The MU radar with an active phased array system
2. In-house equipment

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The MU (middle and upper atmosphere) radar of Japan uses an active phased array system. Each of 475 crossed three-subelement yagi antennas in a circular array is provided with a 2.4-kW peak power amplifier. This system configuration attains a very fast and almost continuous beam steerability at the total peak radiation power of 1 MW. A brief description of the in-house equipment is presented herein.

1. INTRODUCTION

The middle and upper atmosphere (MU) radar, Shigaraki, Shiga, Japan (34.85°N, 136.10°E), is the first mesosphere-stratosphere-troposphere (MST) radar that can steer the antenna beam fast and almost continuously. This capability originates from its unique system configuration.

The conventional radars employ a passive phased array connected to a high-power transmitter [e.g., Green et al., 1979; Schmidt et al., 1979; Czechowsky et al., 1984]. In the MU radar array, each antenna element is fed by a low-power amplifier, and all amplifiers are coherently driven to radiate 1-MW peak output power. Because phase shift and signal division/combination are conducted at low signal levels, fast and almost continuous beam steering, as well as various sophisticated operations, employing several independent beams, are made feasible. For the same reason, the entire system can be easily controlled with the aid of a computer.

The system outline of the MU radar along with a few preliminary results have been presented by Kato et al. [1984], and details of the antenna and transmitter are described by Fukao et al. [this issue] (hereafter referred to as paper 1). The present paper mainly describes the in-house equipment related to transmission, reception, on-line data processing and system control.

2. TRANSMISSION AND RECEPTION

2.1. Reference analog and timing signals

Various analog signals required for transmission (TX) and reception (RX) and timing signals for system control are generated by a combination of a Rubidium-vapor master oscillator, a frequency synthesizer, and a timing signal generator as shown in Figure 1. The intermediate frequency (IF) signal of 5 MHz used for transmission and detection, and the local frequency signal of 41.5 MHz are synthesized from the reference signals of 1 and 5 MHz. The frequency synthesizer also generates the reference digital clock of 4 MHz. The 4-MHz clock is utilized in the timing signal generator where various timing signals required for real time system control are generated according to instructions from the radar controller.

Some details of the control data set by the radar controller are as follows. The MU radar starts/stop its operation by means of TX start/stop control data. The number of subpulses is indicated when pulse compression is conducted. In the case that transmission of multiple pulses [Farley, 1972] (up to seven pulses) is incorporated, a TX pulse sequence and the total length of this sequence are set. The RX gate is opened at a preset time to begin signal sampling. Sampling ends when the desired number of samples have been taken. The coherent-integration-end signal is generated when transmission and reception are repeated the number of times needed for coherent integration. Sampling start timing can be changed by a

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The modulated TX IF signal is sent to the divider and split into 6, each segment being sent to a remote booth accommodating transmitter-receiver (TR) modules. The local signal and T/R switching signal are also split at the divider and sent to each booth. Both the upconvert to RF (46.5 MHz) and power amplification are made in the TR modules (paper I). As shown in the standard level diagram (Figure 4), the signal levels of both IF and local are approximately 0 dBm up to the output port of the divider.

Attenuation is provided in the modulator unit for CW transmission at reduced total radiation power of 50–400 W.

2.3. Reception

The received 46.5-MHz signal is first amplified by the preamplifier and then downconverted to IF at the mixer (MIX) unit in the TR modules (paper I). The IF signals from the 19 modules in each group are then combined into one and sent to combiner in the control building. The IF signals from all 25 groups are combined into one to four channels in any combination. Only one channel is used for normal full power operation. The IF signals are amplified by a 60-dB gain stage to an optimum input level for the detector (Figure 5).

Four coherent detectors are available, corresponding to the four output channels of the combiner. The

2.2. Transmission

The 5-MHz TX IF signal is modulated to provide coded pulses by the modulator as shown in Figure 2. The binary code for pulse compression is loaded by T/R switching signal into the shift register of the code generator unit. At the instant that the TX gate is opened, the code is sent to the modulator unit. The TX IF signal is then pulse-modulated by this code. The linear phase low-pass filter (seven-stage Thompson type) is switched to match subpulse widths of 1, 2, 4, 8, 16 and 32 μs. The phase of the code can be flipped 180° after every two pulses in order to eliminate any system offset. Any kind of binary code with a length of up to 32 elements is applicable. At present, 16- or 32-element complementary codes [e.g., Schmidt et al., 1979; Wakisugi and Fukao, 1985] are being used for observation of the middle atmosphere, whereas a 7- or 13-element Barker code [Gray and Farley, 1973] is employed for observation of the ionosphere. A typical seven-element Barker coded pulse with 1-μs subpulse width is illustrated in Figure 3.
Fig. 3. TX IF pulse modulated by a seven-element Barker code with a subpulse width of 1 μs.

IF signal is split and separately mixed with two phase-quadrature reference signals (5 MHz). This detection enables determination of the sign of the Doppler-shifted echo. The same low-pass filter as is used for the modulator is provided in each detector channel to match TX subpulse widths of 1, 2, 4, 8, 16 and 32 μs. The video amplifier in each channel matches the filtered signal to the desired input level of the analog-to-digital (A/D) converters in the demodulator/integrator.

Twelve-bit digitized signals are decoded for pulse compression and then coherently integrated, as illustrated in Figure 6. Coherent integration prior to decoding is possible only when the characteristic time of atmospheric refractive-index fluctuations is much larger than the period required for coherent integration [Schmidt et al., 1979; Woodman et al., 1980]. Since the MU radar incorporates pulse compression also for the purpose of observing the ionosphere with a characteristic time less than interpulse periods (IPP), decoding prior to/without coherent integration is required.

Figure 7 shows the decoding scheme of the MU radar. Decoding demands cross correlation of $C_i$ and

![MU Radar Diagram]

Fig. 4. Standard level diagram for transmission. The final output power of 63.7 dBm is provided for linear polarizations. The signal level at a few stages is given in units of decibels referred to 1 mW.
Fig. 5. Standard level diagram for reception of an input signal of
-120 dBm.

$R_i$, where $C_i$ and $R_i$ are the transmitted code and the received M bit digital signal of sine/cosine channels, respectively. As $R_i$ is expressed in the following form,

$$R_i = \sum_{k=0}^{M-1} R_i^k 2^k$$

the decoded signal $\overline{R_i}$ is given by

$$\overline{R_i} = \sum_{j=1}^{N} C_j \overline{R_i^{j+1}}$$

$$= \left( \sum_{j=1}^{N} C_j R_i^{j+1} \right) 2^0 + \left( \sum_{j=1}^{N} C_j R_i^{j+1} \right) 2^1 + \cdots$$

$$+ \left( \sum_{j=1}^{N} C_j R_i^{j+1} \right) 2^{M-1}$$

(1)

where $N$ is the code length. The diagram indicates that the convolution is taken at each bit of consecutive data and that summation is performed in a pipeline operation as shown in (1). Because $R_i$ is either 1 or 0 and $C_i$ is either +1 or -1, implementation of the decoder hardware is significantly simplified. This makes it possible to decode the compressed pulse in real time, a capability which is essential to ionosphere observations.

The coherent integrator consists of two memories of 1024-word length for 1024 complex samples, one for each of the phase quadrature data (Figure 6). They are switched alternately to their integration or reading-out modes. Coherent integration is allowed up to 256 times. The integrated data are sent to the buffer memory of the array processor for on-line processing.

3. ON-LINE DATA PROCESSING

The method of processing the coherently integrated, digitized data is schematically shown in Figure 8. The main constituents of the system are a host computer VAX-11/750 (hereafter referred to as VAX) and an array processor MAP-300 (MAP). Fast Fourier transform (FFT) or autocorrelation function (ACF) are calculated in real time by MAP under the supervision of VAX. A 2-Mbyte random access memory (2-MB RAM) of the MAP is used as two concurrently operating buffer memories. One is the input buffer, to which coherently integrated phase quadrature data are sent. The other is the incoherent integration buffer, where power spectra under incoherent integration are temporarily stored.

The on-line processing data flow is schematically shown in the same figure. When the desired number of data are stored in the input buffer, MAP resets ISPL (initial set pulse) to momentarily interrupt TX. During this period MAP reads out the data in order to calculate power spectra by means of an FFT algo-

FIG. 6. Block diagram of the demodulator/integrator. Two phase quadrature signals from each detector channel have their own analog-to-digital (A/D) converters of 1 MHz. MUX indicates a multiplexer.
rhythm. The calculated results are added to the power spectrum sums read out of the incoherent integration buffer. Then MAP sets ISPL to restart TX. This pause occupies no more than a few percent of the total observational time for standard lower stratosphere observations. After incoherent integration has been repeated a preset number of times, the power spectra are transferred to VAX via MAP and stored in the magnetic disk. The data are then read out from the disk files and recorded on magnetic tape (MT). The disk files form a ring buffer storing the 10 most recent pieces of data. These data are immediately available to the operator on a color graphic display, Quick Display, if requested during observation.

The software for the on-line data processing is composed of the following three programs (processes), i.e., control program, data handling program, and Quick Display program. The data handling program controls MAP so as to calculate power spectra (or ACF’s) and to write them in the ring buffer. The control program manages a package of data handling programs and executes individually according to instructions from the radar controller. It is also responsible for transferring data from the ring buffer to MT. Immediate access to the data stored in the ring buffer is provided by the Quick Display program.

It can be assumed that this software structure, with interprocess communications, is much more efficient than a single general purpose program. Such a program would be too lengthy and lack the versatility to be applicable to a variety of observations. Within the MU radar software, only the data handling programs are specially designed to handle the various types of observations; FFT, ACF, power profile mode, etc. Generally speaking, this design principle facilitates development of optimum programs with the fastest possible processing speeds. Also, data transfer from

![Diagram of MU Radar with Active Phased Array System](image)

**Fig. 7.** A detailed block diagram of the digital decoder for pulse compression. Six dummy bits are added to the input data to allow conformance up to 32 summations. The serial-to-parallel conversion is actually performed in the MUX shown in Figure 6.

**Fig. 8.** Principal constituents for on-line data processing (inside the dotted square). Data flow is indicated by thick arrows. The magnetic disk is shown inclusive in VAX because, from a software point of view, it belongs to VAX.
the disk to MT, a comparatively slow process, is not conducted by the data handling program but by the control program, obviating any loss of observation time.

The VAX performs nonlinear fitting of Gaussian functions to the observed turbulent scatter spectra to infer the mean Doppler shift in real time without any loss in data handling time. A typical example of the on-line graphic display output appears in Figure 9.

4. SYSTEM CONTROL

The MU radar system is virtually under full supervision of the radar controller. Its main constituent is a desktop computer HP9835A. The system control programs and various observational parameters are stored in a magnetic disk and read out for use in each observation.

Communication between the radar controller and system hardware is performed via both a 16-bit parallel I/O interface and RS-232C serial I/O interface. The parallel I/O is employed for control of the in-house hardware, i.e., the reference signal generator, modulator/demodulator, divider/combiner, detector and 2-MB RAM, while the serial I/O's are used for communication with VAX and the TR module controllers in the remote booths (paper 1). The transfer speed is 1200 baud.

The control and communication items are listed in Table 1, indicating the sophisticated architecture of the system control. The radar controller sends the control data concerned with transmission, reception, and data processing to the in-house equipment. The control data for the antenna are transferred to the 25 TR module controllers. During observation, the radar controller polls the TR-module controllers for monitor data from the TR modules. As mentioned above, the radar controller supervises the programs on VAX and transfers the observational parameters and name of the assigned data handling program to VAX.

The radar controller allocates the memories of the coherent integrator and the 2-MB RAM for different beams and RX channels, according to the number of FFT points, coherent integration times, and antenna beam steering mode being employed. The staggered sampling within a scattering volume is treated to appear as different beam directions in the memories. Twenty different methods of memory allocation are now feasible. Three beam modes are possible, i.e., fixed, steering every IPP (or every two IPP's), or steering after each FFT calculation. Due to hardware limitations in allocating the memories, the number of available beams is limited to 16 when both beam steering of every IPP and coherent integration are
TABLE 1. Radar Controller: Main Control and Communication Items

<table>
<thead>
<tr>
<th>Hardware</th>
<th>Items</th>
</tr>
</thead>
</table>
| In-house equipment (other than the data processing system) | TX signal control  
subpulse width  
modulator filter  
pulse compression code  
TX pulse sequence  
TX IF attenuation  
IPP  
phase flip  
RX signal control  
sampling start time  
sampling interval  
number of samples  
sampling staggering  
RX channel control  
channel grouping  
RX filter  
RX IF attenuation  
data processing control  
number of coherent integrations  
memory allocation for coherent integrator and 2-MB RAM  
number of FFT/ACF points |
| Data processing system | data handling programs  
observational parameters  
start/stop times |
| TR module | activation of TR modules  
antenna  
grouping  
beam direction  
polarization  
monitor data  
TX/RX amplitude and phase alarms  
power supply  
fan |

conducted. Otherwise, 255 beam directions are allowed.

Because the start/stop of any observation is executed with reference to the clock in VAX, the radar controller instructs VAX of the start/stop time to be used. Switchover to the different observational parameters stored in the radar controller disk can be performed automatically within a couple of minutes at scheduled times for successive observations.

5. PRELIMINARY RESULTS AND CONCLUDING REMARKS

In order to demonstrate that the MU radar functions properly, the radar-deduced winds are com-

Fig. 10. (a) Comparison of winds between the MU radar (solid line) and the rawinsonde launched by the Japan Meteorological Agency (JMA) from Shionomisaki (dotted line with circles) on June 1, 1984. The wind speed and direction are given following meteorological conventions. The MU radar operates with 19 subarrays. The MU radar wind velocity is averaged over a period while the rawinsonde stays in the height range observed. (b) Comparison of winds between the MU radar (thick line with horizontal bars) and a JMA routine rocket sounding at Ryori (thin line). The MU radar winds are averaged over 0613–1158 LT on June 21, 1984. The horizontal bars show wind variation around the averaged value. The observation day of the rocket differs by 1 day as indicated in the figure.
pared with the results of observations using con-
tventional meteorological methods. These observations
are conducted by using the 19 hexagonal subarrays
shown in Figure 3 of paper 1. The antenna beam is
steered every IPP sequentially in three different di-
rections, i.e., the zenith and 10° off from the zenith
toward the north and east.

Figure 10a compares a MU radar wind profile in a
height range of 5.4–24.5 km with that of a routine
rawinsonde launched by the Japan Meteorological
Agency (JMA) from Shionomisaki, approximately
150 km south of Shigaraki. The westerly (eastward
wind) is predominant throughout this height range.
The general agreement seems to be excellent between
the two, considering the distance between the two
observational sites.

In Figure 10b, the meridional and zonal wind ve-
locities obtained in a height range of 67–90 km are
compared with the meteorological rocket sounding
obtained by the JMA at Ryori, about 700 km to the
northeast. Although the two data patterns do not
overlap, the two profiles are likely to be continuous
from 60 to 70 km.

The final detailed examination of the functioning
of the various equipment is currently in progress.
Short-term preliminary observations are also being
conducted, early results of which show that the MU
radar is living up to the high standards of per-
formance specified by the design. Some of these re-
sults are presented by Sato et al. [this issue], by Wa-
kasugi et al. [this issue], and by Tsuda et al. [this
issue]. The system will begin nearly continuous op-
érations in the near future. It is expected that the MU
radar, being the first in the Asian sector, will reveal
interesting features of waves, winds, and turbulence
in the troposphere, lower stratosphere, and some re-
regions of the mesosphere and the ionosphere in this
part of the world.

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