

Multi-Beam Pattern Measurement of the MU Radar Antenna by Satellite OHZORA

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After finishing a series of tests, an antenna pattern monitoring system for the MU radar using satellite OHZORA has been put into the operational stage. We describe a multi-beam measurement technique, with which about 10 of the various MU radar antenna patterns can be measured simultaneously in one pass of the satellite, to make the best use of the limited number of chances for experiments. We also show the results of a preliminary attempt to synthesize a three-dimensional antenna pattern by integrating the data for different satellite passes.

1. Introduction

A joint experiment of the MU (Middle and Upper atmosphere) radar and the scientific satellite OHZORA (EXOS-C) for long-term monitoring of the MU radar antenna pattern (MUM; MU radar antenna Monitor) has been carried out since May 1984 (FUKAO *et al.*, 1985a). The major advantage of using a satellite for antenna pattern measurements is that precise measurement down to low elevation sidelobes can be repeated many times with relatively little labor and cost once the system is established.

On the other hand, a large number of passes are required to cover the whole visible range of the antenna, because only a few passes per week have the high maximum elevation angles of 60° or more. Also, the position of the satellite must be measured very accurately in space and time.

In order to make the best use of the limited chances for observations, a multi-beam measurement technique has been used since March 1985, after completing a series of system checks based on single beams. Here we examine this technique and present some preliminary results of three-dimensional pattern synthesis based on the superposition of measurements obtained on different satellite passes having different subsatellite paths.

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2. Multi-Beam Measurement Technique

The basic idea of the MUM system is to determine the MU radar antenna pattern by comparing the level of received signals on OHZORA transmitted from the MU radar (46.50 MHz) and from an omnidirectional reference antenna (46.55 MHz). Since the active phased array design of the MU radar allows for synthesizing many different patterns (see FUKAO *et al.*, 1985b for the details of the system), it is important to measure antenna patterns of as many different kinds as possible to ensure high system performance.

Considering the fact that a sampling rate of 100 msec is sufficient to make a detailed measurement of the antenna pattern, and that a sampling rate of 2 msec is available for the data processing unit of OHZORA, it is possible to measure about 10 different patterns simultaneously by switching them periodically during one pass of the satellite.

If the accurate position of the satellite is known, determination of the MU radar antenna pattern is straightforward. Unfortunately, however, the only means of locating OHZORA on a routine basis is via a radar transponder system using an S-band telemetry antenna. The range between the satellite and the tracking station (KSC) is measured accurately with this system, but observations of satellite direction, obtained through mechanical motion of the tracking antenna, seem to be insensitive to small angular deviations of the satellite when it is in the main lobe of the tracking antenna. The overall accuracy of this location system under the practical conditions of tracking a moving target is not known. The satellite position above the MU observatory, calculated from its orbital elements routinely determined by this system every week, sometimes shows a discrepancy of up to about 1° between its predicted direction from the MU radar and the observed position using the MUM system.

The main beam direction of the MU radar antenna has already been calibrated by using the radio star Cassiopeia-A, which is often used for antenna pattern measurements (GUIDICE and CASTELLI, 1971). We observed Cassiopeia-A by the MU radar antenna with 8 beam positions arranged in the meridian plane at 2° intervals around the position of the star. The temporal variation of the received signal strength due to the rotation of the earth gives us the longitudinal patterns of the antenna at each beam position. Although the meridional pattern cannot be measured directly, we can measure the pattern of the antenna steered in the meridional plane against a fixed target. The expected time and the zenith angle of the maximum signal strength calculated from the known direction of the star were then compared with the observed ones. The agreement was very good, and the angular error is estimated to be about 0.1° at most, which is the accuracy of the measurement determined by the signal-to-noise ratio and the statistical fluctuation of the signal. Also, the main beam direction of an array antenna is, in general, hardly affected by random error in the amplitude and phase of individual elements of the array if the number of elements is sufficiently large (e.g., STEINBERG, 1975). A

computer simulation using practical random error values in amplitude and phase of the TR modules of the MU radar showed no detectable error in the gain and direction of the main beam, although it predicted an appreciable increase in low-level sidelobes.

Therefore, it seems to be more practical to rely on the main beam direction of the MU radar, rather than to depend on the tracking system having an unknown accuracy. In order to determine the direction of a satellite, at least two beams are required. Figure 1 schematically shows a method of using two "pilot beams".

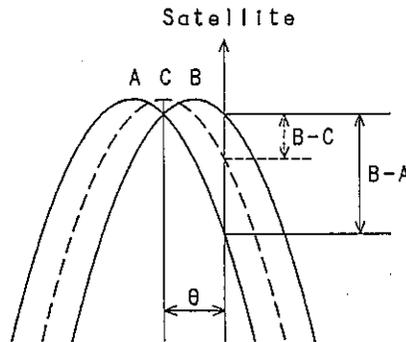


Fig. 1. Principle of satellite location using pilot beams.

Suppose that beams A and B are pointed in two directions separated by a few degrees in a plane perpendicular to the expected path of the satellite. Then the angular deviation θ of the actual path is obtained from the difference (or ratio) between the maximum signal levels of beam A and B if the pattern of the main lobe is known. The deviation of the satellite position along the path can be obtained from the time of maximum output level.

It should be noted that this method depends only on the difference between two beam patterns, and is not affected by the transmitter power, receiving antenna pattern or other factors. It does not even need a reference signal for the purpose of location.

Since the angular error of the expected path of OHZORA computed according to the orbital elements issued weekly by NASDA is usually within $\pm 1^\circ$ in the direction seen from the MU radar, the separation of the two beams is chosen to be 2° . Figure 2 shows the computed differential output of the pilot beams versus the angular deviation of the satellite path from the center of the two beams.

In order to check the self consistency of this method, an experiment was made using three pilot beams by adding beam C between beam A and B. In this case, θ can be estimated independently from $B-A$ and from $B-C$. The resulting difference between the two estimates was 0.05° . Although this value does not guarantee the absolute precision of this technique, it at least gives an estimate for the order of

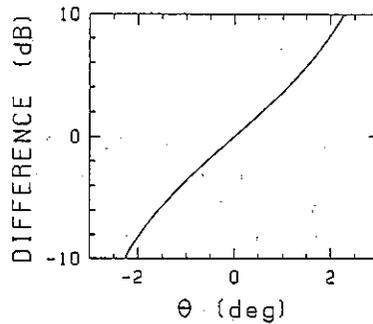


Fig. 2. Computed differential output of two pilot beams versus the angular deviation of the satellite path. The two beams are separated by 2° .

magnitude of the random error as well as the error due to possible differences between the real and computed main lobe patterns.

Once the deviation of the actual satellite path from the expected one is measured at one point on the path, it is possible to compute the satellite position for the rest of the same path by adjusting the orbital elements so that the orbit passes through the measured point. Since our object is to determine the satellite position for a short period around a given time, and since the required correction is usually very small, we do not have to modify all of the orbital elements. Instead, it is sufficient to modify only those elements which are most sensitive to the measured deviations. The deviation in the horizontal direction perpendicular to the path can be expressed in terms of a small change in the right ascension of the ascending node (Ω), and the deviation along the path in a change of the mean anomaly (θ). For example, when the perigee of the path is above the MU radar, 1° of deviation seen from the MU radar in the direction perpendicular and parallel to the path corresponds to a change of 0.067° in Ω and 0.052° in θ , respectively.

In practice, MUM experiments are carried out when the zenith angle of OHZORA at its apex of the expected path seen from the MU radar falls within 30° , the design limits within which the MU radar main beam direction can be steered with negligible complications from grating lobes. Then twelve beam directions are switched periodically at intervals of 7.622 msec. One of these directions is used as a timing marker by shutting down the transmitter. The shutdown period occupies the same interval as other beam directions, but the transmitter does not send any pulse during that period. The absence of the transmitter pulse can be readily identified in analyzing the received signal, as will be shown later. Two pilot beams are arranged around the apex, separated by 2° in a plane perpendicular to the path. Thus, the remaining 9 directions can be used for the purpose of monitoring. They include the vertical direction and the north, east, south and west directions at two zenith angles of 15° and 30° .

3. Results

Figure 3 shows an example of unprocessed output of the AD converter on OHZORA for one pass. Each dot denotes a sampled point obtained at 2 msec intervals. The horizontal line around 150 digits is the output of the reference signal, to which the automatic gain control (AGC) is applied. Fluctuation around the mean level of the reference signal show the fading of the input signal level with periods shorter than the time constant of the AGC feedback loop. These outputs are converted into input field strengths using the input-output characteristics of the MUM receiver measured on the ground before the satellite was launched.

Since the antenna beam of the MU radar is switched periodically to 12 different directions, the data contains the pattern of these beams interlaced with each other. For example, the three lobes overlayed around 38 sec show the three pilot beams including the vertically pointing one. Somewhat lower lobes seen around 18 sec and 58 sec are the northward- and southward-pointing beams, respectively, at a zenith angle of 15° .

These interlaced data for different beam directions are separated based on timing provided by the reference shutdown period which appears every 91.464 msec. Although the beam switching of the MU radar and the sampling on OHZORA are not synchronized, the data are safely separated by discarding marginal points, since

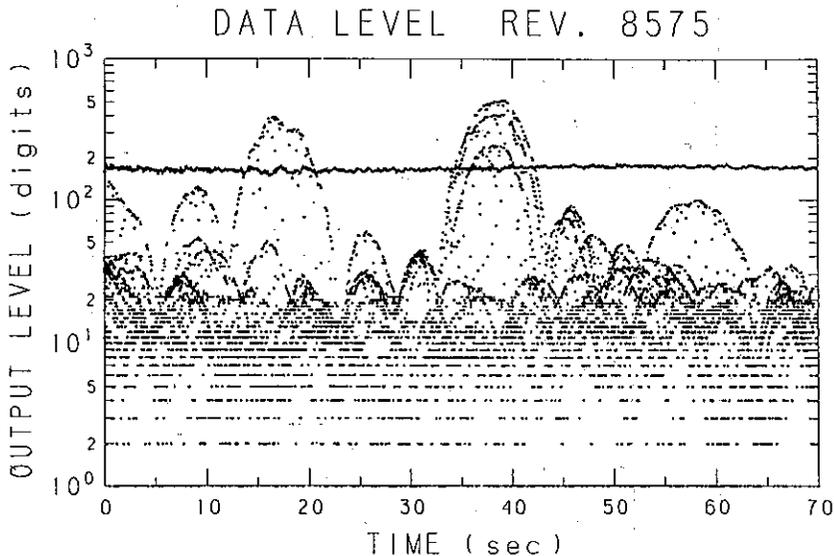


Fig. 3. An example of unprocessed data from a single multi-beam experiment. Each dot denotes a sampled point taken at 2 msec intervals. The horizontal line around 150 digits is the output level of the reference signal.

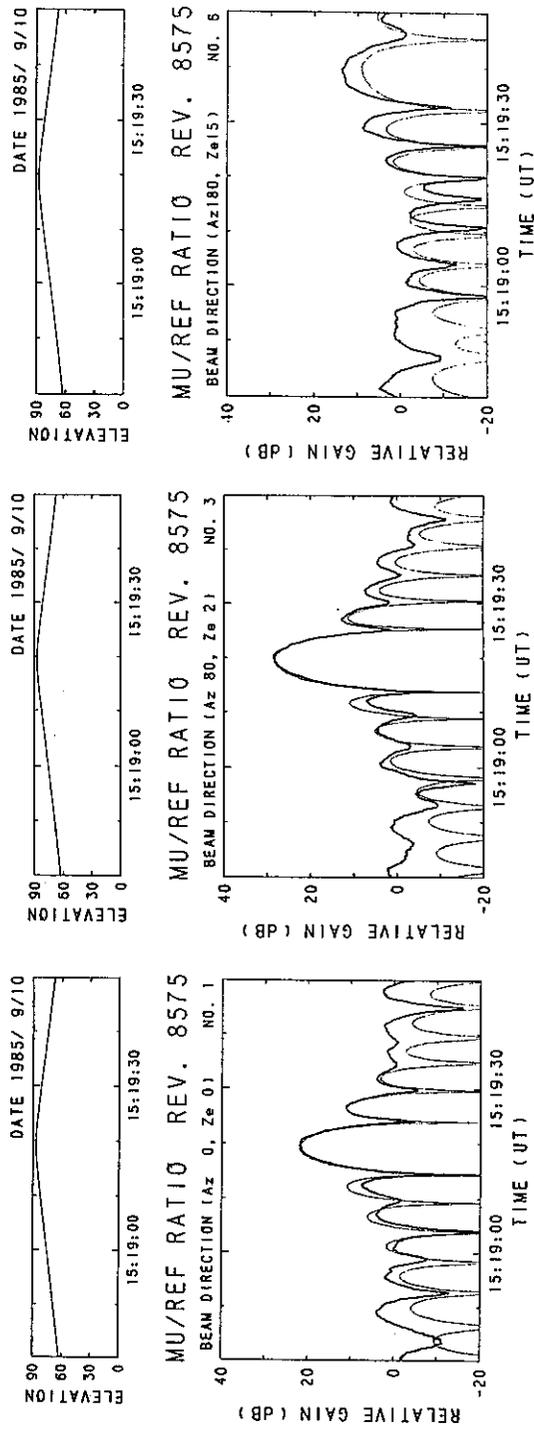


Fig. 4. Relative gain of the MU radar antenna over the reference antenna (thick line) for each beam direction, extracted from the data of Fig. 3. The thin line shows the theoretical pattern computed based on the revised orbital elements of OHZORA. The top frame of each figure shows the computed elevation angle of the satellite seen from the MU radar.

the antenna beam remains in the same direction at least for three contiguous sampling points. The received signal level during the shutdown period gives a good indication of any external interference or noise or any possible cross-talk from the reference signal channel. It is found that the signal from the main lobe of the MU radar usually has a margin of more than 50 dB against these types of undesired input.

Figure 4 shows several examples of the antenna pattern for various beam directions separated from the data of Fig. 3. The measurements (thick lines) are expressed as the relative gain of the MU radar over the reference antenna, which has a maximum gain of 8.3 dB in the vertical direction. The thin line shows the theoretical pattern computed based on the revised orbital elements as discussed before. The top frame of each figure denotes the elevation angle of OHZORA as seen from the MU radar.

The agreement of the measured and theoretical patterns is excellent for the main lobe, even counting the fact that orbital elements are modified to match the main beam direction. The position and shape of the sidelobes are also in good agreement, but the levels disagree by 5–10 dB, especially for the high order sidelobes which appear at points away from the main lobe. This is probably due mainly to the fact that several TR modules are disconnected for periodical inspection. It is necessary to carry out a more precise theoretical computation including this effect for more detailed comparison, though it is difficult to take the effect of mutual coupling between antenna elements into account for such cases of randomly missing sources.

By integrating this kind of experiments for many passes of the satellite, it is possible to synthesize three-dimensional patterns for the chosen 9 beam directions. Figure 5 shows a preliminary drawing of this attempt for the vertical beam direction based on 7 passes. The concentric circles indicate zenith angles of 10° , 20° and 30° . Although still far from completion, this figure shows well the shape of the main lobe and surrounding first sidelobes. Continuation of this effort would result in a total understanding of the radiation pattern of a large array antenna under operational conditions, which has not yet been established so far.

4. Conclusion

The multi-beam measurement technique, which is the major advantage of the MU radar over other existing MST radars, has also been used in the monitoring of the MU radar antenna pattern using the satellite OHZORA. This improvement substantially reduced the largest limitation on monitoring of antenna patterns using a satellite, namely, the low frequency of measurement opportunities. In the present study the antenna beam was pointed to 12 different directions switched periodically at 7.622 msec interval during a pass of OHZORA, which enabled us to measure the antenna pattern along the path for 12 different beam directions in parallel. Also we succeeded in using two (or three) pilot beams to resolve small errors in the measured orbit of the satellite.

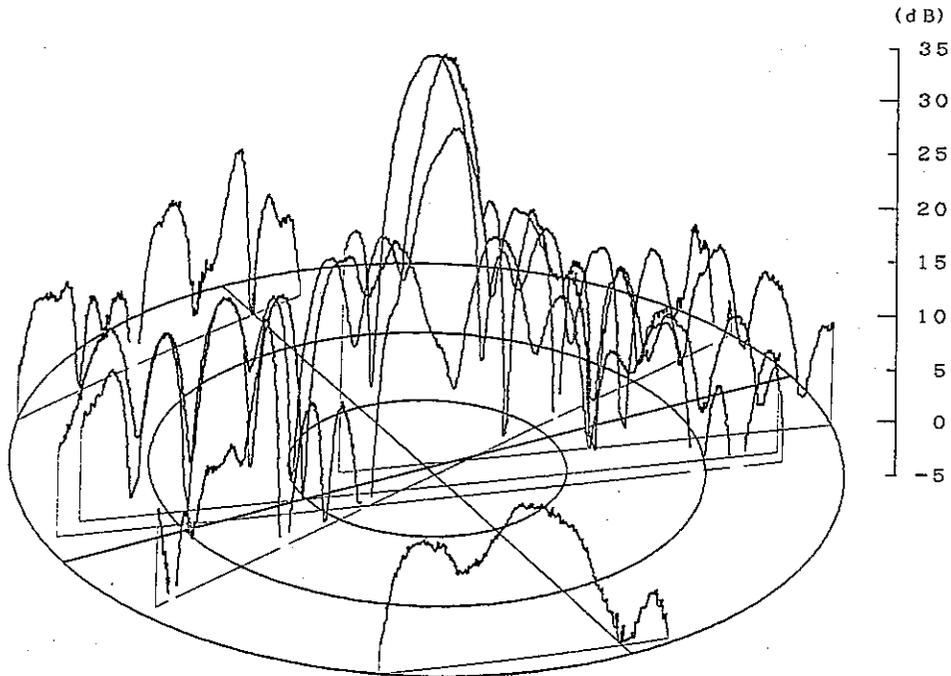


Fig. 5. A three-dimensional plot of the measured MU radar antenna pattern for the vertically pointing beam using 7 passes of OHZORA.

Interlaced data for different beam directions were successfully separated by detecting the shutdown period used as a timing marker in the transmission of the MU radar signal. Antenna patterns for each beam direction were then compared with theoretical ones, showing good agreement and confirming the good performance of MU radar antenna. Finally, the preliminary result of an attempt to synthesize a three-dimensional pattern by integrating different passes of the satellite was presented.

The success of the multi-beam measurement developed here has enabled an order of magnitude more efficient use of the MUM system than was possible before. It has confirmed the practicability of an antenna pattern measurement technique using a satellite for the long-term monitoring of the total performance of large antenna systems.

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