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Accurate measurement of the radiation pattern of ground-based large array antennas in the VHF band has been a difficult task due to a large distance required to achieve the antenna far field in the vertical direction. A new system for a long-term monitoring of the MU radar antenna pattern has been developed using the Japanese scientific satellite OHZORA (EXOS-C).

1. Introduction

The first large VHF Doppler radar for the observation of the earth's atmosphere in Asia was completed at Shigaraki, Japan (34.8°N, 136.1°E) in November 1984 (FUKAO *et al.*, 1980; KATO *et al.*, 1984). This radar is named MUR or MU radar after the middle and the upper atmosphere of the earth that will be principally investigated with this system.

The MU radar is sensitive enough to detect echoes which originate from atmospheric refractive-index fluctuations with dimensions of half the radar wavelength, i.e., a few meters. The echoing mechanisms vary with height and include such variables as humidity, temperature, and electron density (e.g., BALSLEY and GAGE, 1980). The background wind velocity is inferred from the Doppler shift of these echoes. This radar is expected to be extensively used for observation of three-dimensional wind fields, including a small but important vertical component, continuous both in time and in space with good temporal and spatial resolution. These knowledges are indispensable to further understanding of various dynamical processes, especially in microscale and mesoscale, occurring in the middle and upper atmosphere.

As the first attempt among this kind of radars, the MU radar features an active phased array system. Unlike the conventional large VHF radars, in which output power of a large vacuum tube is distributed to individual antenna elements, each of 475 solid-state power amplifiers feeds each antenna element. This system configuration enables very fast beam steering as well as various flexible operations by dividing the antenna into independent subarrays, because phase shift and signal division/combination are performed at a low signal level using electronic devices under control of a computer network. The antenna beam direction can be switched within 10 μsec to any direction within the zenith angle of 30°. The basic parameters of the MU radar are summalized in Table 1.

Since a precise phase alignment of each element is crucial to realize the excellent performance of this system, careful calibration of the output phase of each power amplifier and antenna element has been carried out. However, it is necessary to confirm the total performance by measuring the radiation pattern of the whole array from distant places where the antenna far field condition is satisfied.

Among various aircrafts which may be used for this purpose, e.g., airplanes, helicopters or balloons, artificial satellites have an advantage of being able to make a long-term monitoring with the same system. An antenna pattern monitoring system for the MU radar has been developed using the scientific satellite OHZORA (EXOS-C) which was launched on February 14, 1984. OHZORA has an almost circular orbit with the apogee of 815 km, perigee of 350 km and a high inclination of 74.6°, which are quite suitable for the purpose of monitoring.

A receiver named MUM (MU radar antenna Monitor) on board the satellite measures a CW signal of 100–400 watts transmitted from the MU radar. The received signal strength is transferred to the tracking station (Kagoshima Space Center of ISAS; KSC) through a telemetry channel. The overall antenna pattern is synthesized by integrating the data over many passes with different zenithal and azimuthal angles.

Table 1. Basic parameters of the MU radar.

Radar system:	Monostatic pulse radar. Active phased array system.
Frequency:	46.5 MHz.
Antenna:	Circular array of 475 Yagi's.
Aperture:	8330 m^2 (103 m in diameter).
Beam width:	3.6° (full antenna).
Steerability:	Steering is completed in IPP.
Beam directions:	1657; 0–30° zenith angle.
Transmitter:	475 solid-state amplifiers (each with output power of 2.4 kW peak and 120 W average).
Peak power:	1 MW.
Average power:	50 kW (duty ratio of 5% max).
Bandwidth:	1.65 MHz max (pulse length: 1–512 μs variable).
IPP:	400 μs-65 ms (variable).
Receiver:	
Dynamic range:	≥ 70 dB.
IF band width:	1.65 MHz max (variable).
Master oscillator:	Rubidium vapor.

A brief description on the monitoring system and a preliminary result is presented in the following.

2. Principle of the Measurement

The received signal strength is affected not only by the transmitting antenna pattern, but also by height and attitude of the satellite, the receiving antenna pattern and its radiation impedance. In order to remove these factors, a small omnidirectional reference antenna is installed at the MU radar site, which transmits a CW signal of a frequency of 50 kHz offset from the MU radar frequency. The level of this reference signal is compared with the MU radar signal on the satellite, and the MU radar antenna pattern is determined as the relative gain to that of the reference antenna. A turnstile antenna with a ground plane in a grid structure of 5 m×5 m is located as the reference antenna on the top of the control building of the MU radar. Figure 1 illustrates the scheme of the measurement.

Since there is no space for a receiving antenna equipped exclusively for this

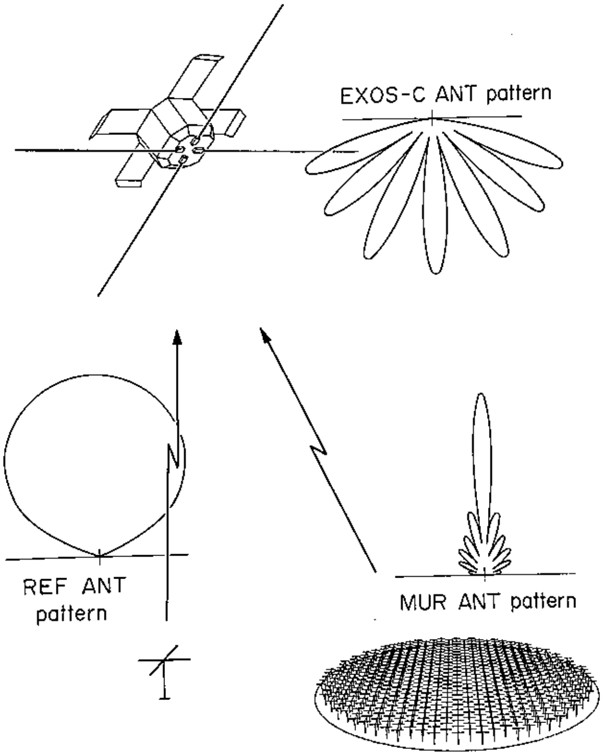


Fig. 1. Principle of the MU radar antenna pattern measurement. The received level of the MU radar signal is calibrated by that of the reference signal level.

purpose on the satellite, a pair of long wire dipole antennas of 40 m tip-to-tip installed for other physical instrument, PPS (Planetary Plasma Sounder), is utilized as the receiving antenna of MUM. As the length of this antenna corresponds to 6-wave dipoles at the frequency of the MU radar, the receiving antenna pattern becomes quite complicated. Also, the range of the satellite from the MU radar site varies from about 300 to 3000 km. In order to adapt to the expected wide dynamic range of the received signal due to these effects, an automatic gain control (AGC) is applied relative to the reference signal level.

The angular velocity of the satellite seen from the MU radar is 1.5°/sec at most, which is fairly slow considering the main beam width of 3.6° of the MU radar antenna. Therefore, a received-signal sampling rate of 100 msec is sufficient to make a detailed measurement of the antenna pattern. Since a sampling rate of as fast as 2 msec is available for the data processing unit of OHZORA, the MU radar antenna beam can be pointed to about 10 different directions switched periodically during one pass of the satellite, still allowing for several contiguous samples in each beam direction.

As the sampling rate of the reference signal can be much lower than that of the MU radar signal because of the smoother pattern of the reference antenna, the multiplex ratio of both channels is chosen to be 8:1. Figure 2 schematically shows the relation of these timings.

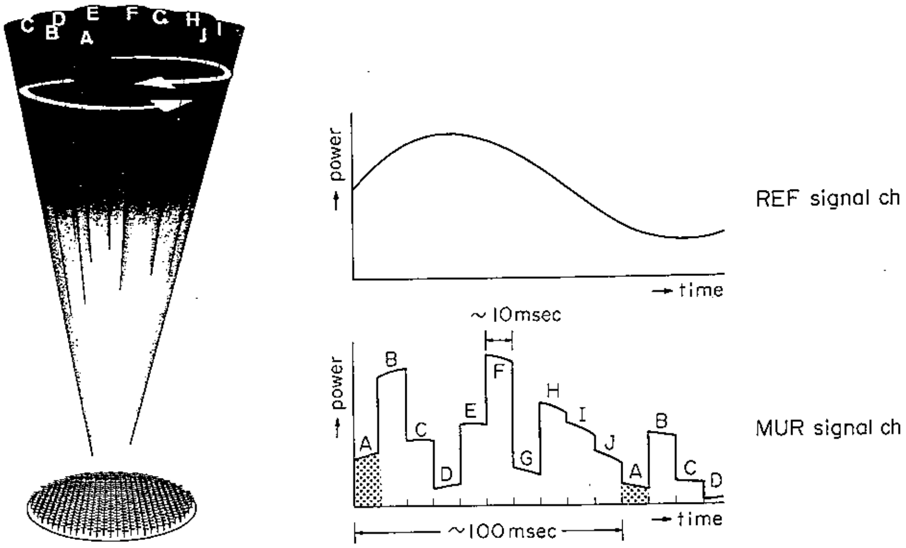


Fig. 2. Schematic diagram of the temporal variation of the received signal levels. The antenna beam is switched in a sequence of A, B, C, ... J in this example. In practice, one of these beam direction (A) is used as a timing marker by shutting down the transmitter.

3. The MUM Receiver

The MUM receiver has the function to receive both the MUR signal (46.50 MHz) and the REF signal (46.55 MHz), separate, detect and A/D convert them. Figure 3 shows the dynamic range of the receiver and the AGC range. The MUR and REF signals have comparable intensity in the sidelobe region of the MU radar antenna, whereas the intensity ratio amounts to 34 dB when the satellite passes over the main lobe. As for the low level sidelobes, MUM is designed to monitor the level of down to −20 dB below the uniform level. Therefore, the dynamic range of the receiver should be at least 54 dB.

The AGC range is determined by variation of the distance between the MU radar and the satellite, and by the receiving antenna pattern. The distance varies from 300 to 3000 km, and the receiving antenna pattern is expected to vary about 20 dB as discussed later, resulting in the received signal level variation of about 40 dB, which is the required AGC range.

Figure 4 shows the receiver block diagram. The input signal is passed through a band-pass filter (BPF) of 1 MHz bandwidth, a limiter (LIM) for protection against an excess input and an RF amplifier, and then converted to the first IF of 10.7 MHz. The signal is then passed through another BPF, applied to the AGC, and divided into two channels. They are converted by the second local

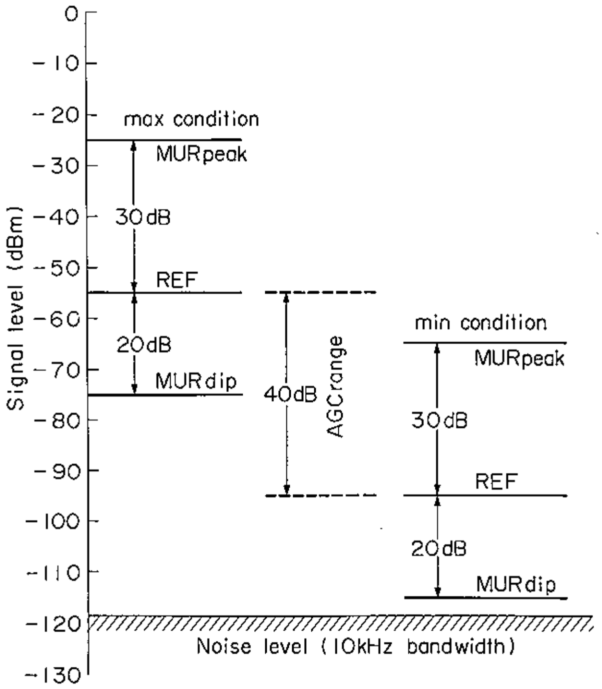


Fig. 3. The dynamic range and the AGC range of the MUM receiver.

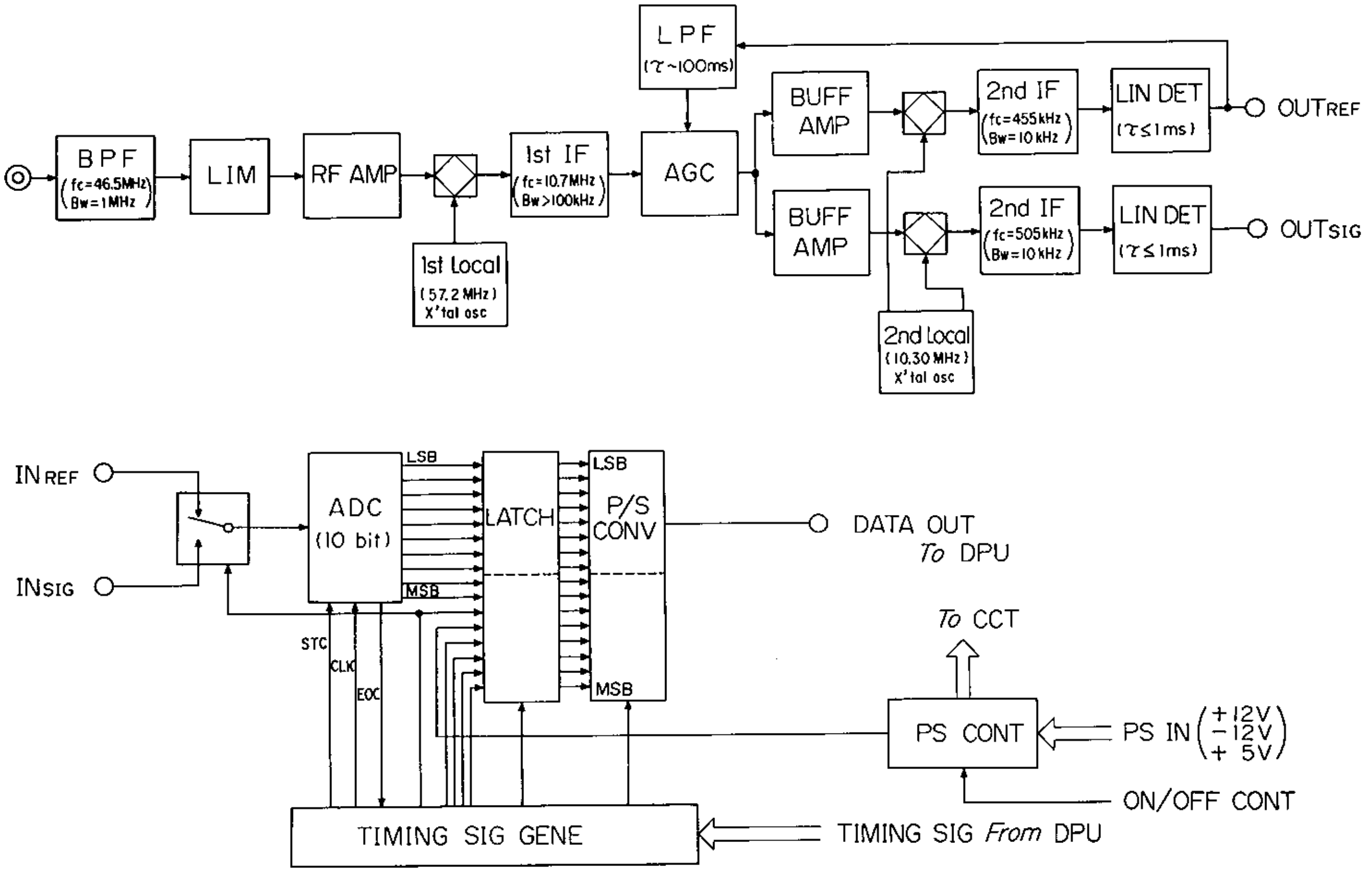


Fig. 4. The block diagram of the MUM receiver.

of 10.3 MHz into the MUR signal of 505 kHz and the REF signal of 455 kHz. The signal of each channel is detected by a linear detector, converted into digital signal by a 10-bit A/D converter, and then transferred to the tracking station (KSC) through a telemetry channel. The output of the REF channel is feedback to the AGC circuit after being applied a low pass filter of a time constant of 100 msec.

Figure 5 shows the receiver characteristics measured by changing the input level of MUR and REF signals. The characteristic of the REF channel shows that the AGC works for the input level above −100 dBm, and the output/input variation ratio is 0.08 (dB/dB). The characteristic of the MU channel indicates that the dynamic range of the MU channel covers a range from about −20 dB to +34 dB over the REF channel level.

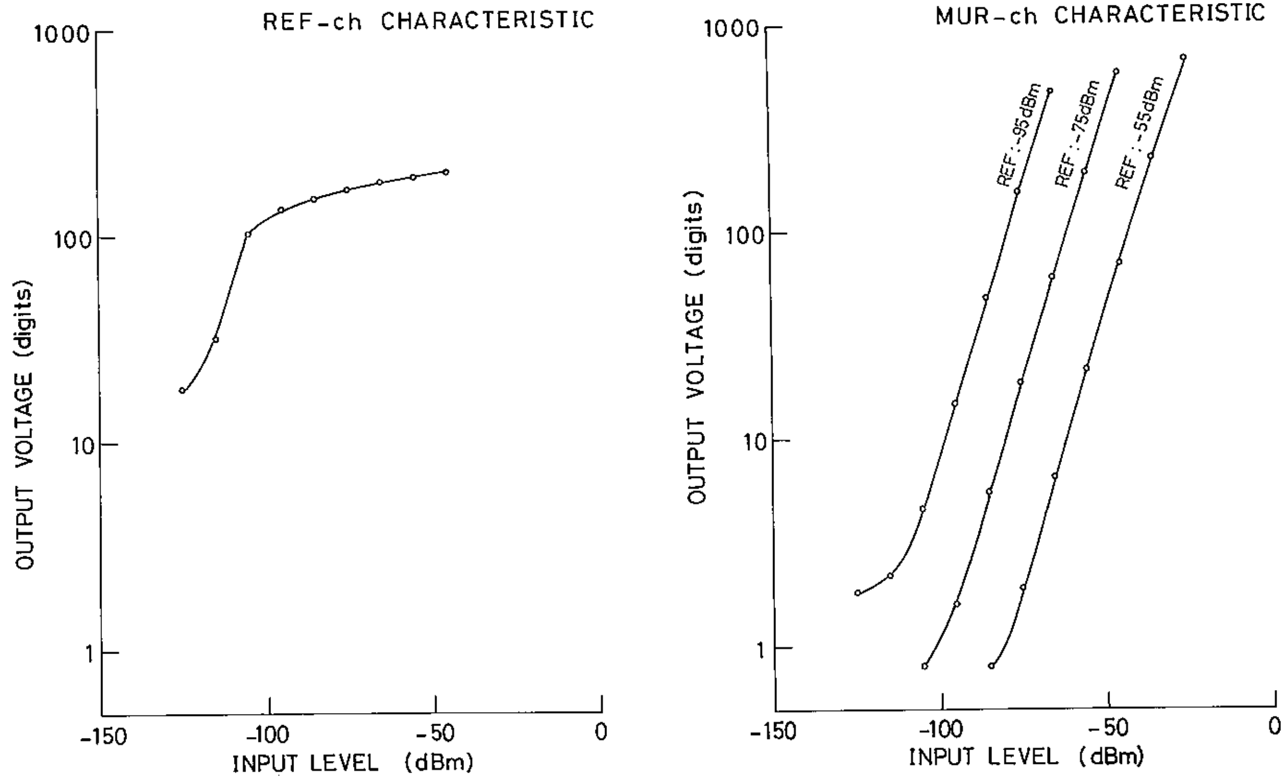
4. The Receiving Antenna

The PPS antenna used for reception of the MUM are two pairs of cylindrical bi-stem antennas, which were fully stretched in the space after the satellite stopped its spin motion. When these antennas are used as dipoles of 40 m tip-to-tip, they work as a 6-wave dipole antenna at the frequency of 46.5 MHz. Since the radiation impedance and the antenna pattern become quite complicated for such a long wire antenna, it is important to carefully examine its performance. A 1/10-scale-model experiment and some theoretical calculation have been performed because measurement using the real antenna is difficult on the ground.

The scale model was made of an aluminum block with four aluminum paddles and brass wire antennas of 2 mm in diameter. It was set in a radio anechoic chamber of the Kamakura Branch of Mitsubishi Electric Corporation, Kamakura, Japan, and the input impedance was measured by a network analyzer. The antenna pattern, which was hard to measure directly in a small room, was calculated theoretically based on the current distribution along the antenna measured by a current probe.

Figure 6 shows the theoretical and measured current distribution along the wire antenna. Theoretical curve is obtained by the moment method with 400 segments. Circles and crosses show measured amplitude and phase of the current, respectively, which correspond to the solid and dashed lines of the theoretical curves. Theoretical and measured values agree well except near the satellite body. Figure 7 shows the antenna pattern calculated based on the measured current distribution. The variation of the pattern versus direction falls in a range of 20 dB except around 90°, which is quite acceptable because the AGC covers a dynamic range of 40 dB.

A loss due to impedance mismatching was estimated from this scale model experiment and some theoretical considerations, and found to be less than 10 dB including the additional losses due to switches, cable and connectors between the antenna and the output port of MUM. This value is less than the one anticipated in designing the MUM system.



(a)

(b)

Fig. 5. Characteristics of the MUM receiver. (a) REF channel, and (b) MUR channel for the REF input level of −95 dBm, −75 dBm and −55 dBm.

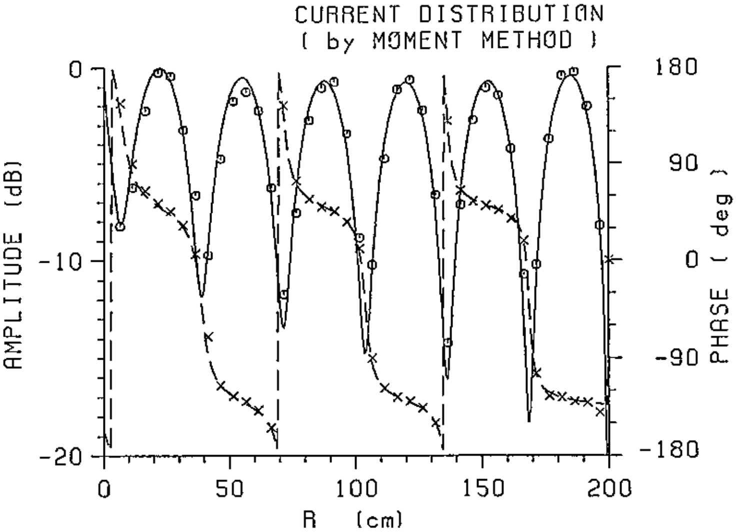


Fig. 6. Current distribution along the PPS antenna at a frequency of 46.5 MHz (1/10-scale model). Circles and crosses are for the measured amplitude and phase of the current, respectively, and the solid and dashed curves show corresponding theoretical values, respectively.

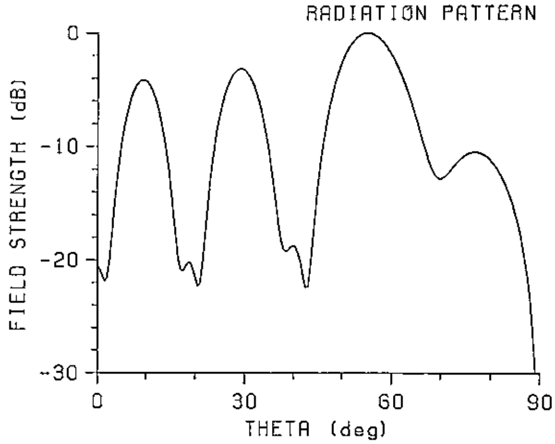


Fig. 7. The receiving antenna pattern calculated based on the measured current distribution of Fig. 6.

5. Preliminary Results

The MUM system started test operations in May, 1984, and some preliminary results have already been obtained. The MU radar antenna beam is pointed to the apex (the point where the elevation angle of the satellite becomes maximum) of the expected path of the satellite. The expected orbit of the satellite is given every week by osculating elements and their time derivatives based on the latest observations, and usually agrees with the real orbit determined later with an accuracy of 1–2° in the elevation angle. Thus, the radiation pattern along a plane which includes the main lobe is measured in one pass of the satellite.

Figure 8 shows an example of such measurement made on July 23, 1984, using a partial system with 19 of 25 subarrays which were then completed. The top diagram shows the elevation angle of the satellite seen from the MU radar (solid line), and the angle between the direction of the satellite and the axis of the main beam of the MU radar (dashed line) versus time. The bottom diagram gives the theoretical (thick line) and measured (thin line) relative gains of the MU radar antenna over the reference antenna. Since the reference antenna has almost constant gain of 6–8 dB for the elevation angles shown in this figure, the bottom diagram is regarded as the directivity pattern of the MU radar antenna if the above mentioned gain of the reference antenna is added.

This figure shows that both main beam direction and gain agree very well

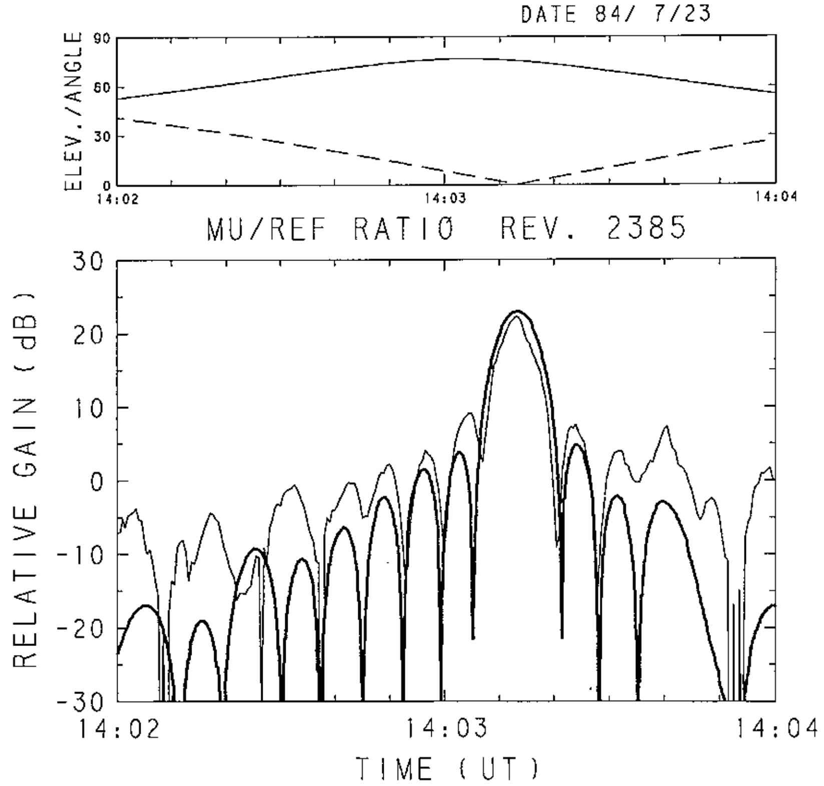


Fig. 8. Bottom: An example of the MU radar antenna pattern measured by MUM (thin line), and the corresponding theoretical antenna pattern (thick line). Top: Elevation angle of the satellite OHZORA (solid line) and the angle between the direction of the satellite and the antenna beam axis (dashed line).

with the theoretical ones, indicating that both the MU radar and the MUM system are working properly. A slight difference of about 0.5 dB in the main lobe gain can be attributed to the uncertainty in determining the output power of the MU radar as well as the reference transmitter.

The sidelobe levels, on the other hand, show some discrepancy of 5–10 dB between the theoretical and measured patterns, although the positions of sidelobes agree fairly well down to low elevation sidelobes. The consistent offset in the gain throughout the sidelobe region seems to suggest that a slightly larger random phase errors might remain in the individual power amplifiers and/or antenna elements of the MU radar, which are inseparably related in radars with an active phased array system. Apparently more detailed and continuous monitoring of the radiation pattern as well as careful calibration of individual amplifiers and antennas is necessary in order to establish the performance of this system.

6. Conclusion

A new monitoring system of a large VHF active phased array antenna of the MU radar has been developed using the scientific satellite OHZORA (EXOS-C). Basic idea of the system and the hardware configuration are briefly described. Although the antenna designed for a different purpose is shared with MUM on board the satellite, the experimental and theoretical considerations show that it does not cause any serious problem.

Finally, a preliminary result of measuring the MU radar antenna pattern is presented. A good agreement is found between theoretical and measured patterns in both main lobe gain and direction, but some discrepancy exists in the sidelobe region, suggesting random phase errors among antenna elements and/or power amplifiers of the MU radar.

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