Height Distribution of Orbital Objects Observed by the MU Radar

By

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Summary: Distributions of orbital debris versus height and scattering cross section are determined from a series of observations made with a high-power VHF Doppler radar (MU radar) of Japan. An automated data processing algorithm has been developed to discriminate echoes of orbiting objects from those of undesired signals such as meteor trail echoes or lightning atmospherics. Although the results are preliminary, they showed good agreement with those from NORAD tracking radar observations using a much higher frequency. It is found that the collision frequency of an space station of 1 km × 1 km size at an altitude of 500 km with orbiting debris is expected to be as high as once per two years.

1. INTRODUCTION

The MU (Middle and Upper atmosphere) radar was constructed at Sigaraki, Shiga prefecture, Japan in 1984 mainly for the purpose of investigating atmospheric and plasma dynamics in the wide region from the troposphere to the ionosphere [*1*]. The radar is a 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. The antenna aperture is 8,330 m^2, and the peak output power is 1 MW. The details of the system are described elsewhere [*2, 3*].

As a different application of the radar, orbiting objects, such as satellites, launching vehicles and their fragments have been explored to investigate their height distribution, which will become an important information for safety operation of the future space stations. Although such a height distribution has been collected by NORAD system in the United States [*4*], monitoring of the satellites and orbiting debris at various wavelengths in various latitudes and seasons over a long range is necessary for the above mentioned purpose. Especially, a comparison of the scattering section of a target measured by radars with different frequencies provides important information on the shape of the target.

Here we present the experimental setup and preliminary results of a series of observations made with the MU radar as the first attempt of monitoring at the VHF band.

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2. Observations

Capability of the MU radar for a hard target is about $1.5 \times 10^{-4} m^2$ in its cross-section at an altitude of 300 km and about $3.7 \times 10^{-2} m^2$ at an altitude of 1,240 km, which correspond to diameters of perfect conducting spheres of 13 cm and 34 cm respectively.

Among various kinds of the operation modes for the MU radar, there is an ionospheric sounding mode regularly operated about 48 hours every month, in which the amplitudes and frequency spectra of ionospheric scattered echoes are measured. The same data of those observations can be utilized to pick up hard-target echoes from the orbiting objects for a height range between 300 km to 1,240 km so that a long time range statistical data can be obtained. 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 by 64 μs subpulses has been used for the amplitude mode of ionospheric observation and the received echo signals are distributed into 207 different altitude bins (memories) with a 4.8 km altitude separation, and are summed up over 25 transmitting pulses for incoherent integration. The resultant time resolution is about 1 second.

3. Data Analysis

In these data, it has been found that in addition to the echoes from the hard targets, there are several other kinds of signals included, such as cosmic noise, incoherent scatter echoes from the ionosphere, coherent echoes from the ionospheric field-aligned irregularities due to spread F layers or sporadic E layers, and impulsive signals like lightning atmospherics.

Also, the observed hard targets include a large number of meteor trails as well as the desired artificial orbiting objects.

We have developed an automated algorithm to select echoes from the orbiting objects out of all signals included in the radar echo data. The procedure makes use of the known statistical characteristics of each type of echoes and interferences in classifying them. It first picks up all echoes with power larger than seven times the standard deviation of the statistical fluctuations of the cosmic noise plus the incoherent scatter echoes from the ionosphere. This threshold is determined so that the possibility of mis-interpreting statistical fluctuations of the noise as echoes from targets to be small enough, *i.e.* about 1.1×10^{-7}.

We then examines the time and height patterns of the individual echo. Peculiar time and height patterns accompanied with some kinds of interferences, such as the echoes from over-dense meteor trails or external impulsive noises, are used to identify and remove them before examining the echo pattern in details. For example, echoes from hard targets show impulsive height pattern after the pulse de-compression operation, which is to take cross correlation of the received signal time series with the transmitted pulse code sequence. In contrast, external impulsive noises have impulsive height pattern *before* the de-compression, so that they show box-car height pattern of the pulse code itself after the cross correlation operation. Figure 1 shows an example of the time and height pattern due to impulsive noise. The dashed curve in the time pattern is explained below. The noise level, which is indicated as a straight line, is subtracted from the signal intensity. This type of signals can be identified relatively easily by examining the height pattern.

After rejecting such peculiar interferences, the time patterns of the signals are examined by comparing them with theoretical time patterns of orbiting objects. Since we can calculate the time variation of an orbital object passing through the antenna beam of the MU radar at a given height, it is possible to discriminate the echoes of orbital objects from those of other targets and noises by numerically fitting the theoretical pattern to the observed one. Figure 2 shows two examples of echo time patterns due to orbital objects (left panel) and of meteor trails (right panel). The dashed curve in the figure indicates the best fit theoretical time pattern obtained assuming that the echo is due to an orbital object, and the horizontal line shows the background noise level. A clear difference in the residual of fitting for these two cases enables us to automatically selects orbital objects out of many other signals. The threshold for the discrimination has been adjusted empirically so that the result of automatic selection agrees with that made by human intelligence.

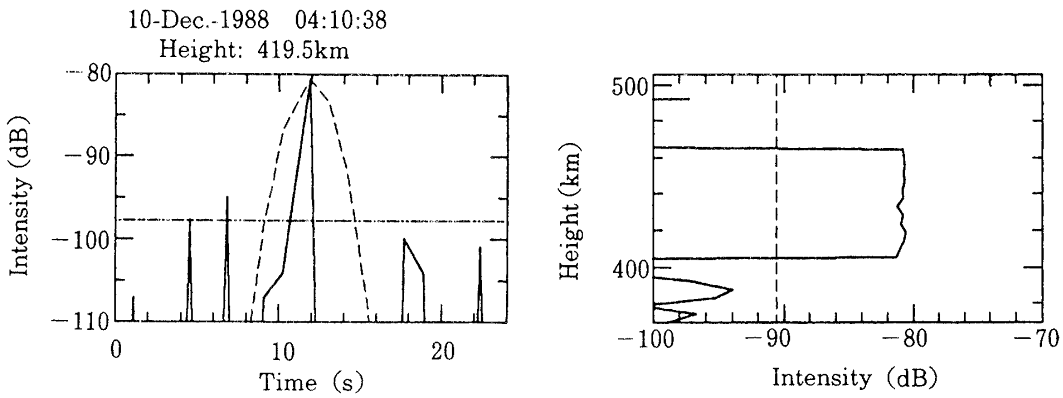

Fig. 1. An example of time and height pattern due to external impulsive noise.

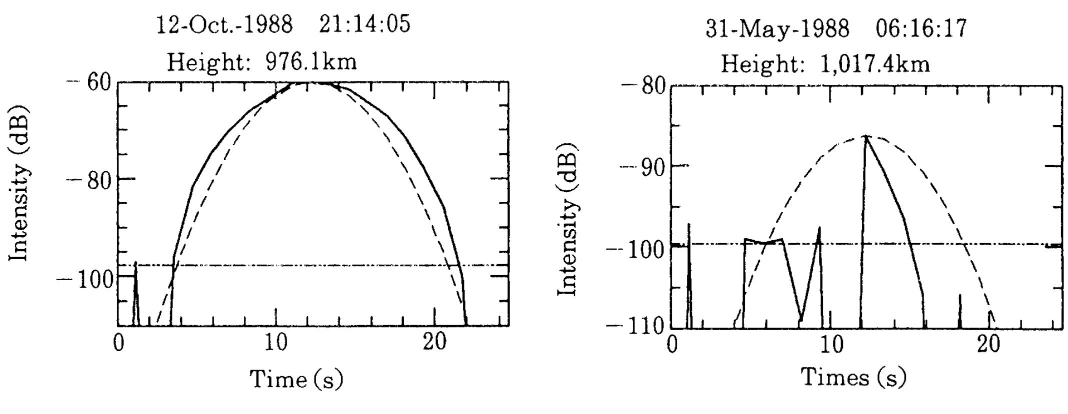

Fig. 2. Examples of the echo patterns due to orbital objects (left) and meteor echoes (right).

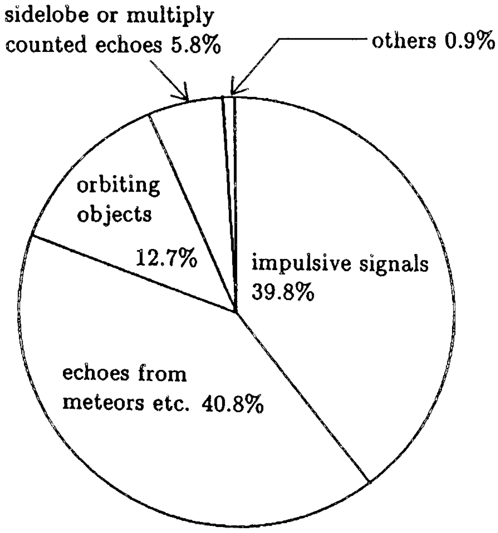

Fig. 3. Percentage of various types of echoes classified by the automatic data processing algorithm.

When an orbital object with a large scattering cross section passes through sidelobes of the radar, we get multiple peaks with small intervals in the received time pattern. Although they are interpreted as separate echoes by the automatic selection procedure, they ar later recognized as the echo from identical object by checking the intervals between occurrence of echoes. The percentage of occurrence of various types of echoes thus classified are illustrated in Figure 3. The category "others" includes continuous echoes due to the occurrences of spread-F or sporadic-E echoes.

Weak echoes at low altitudes are hard to classify individually, because they often appear in only one or two time samples taken at 1 sec intervals. Instead, a statistical compensation procedure is applied to remove the effect of meteor trail echoes and cosmic noises, which are the major sources of weak contamination at low altitudes, after the height distribution of the targets is calculated.

4. Statistical Distribution of Orbiting Objects

The above algorithm has been applied to the MU radar data obtained for a period from May 1988 to January 1989 to obtain the distribution of orbital objects with respect to the height and the scattering cross section. Echoes from orbital objects are detected about once per two minutes. Figure 4 shows the observed height distribution of the orbital objects for several ranges of the scattering cross section denoted by gray scales. The distribution shows maxima at around heights of 600 km, 800 km, and 1,000 km, which agree with those of the distribution estimated by NASA based on the tracking data of NORAD [5]. The flux, or the number of orbital objects passing through a unit area in the meridional plane per unit time, is 1–2 $\times$ $10^{-6}/m^2/year$ at this height range. Figure 5 draws the same distribution versus the scattering cross section and the diameter of the equivalent conducting sphere. The dashed line denotes the minimum observable cross section at the maximum height of 1,240 km. The flux for the cross section smaller than this value is therefore obtained from the data of lower height ranges.

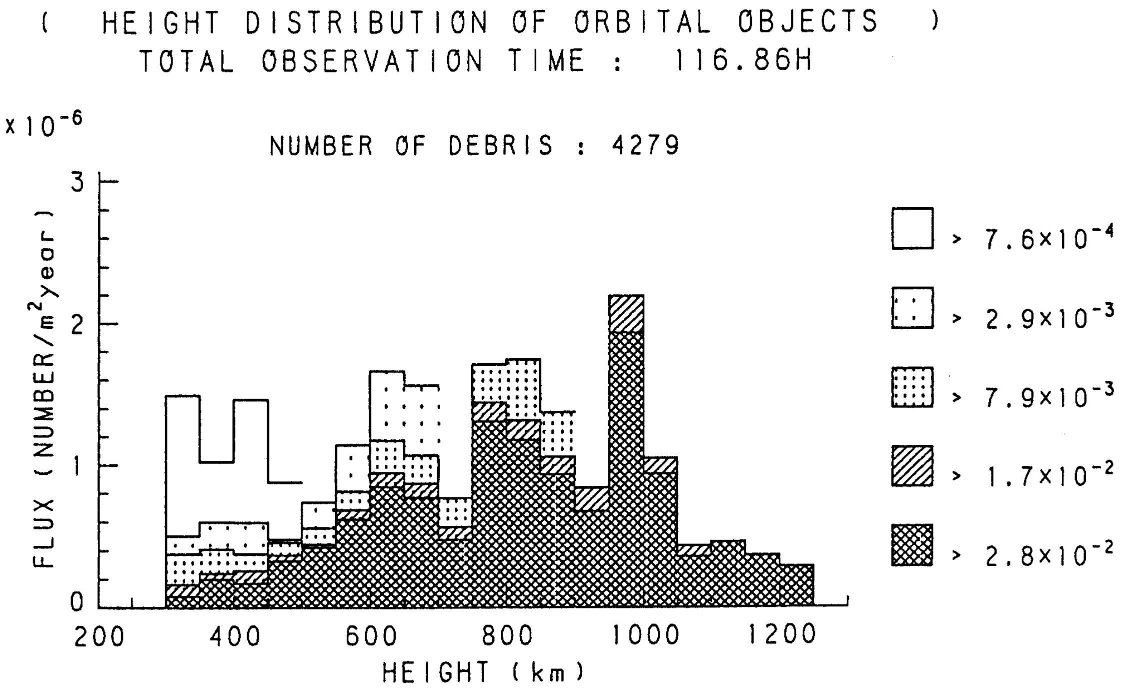

Fig. 4. The observed height distribution of the orbital objects. The ordinate is expressed in terms of the number of objects passing through a unit area per unit time. Gray scales indicate the scattering cross section of the objects as shown on the right of the figure.

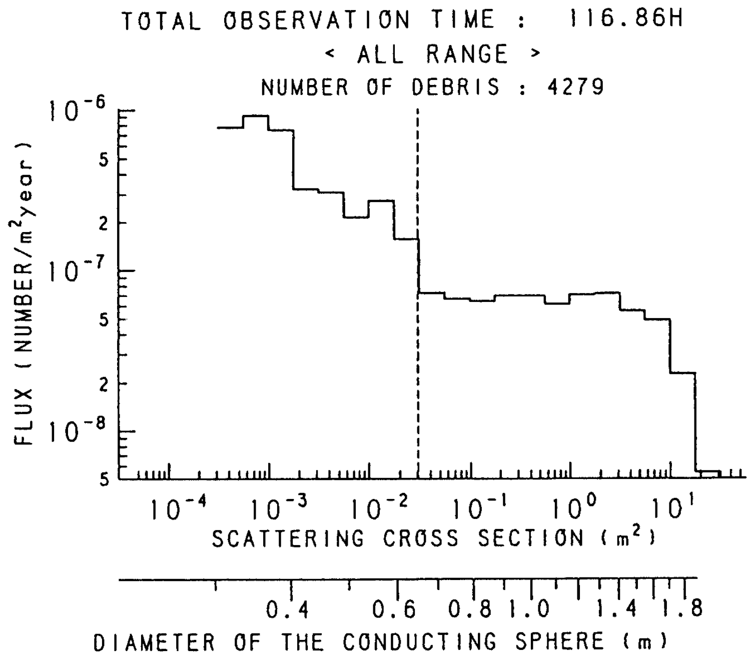

Fig. 5. The flux of orbital objects versus the scattering cross section. The dashed line denotes the minimum observable cross section at the maximum height of 1,240 km.

If we consider a satellite of 2 m in diameter at an orbital height of around 500 km, for example, its mean collision frequency with orbital objects is estimated based on the observed distribution to be about once per 7,600 years. Although this value may give an impression that the probability of collision is extremely low, it turns out that the frequency increases to about once per *two* years when a space station of 1 km × 1 km size is considered. Since construction of such a station is not unrealistic anymore, an extensive survey of orbital objects is strongly needed.

5. Summary

Preliminary results of a series of observations made with the MU radar to determine height distribution of orbital debris were presented. An automatic data processing procedure was first developed to discriminate backscatter echoes from orbiting objects from those of meteors or other interferences. The height distribution of the debris showed good agreement with that obtained from NORAD data using microwave frequency tracking radars, and has shown that the number density of debris is already high enough to affect future plans of space stations.

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