, "MU radar measurements of orbital debris," *J. Spacecraft* 28, 677-682 (1991).
3. T. Sato, T. Wakayama, T. Tanaka, K. Ikeda and I. Kimura, "Shape of space debris as estimated from RCS variations," *J. Spacecraft* 31, 665-670 (1994).
4. D. Mehrholz, "Radar tracking and observation of noncooperative space objects by reentry of Salyut-7/Kosmos-1686," *Proc. Internat. Workshop on Salyut-7/Kosmos-1686 Reentry*, No. ESA SP-345, pp. 1-8 (1991).

TORU SATO and
IWANE KIMURA

Toru Sato and Iwane Kimura are affiliated with the Graduate School of Electronics and Communication at Kyoto University in Japan.