Radio Science, Volume 25, Number 4, Pages 477–485, July–August 1990

MU radar: New capabilities and system calibrations

Shoichiro Fukao, Toru Sato,[1] *Toshitaka Tsuda, Mamoru Yamamoto, Manabu D. Yamanaka, and Susumu Kato*

Radio Atmospheric Science Center, Kyoto University, Uji, Kyoto, Japan

(Received May 10, 1989; revised August 31, 1989; accepted October 11, 1989.)

The middle and upper atmosphere (MU) radar of Japan is a unique mesosphere-stratosphere-troposphere type radar with an active phased array system. The MU radar has proved so reliable that continuous trouble-free operations over many days are possible. A brief description of new capabilities recently implemented and calibrations made to confirm the performance of the system are presented herein.

1. INTRODUCTION

As a new development of mesosphere-stratosphere-troposphere (MST) type radars, the middle and upper atmosphere (MU) radar, located at Shigaraki, Japan (34.85°N, 136.10°E), features a fully active phased array system [*Fukao et al.*, 1980, 1985*a*, *b*]. The whole system was realized by using only available commercial equipment and devices. This unique system configuration enables fast steering of the antenna beam as well as flexible operations of the MU radar.

This system has been used primarily, since its initial observations with a partial system in 1983, to observe the coherent scatter from irregularities in the troposphere, stratosphere, and mesosphere. Efforts to implement new capabilities to the MU radar have been made since the completion of the whole system in November 1984. Recently, it has been experimentally confirmed that observations of the very weak incoherent scatter (IS) signal from free electrons as well as the intense coherent scatter signal from plasma irregularities in the ionosphere are possible, though to a limited extent, by this system [*Sato et al.*, 1989*a*; *Fukao et al.*, 1988].

Also, simultaneous observation of different height ranges below 100 km with different height and time resolutions appropriate for each range has been made feasible since June 1985. This capability has not been implemented at other existing MST radars.

The MU radar observations generally employ pulse-to-pulse beam steering. Therefore it is necessary to confirm these capabilities by measuring the antenna pattern under operation. For this purpose, two measurements of the antenna pattern have been performed from distant locations where the antenna far field condition exists. One measurement was made by using moon-reflection echoes and the other by using an artificial satellite [*Fukao et al.*, 1985*c*; *Sato et al.*, 1989*b*].

The present paper describes these new implementations and the pattern calibrations of the antenna.

2. MU RADAR SYSTEM

The 46.5-MHz MU radar is composed of 475 Yagi antennas and an equivalent number of solid-state power amplifiers (transmitter-receiver (TR) modules) [*Fukao et al.*, 1985*a*, *b*]. Each Yagi antenna is driven by a TR module with peak output power of 2.4 kW. The nominal peak and maximum average radiation powers of the whole system are 1,000 and 50 kW, respectively. Because phase shift and signal division/combination are conducted at low signal levels (approximately at 1 mW), fast and almost continuous beam steering is made feasible in each interpulse period. The antenna is fully steerable. No grating lobe appears when the main lobe is directed within 30° of zenith.

For the same reason mentioned above, various sophisticated operations, employing up to four independent beams, are made feasible, and the entire system can be easily controlled with the aid of a

[1] Now at Department of Electrical Engineering, Kyoto University, Kyoto, Japan.

Copyright 1990 by the American Geophysical Union.

Paper number 89RS03242.
0048-6604/90/89RS-03242$08.00

TABLE 1. Basic Parameters of the MU Radar

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	fully steerable; no grating lobe appears when steered to 0°–30° off zenith angle
polarizations	linear and circular
Transmitter	475 solid state amplifiers (transmitter-receiver modules; each with output power of 2.4-kW peak and 120-W average)
peak power	1 MW (maximum)
average power	50 kW (duty ratio 5%)(maximum)
bandwidth	1.65 MHz (maximum) (pulse width: 1–512 μs variable)
IPP	400 μs to 65 ms (variable)
Receiver	
bandwidth	1.65 MHz (maximum)
IF	5 MHz
analog to digital converter	12 bits × 8 channels
Pulse compression	binary phase coding up to 32 elements; Barker and complementary codes presently in use

IPP is the interpulse period. Table taken from *Fukao et al.* [1985*a*].

computer [*Fukao et al.*, 1985*b*]. The basic parameters of the MU radar are given in Table 1. Further details of the system have been given by *Fukao et al.* [1985*a*, *b*].

3. IMPROVED CAPABILITIES

There have been the following three improvements made primarily in the software of the MU radar since *Fukao et al.* [1985*a*, *b*] reported the initial status of the MU radar system.

First, the MU radar has been provided with a capability to observe different height ranges below 100 km almost simultaneously. The MU radar system is under full supervision of the radar controller (HP9835A) [*Fukao et al.*, 1985*b*]. The communication of the radar controller with the in-house hardware, i.e., the reference signal generator, modulator/demodulator, divider/combiner, detector, and 2-Mbyte random access memory, is performed via a 16-bit parallel input/output (I/O) interface, while the communication with the host computer VAX-11/750 and 25 TR module controllers in the remote booths is performed via RS-232C serial I/O interface. It takes less than 15 s to send the parameters to the in-house equipment via the serial and parallel I/O interfaces, while it takes almost three minutes to send all parameters to the remote booths via the serial I/O interface. The parameters of the in-house equipment determine observation range, height resolution, and time resolution. By swapping the parameters for the in-house equipment in such a short time, the MU radar can almost simultaneously observe the different height ranges with different height and time resolutions appropriately fine for the respective ranges. At most four different sets of observational parameters can be altered in one sequence. The limitation of this technique is that neither beam direction nor wave polarization can be changed because they require the parameters to be sent to the remote TR module controllers, which takes time.

This technique has been used for the standard observations of the mesosphere, the stratosphere and the troposphere, which have been conducted by the MU radar for four consecutive days every month since June 1985. Table 2 shows the observational parameters. We switch the mesospheric and stratospheric observation modes in the daytime (0800–1600 JST; Japan Standard Time), and the tropospheric and stratospheric ones in the nighttime (1600–0800 JST). The time resolution in Table 2 includes the time necessary to switch the observation modes.

TABLE 2. Standard Observational Parameters of the MU Radar for the Mesosphere, Stratosphere, and Troposphere

	Troposphere	Stratosphere	Mesosphere
Observation period	nighttime (1600–0800)	all day	daytime (0800–1600)
Observation range	2–19 km	5–24 km	60–98 km
Beam directions (θ: zenith angle)	zenith northward ($\theta = 10°$) eastward ($\theta = 10°$) southward ($\theta = 10°$) westward ($\theta = 10°$)	zenith northward ($\theta = 10°$) eastward ($\theta = 10°$) southward ($\theta = 10°$) westward ($\theta = 10°$)	zenith northward ($\theta = 10°$) eastward ($\theta = 10°$) southward ($\theta = 10°$) westward ($\theta = 10°$)
Range resolution	150 m	150 m	600 m (sampled every 300 m)
Time resolution	150 s	150 s	150 s
IPP	400 μs	400 μs	730 μs
Pulse compression	single pulse	16-bit complementary	8-bit complementary
Coherent integration	38 times	38 times	20 times
Incoherent integration	6 times	6 times	6 times

IPP is the interpulse period.

Second, the MU radar that is capable of transmitting circular polarization waves has demonstrated its capability to detect the weak IS from free electrons in the ionospheric F region below 600 km [*Oliver et al.*, 1988; *Sato et al.*, 1989*a*]. The major detriment for IS observation with the MU radar is the high system noise temperature of about 10,000°K. This is unavoidable background cosmic noise encountered at the MU radar operating frequency. Its effect is to degrade the signal-to-noise (S/N) ratio achievable and to render the MU radar considerably less sensitive than most of the other IS radars in the world. However, *Sato et al.* [1989*a*] show that S/N ratios in excess of 10 are attainable with a single pulse of 512 μs, which is the longest pulse available to the MU radar. Either a single pulse of this width or the phase-coded one with 7-bit Barker code is used for power profile measurements. Integration time of more than 5 min is required to achieve acceptable accuracy.

Practical spectral measurements, however, often experience S/N ratios of only a few percent, and hence long integration times are required to achieve acceptable accuracy [*Sato et al.*, 1989*a*]. In order to achieve the best possible S/N ratio for ion and electron temperature measurements, a standard 4-pulse scheme with 96-μs pulses has been implemented. A waveform consisting of two 256-μs pulses separated by a gap of 256 μs (two-pulse scheme) has been found to give the best S/N ratio for ion drift velocity measurements. This total of 512 μs transmission time during one interpulse period is the maximum available to the MU radar. Both drift and temperature measurements require integration times of 45 min to achieve acceptable accuracy. A power profile measurement mode is usually alternated either with the ion drift velocity mode or temperature mode, by swapping the observational parameters as is done in the atmospheric observations.

Finally, the beam steerability of the MU radar has been utilized to observe the field-aligned plasma irregularities (FAI's) in the ionospheric E and F region. It has been found that the FAI echo intensity sometimes exceeds the cosmic noise level by more than 20 dB for a 100-kW pulse coded by 7-bit Barker code with 32-μs baud length. Steered multiple beams have also been used to study the east-west movement of the echo centers. This capability essentially does not require any fast beam steerability but one or several beam positions perpendicular to B. It is a new technique that will be interesting for some of the less sensitive MST radars at midlatitudes to implement. Details of this technique will be discussed in section 6.

4. MOON-REFLECTION MEASUREMENT OF ANTENNA PATTERN

Since passive arrays have reciprocal antenna patterns for transmission (TX) and reception (RX), their antenna patterns are ordinarily known by measuring the pattern in the receiving mode only. Such pattern measurements have extensively been made by various antennas using radio stars [e.g., *Guidice and Castelli*, 1971]. The main lobe direction

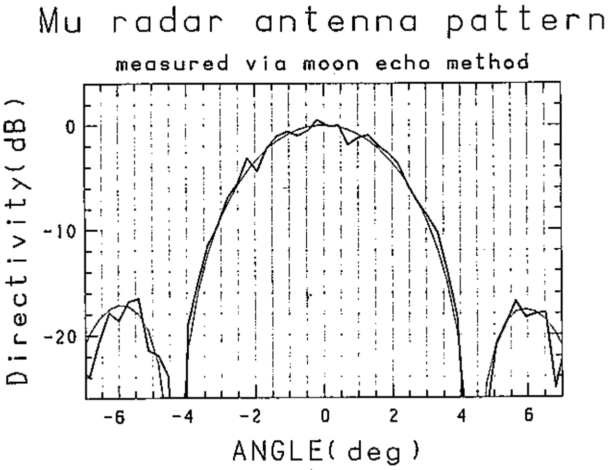

Fig. 1. Relative gain of the MU radar antenna pattern (thick line) measured by moon-reflection echoes and the corresponding theoretical gain (thin line). The antenna beam is tilted by 8° from the zenith and 40° west from the south.

of the MU radar antenna was also calibrated by using the radio star Cassiopeia-A, which has often been used for pattern measurements of MST radar antennas [e.g., *Czechowsky et al.*, 1984; *Fukao et al.*, 1985*a*]. 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 statistical fluctuations of the signal.

The phase of every TR module of the MU radar is kept equalized to an accuracy of 1.4° [*Fukao et al.*, 1985*a*]. The output power of the TR modules is also adjusted to vary no more than 0.1 dB. A numerical computation using these measured values of amplitude and phase, considering the amplitudes and phases to be distributed randomly among the TR modules, showed no detectable error in gain and direction of the main beam, although it revealed less than 5 dB increase in the low-elevation sidelobes.

On the other hand, the TX/RX patterns of an active phased array are, in general, not the same and are inseparably related to the distributed transmitter and receiver characteristics. Therefore it is required for the MU radar to measure the antenna patterns by taking amplitude and phase characteristics of all TR modules into consideration.

One test was made by using moon reflection echoes. A one-way array pattern along a plane which contains the moon orbit was measured during passage of the moon. The measurement was conducted during a 1-hour period of 0000–0100 JST on December 28, 1985. The beam was fixed in the direction 8° from the zenith and 40° west from the south where the apparent velocity of the moon relative to the MU radar on the Earth became zero at 0037 JST. A 1-MW pulse using right-hand circular polarization was transmitted with a phase modulated by a 13-bit Barker code with 32-μs baud length. The interpulse period was 20 ms. The baseband signal was sampled at 1024 points spaced at 4.8-km intervals. Coherent integration was performed twice. Then, 256-point complex fast Fourier transforms (FFT's) were calculated in real time to obtain Doppler velocity spectra for each 20-s period. The resulting power spectra were averaged for approximately 1 min before being written on magnetic tape. The antenna pattern was obtained by choosing the peak of the spectrum at a range of maximum echo power of each 1-min data set, and plotting it versus time.

Figure 1 gives a cross section of the measured (thick) and the theoretical (thin) relative gains of the MU radar approximately in the east-west direction. In this figure a one-way antenna pattern which is an average of TX and RX patterns is represented based

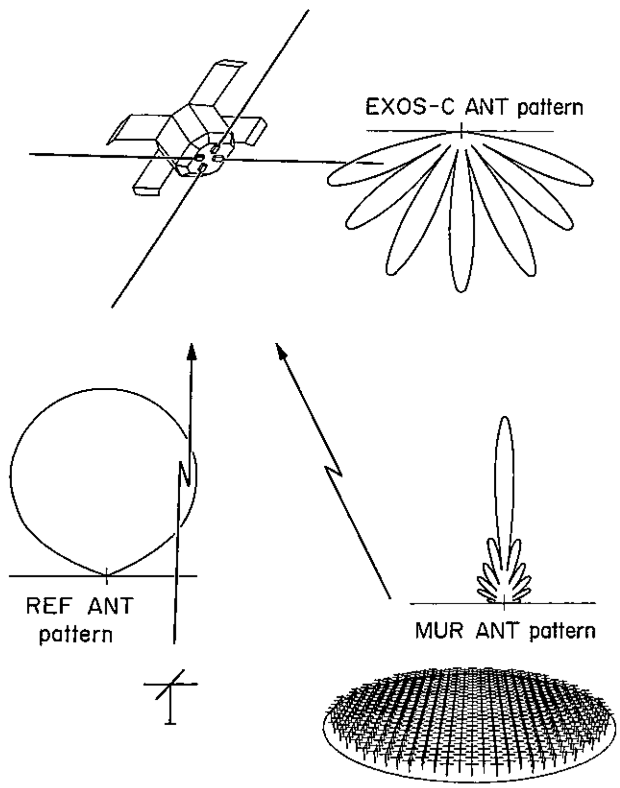

Fig. 2. Principles of the MU radar antenna pattern measurement using the satellite Ohzora. The received signal strength of the MU radar CW signal is calibrated by that of the reference signal strength [*Fukao et al.*, 1985*c*].

on the measured two-way pattern. It is shown in this figure that both direction and gain of the main beam are in close agreement with the theoretical values. The first sidelobes are relatively in close agreement, showing the suppression of approximately 17 dB with respect to the main lobe. This value is consistent with the theoretically expected value for the present main beam direction of 8° off from the zenith.

The fluctuations of the measured values, having a period of a few seconds, are attributed both to the scintillation and to the libration or the slow apparent rotation of the moon relative to the MU radar [*Evans*, 1974].

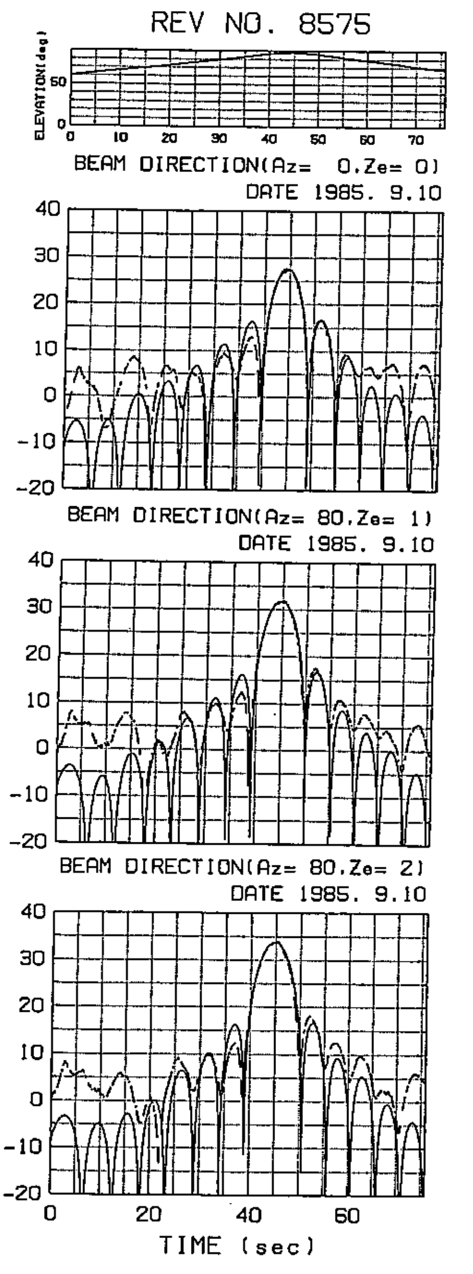

Fig. 3. The MU radar TX antenna patterns (thick broken line) measured by the satellite Ohzora passing around 2° from zenith toward the east, and the corresponding theoretical antenna gain (thin line) relative to the reference antenna. Az is the azimuth angles counted clockwise from the north, and Ze is the zenith angles. The top two patterns show cross-sectional patterns at approximately 2° and 1° from the main lobe peak, respectively.

5. SATELLITE MEASUREMENT OF ANTENNA PATTERN

An antenna pattern measuring system for the MU radar has been developed using the Japanese scientific observation satellite Ohzora (EXOS C) which was launched on February 14, 1984 [*Fukao et al.*, 1985*a*, *c*]. Ohzora has an almost circular orbit with an apogee of 750 km, a perigee of 350 km and a high inclination of 74.5°, which is quite suitable for this measuring purpose.

Transmission from the MU radar and reception by the satellite are not synchronized, so that the normal pulsed transmission mode cannot be used for these calibrations. Instead, the MU radar is made to transmit a 300-W CW signal. A receiver named MUM (MU radar antenna Monitor) on board the satellite measures this CW signal. A TX antenna pattern along a plane which contains the satellite orbit can be measured during each passage of the satellite. The received signal strength varies according to the transmitting antenna pattern as well as to height and attitude of the satellite and to the pattern and radiation impedance of the receiving antenna on board the satellite. In order to remove these factors, a small omnidirectional reference antenna installed at the MU radar site simultaneously transmits a 300-W CW signal at a frequency 50 kHz offset from the MU radar frequency, i.e., 46.55 MHz. A turnstile antenna with a 5 m × 5 m ground plane and a maximum apex gain of 8.3 dB in the zenithal direction is used as the reference antenna.

The MU radar and the reference signal are received in separate narrow-band filters of the MUM receiver on board the satellite. The output signals of the receiver are converted into the input field strength according to the input-output characteristics of the MUM receiver measured on the ground prior to the satellite launching. The level of the reference signal is compared with the level of the MU radar signal, and the MU radar antenna pattern

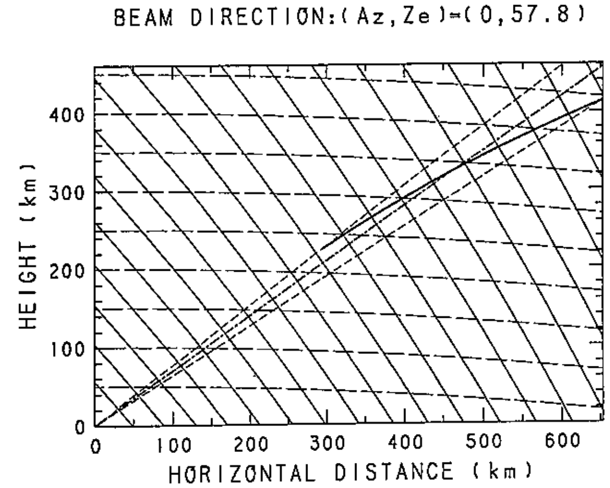

Fig. 4. An antenna beam used for F region FAI observations that is tilted 57.8° toward due north, and its relation with the locus (thick line) of perpendicularity to B (thin solid lines).

is determined as the gain relative to that of the reference antenna. Figure 2 illustrates the scheme of the measurement. Other technical details are referred to in the work of *Fukao et al.* [1985*c*].

Recently, *Sato et al.* [1989*b*] have developed a technique for continuous determination of the antenna pattern for 11 different pointing positions, by periodically steering the MU radar beam into different directions. Figure 3 shows examples of the antenna patterns for three beams near the zenith thus obtained. The thick broken lines are the measured gains of the MU radar antenna relative to those of the reference antenna, while the thin lines indicate the theoretical patterns obtained for an ideal infinite and perfectly reflecting ground plane [*Stark*, 1966]. The top frame of the figure denotes the elevation angle of Ohzora versus time as seen from the MU radar.

The agreement of the measured and the theoretical patterns is excellent for the main lobe. The positions and shapes of the sidelobes are also in good agreement down to elevation angles of about 20°, but the gains, especially for lower sidelobes, are 10-20 dB higher than the theoretical values. The antenna patterns are found to be asymmetric between the south and north sides with respect to the zenith. Some of the low-elevation sidelobes in the south are found to be 5–10 dB higher than those in the north. This is considered to reflect an effect of the terrain shape around the antenna plane. The antenna array is surrounded by the hills 50 m high in the south and by a bank 15 m high topped by a metallic net fence 10 m high in the north. By this measurement, performed approximately once a month in 1985–1987, it is confirmed that the MU radar system properly functions as expected.

6. BEAM STEERING NORMAL TO GEOMAGNETIC FIELD LINES

The MU radar can view perpendicular to the geomagnetic field B in the midlatitude E and F region, and can see field-aligned irregularities (FAI's) from approximately 38° to 43°N latitude and 100° to 160°E longitude [*Fukao et al.*, 1988].

Figure 4 shows the locus of perpendicularity between B and a beam looking due north (5° off geomagnetic N) at 57.8° zenith angle, calculated using the IGRF 1985 model. The two-way half-power horizontal/vertical beamwidth is 2.3°/4.5° (the 2.3° beam near the zenith distorts at small elevation angles). The east-west resolution is 20 km at 500-km range. The vertical resolution when the radar beam is perpendicular to B is set by an aspect sensitivity consideration, which limits the echoes to viewing directions within a small angle of perpendicularity. *Woodman and LaHoz* [1976] attribute an aspect sensitivity of less than 0.034° to echoes which are slowly fading. The present echoes of the MU radar are also slowly fading with a typical spectral width of approximately 10 Hz. Considering the curvature of B, the echoes are thus limited to a region about 0.1° wide in zenith angle. The locus of perpendicularity in Figure 4 follows a curved path into the beam near 350-km range (approximately 200-km altitude) and out again beyond 800 km range (approximately 500-km altitude). Using other beams containing this locus at smaller ranges, at altitudes from 100 to 140 km, we see E region FAI's.

These zenith angles are outside the design limits of the MU radar antenna array, and consequently two grating lobes appear to the south. Figure 5 shows the relative antenna gain pattern in the form of a contour map for the beam direction of Figure 4. The incoherent scatter signal is well below the cosmic noise level, and all FAI echoes come from the north lobe, so the south lobes can be ignored.

Figure 6*a* shows FAI echo power in a RTI (range-time-intensity) format. A right-hand circularly polarized pulse of 4.8 km or 32-μs length and

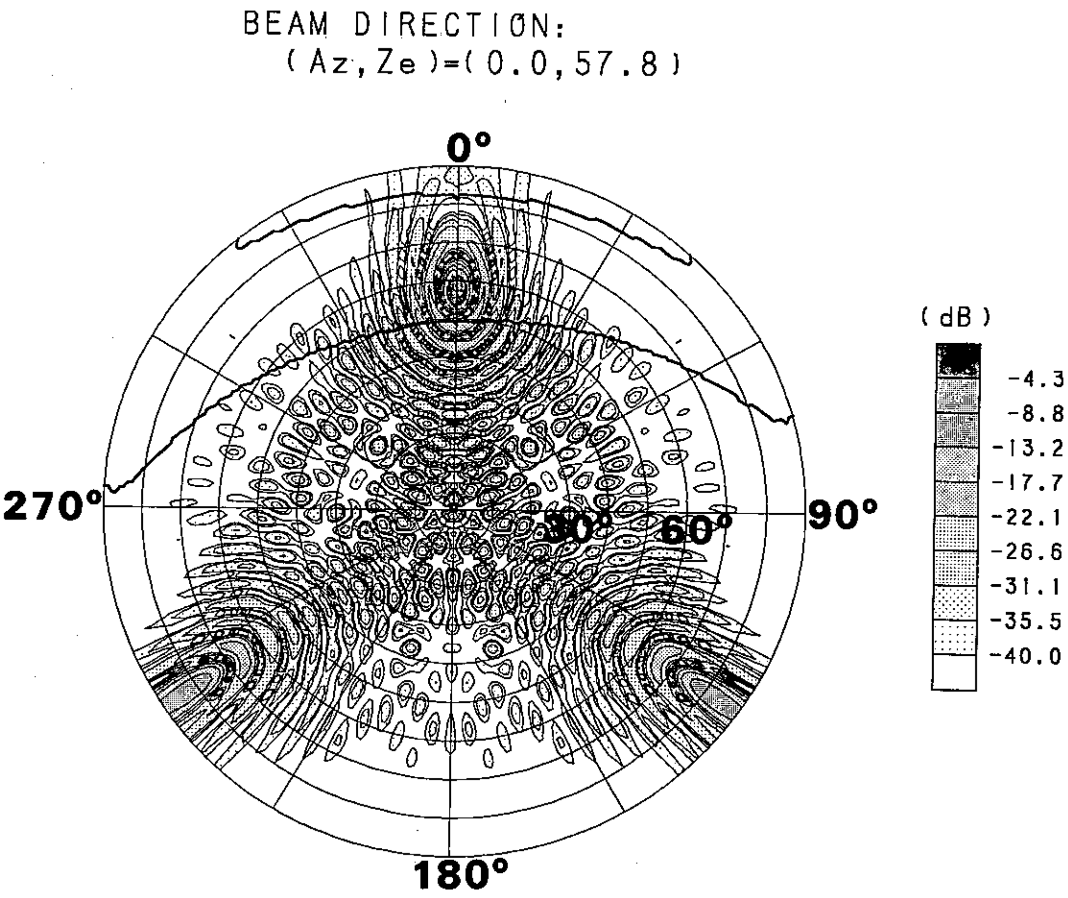

Fig. 5. Contour map of the MU radar relative antenna gain pattern in the beam direction of Figure 4. The thick curves enclose the azimuth-elevation domain of possible perpendicularity between the magnetic field lines and the half-power points of the radar beam for various pointing directions and 50–2000 km range.

100-kW peak power is used. The maximum echo intensity is more than 25 dB larger than the cosmic noise level. In Figure 6*a* the echoes appeared first near 700-km range at approximately 2210 JST and progressed to lower ranges near 400 km around 2240 JST. After this appearance we could see three distinct regions near 500-km range at 2240, 2255, and 2310 JST, which moved to higher latitudes for about 45–60 min, and then faded out.

The plot in Figure 6*b* is a representation of the line-of-sight velocity which has been determined from the first moment of the echo spectrum. Since these Doppler shifts correspond to radial velocities we have represented them using the arrows as shown on the right hand side [*Woodman and La-Hoz*, 1976]. The line-of-sight velocity then corresponds to the angle of the arrow so that a horizontal arrow implies zero velocity. The scale of the vertical projection of the arrows is chosen so that the arrow slopes conform to the tilt of echo regions in Figure 6*a*. A positive velocity corresponds to an upward and nearly geomagnetically northward flow. The observed line-of-sight velocities coincide well with the velocities inferred from the slopes of the echo power contours.

7. CONCLUDING REMARKS

It has been demonstrated by two measurements that the MU radar antenna beam is properly steered and formed as designed. One measurement has used moon-reflection echoes for a fixed beam, while the other has utilized a receiver on board a satellite for beams steered very fast, virtually, from pulse to pulse. The long-term stability of the antenna pattern, confirmed by the repeated satellite measurements, has proved the reliability of the active phased array system of the MU radar.

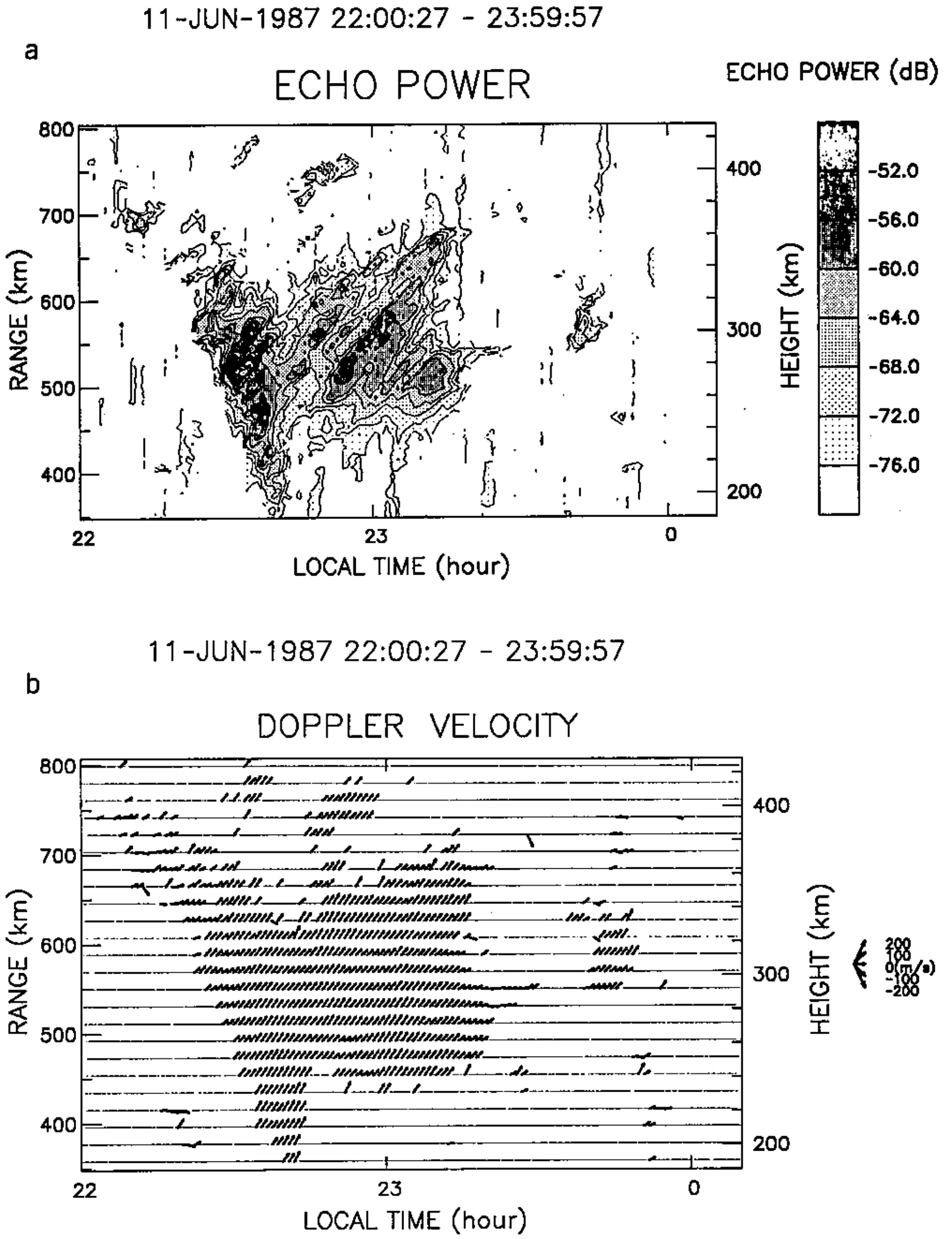

Fig. 6. (*a*) Range-time contours of FAI echo signal strength in the direction perpendicular to B in the *F* region for June 11, 1987. The echo power is given in arbitrary units. (*b*) Line-of-sight Doppler velocity for the same period. The velocity corresponds to the angle of the arrow from the horizontal line as shown on the right-hand side.

The MU radar has attained an important capability to observe simultaneously the troposphere, the stratosphere, and the mesosphere with different height and time resolutions appropriate to the respective height ranges. Also, it has been shown that the MU radar can observe the weak IS from the ionospheric *F* region, although the MU radar is considerably less sensitive for this purpose than most other operational IS radars. The capability of the MU radar to observe FAI's in the *E* and *F* region can be implemented at other less sensitive MST radars at mid-latitudes, since the echo intensity is as large as that of the lower atmospheric echoes.

Acknowledgments. The authors thank W. L. Oliver of Boston University for careful reading of the manuscript. The MU radar belongs to and is operated by the Radio Atmospheric Science Center of Kyoto University.

REFERENCES

Czechowsky, P., G. Schmidt, and R. Rüster, The mobile SOUSY Doppler radar: Technical design and first results, *Radio Sci.*, *19*(1), 441–450, 1984.

Evans, J. V., Some post-war developments in ground-based radiowave sounding of the ionosphere, *J. Atmos. Terr. Phys.*, *36*, 2183–2234, 1974.

Fukao, S., S. Kato, T. Aso, M. Sasada, and T. Makihira, Middle and upper atmosphere radar (MUR) under design in Japan, *Radio Sci.*, *15*(2), 225–231, 1980.

Fukao, S., T. Sato, T. Tsuda, S. Kato, K. Wakasugi, and T. Makihira, The MU radar with an active phased array system, 1, Antenna and power amplifiers, *Radio Sci.*, *20*(6), 1155–1168, 1985*a*.

Fukao, S., T. Tsuda, T. Sato, S. Kato, K. Wakasugi, and T. Makihira, The MU radar with an active phased array system, 2, In-house equipment, *Radio Sci.*, *20*(6), 1169–1176, 1985*b*.

Fukao, S., T. Sato, and S. Kato, Monitoring of the MU radar antenna pattern by satellite OHZORA (EXOS-C), *J. Geomagn. Geoelectr.*, *37*, 431–441, 1985*c*.

Fukao, S., J. P. McClure, A. Ito, T. Sato, I. Kimura, T. Tsuda, and S. Kato, First VHF radar observation of mid-latitude *F*-region field-aligned irregularities, *Geophys. Res. Lett.*, *15*(8), 768–771, 1988.

Guidice, D. A., and J. P. Castelli, The use of extraterrestrial radio sources in the measurement of antenna parameters, *IEEE Trans.*, *AES-7*, 226–234, 1971.

Oliver, W. L., S. Fukao, T. Sato, T. Tsuda, S. Kato, I. Kimura, A. Ito, T. Saryo, and T. Araki, Ionospheric incoherent scatter measurements with the MU radar: Observations of F-region electrodynamics, *J. Geomagn. Geoelectr.*, *40*, 963–985, 1988.

Sato, T., A. Ito, W. L. Oliver, S. Fukao, T. Tsuda, S. Kato, and I. Kimura, Ionospheric incoherent scatter measurements with the middle and upper atmosphere radar: Techniques and capabilities, *Radio Sci.*, *24*(1), 85–98, 1989*a*.

Sato, T., Y. Inooka, S. Fukao, and S. Kato, Multi-beam pattern measurement of the MU radar antenna by satellite OHZORA, *J. Geomagn. Geoelectr.*, *41*, 743–751, 1989*b*.

Stark, L., Radiation impedance of a dipole in an infinite planar phased array, *Radio Sci.*, *1*, 361–377, 1966.

Woodman, R. F., and C. LaHoz, Radar observations of F region equatorial irregularities, *J. Geophys. Res.*, *81*(31), 5447–5466, 1976.

S. Fukao, S. Kato, T. Sato, T. Tsuda, and M. Yamamoto, Radio Atmospheric Science Center, Kyoto University, Uji, Kyoto 611, Japan.