Indian Journal of Radio & Space Physics
Vol. 13, December 1984, pp. 171-175

VHF MST Radar & Its Application to Cloud Physics*

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Received 9 *May* 1984

The mesosphere-stratosphere-troposphere (MST) radar technique and the associated principles and mechanisms underlying the signature of radar returns are briefly outlined. Some of the important applications of the VHF MSF radar to cloud physics research are reviewed. The possibility of studying the interactions between cloud dynamics and cloud microphysics—an aspect which needs immediate attention in the field of cloud physics—has been stressed.

1 Introduction

The coherent radar systems that can examine the troposphere, stratosphere and mesosphere are conveniently referred to as mesosphere-stratosphere-troposphere (MST) radars. The systems that can observe only the troposphere and lower stratosphere are referred to as stratosphere-troposphere (ST) radars, even though they use the MST technique[1]. These radars operate in VHF (30-300 MHz) and UHF(300-3000 MHz) ranges and are referred to also as VHF radars. The great advantage of MST radar technique over the other ground-based techniques, such as of meteor wind, laser and airglow, lies in the continuity of data in both time and height. The lower the frequency of the radar, the greater is the altitude from where detectable power is scattered. Also, the use of frequency in the VHF band makes possible the construction of these radars suitable for making studies in cloud physics at a cost that is low compared to the cost of more conventional radars employing dish antennas. The probing frequency for an MST radar should be necessarily below 100 MHz and frequencies below 50 MHz are recommended[2]. A 30 MHz lower limit has also been suggested to avoid the unwanted echoes from ionospheric reflections, round-the-world echoes and HF spectrum pollution.

During the past several years, conventional pulse Doppler radars have been used in cloud physics research[3-8]. Though these radars have been greatly improved from time to time by their unambiguous range and Doppler frequency measurements, they suffer from poor detectability of weak signals due to their low average transmitter powers. In the past decade, pulse Doppler radars have been made supersensitive in both experimental and data processing techniques[9-15]. In the last few years, a new generation of pulse Doppler radars has been developed that can routinely observe the three-dimensional wind velocity vectors, waves, distribution of turbulence and atmospheric stability from the boundary layer ($\simeq 1$ km) up to the turbopause ($\simeq 100$ km). Reviews of the extensive studies made with these radars have recently appeared[1,16-18]. Also, one special issue of a current periodical (Radio Science, March-April 1980) has been devoted to the various aspects of this new field.

An attempt is made in this paper to review the possibility of application of this sensitive radar and similar radars elsewhere to studies in cloud physics with particular reference to the study of the interdependence between cloud dynamical and microphysical parameters dealing with precipitation mechanisms. For this purpose, the MST/ST radar facilities currently available in the world, the principles and mechanisms involved in their echo-returns and their role in the studies relating to cloud physics are briefly summarized below.

2 Existing and Planned VHF MST Radar Facilities

A list of VHF MST radar facilities, with relevant parameters, existing and planned for atmospheric studies, throughout the world is given in Table 1. Very recently, MST radars have been sub-divided into two categories, viz. (i) Doppler and (ii) spaced antenna, depending on the type of technique employed in the system. In the case of MST system of Doppler type, the radar echoes are caused by refractive index irregularities in the clear air and the Doppler shift of the echoes is a measure of the wind component in the direction of the radar beam. The MST radar systems of spaced antenna type work at vertical incidence and the motions of irregularities are deduced by comparing the

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* Paper presented in part at the National Workshop on 'Atmospheric Studies Using High Power VHF Radar' held at Physical Research Laboratory, Ahmedabad, during 2-4 Feb. 1981.

Table 1—Available VHF MST Radar Facilities with Relevant Parameters

Facility	Location	Type	Frequency MHz	Average power aperture Wm^2	Beam width deg	Antenna configuration
Jicamarca	Peru	Doppler	49.9	2.0×10^{10}	1.00	Phased dipole array
Urbana	Illinois	Doppler	40.9	1.0×10^{10}	1.00	Phased dipole array
Poker Flat*	Alaska	Doppler	49.9	2.6×10^{9}	1.50	Phased dipole array
EISCAT*	N. Scandanavia	Doppler	224.0	2.0×10^{9}	1.90×0.58	Steerable parabolic cylinder
MU†	Japan	Doppler	48.0	5.0×10^{8}	3.00	Phased dipole array
SOUSY	Germany	Doppler	53.5	1.3×10^{8}	10.00	Phased Yagi array
Altair	Kwajalein	Doppler	155.0	1.0×10^{8}	2.80	Steerable dish
Chung-Li†	Taiwan	Spaced antenna/ Doppler	53.0	1.7×10^{7}	3.00	Yagi arrays
Sunset	Colorado	Doppler	40.5	5.0×10^{6}	5.00×9.00	Phased dipole array
Platteville	Colorado	Doppler	49.9	5.0×10^{6}	3.00×3.00	Phased dipole array
Adelaide†	Australia	Spaced antenna	54.1	2.7×10^{6}	3.20	Transmitter:Dipole array Receiver:Yagi array

* Under construction

† Planned

time variations of the amplitude pattern of backscattered radio waves sampled at a number of spaced antennas.

Almost all the systems listed in Table 1 are of Doppler type except some planned systems, one at Adelaide, which utilizes spaced antenna technique and the other at Chung-Li, which operates in both the Doppler mode and the spaced antenna mode. Application of the system based on Doppler technique to clear air studies in the height range 1-100 km has been documented well[1] whereas the potentiality of systems of spaced antenna type has to be examined further[19]. The more sensitive system at Jicamarca and the European Incoherent Scatter (EISCAT) facility have been designed primarily for ionospheric investigations. The other systems indicated in Table 1 have been or being developed/planned specifically as MST/ST radars.

3 The Indian MST Radar

The planned Indian MST radar, which is proposed to be installed near Tirupati, is essentially a VHP pulse Doppler radar similar to the one in operation at Poker Flat, Alaska. As the proposed site is near to SHAR Centre, it would facilitate well coordinated observations from ground and rocket borne experiments to study the atmosphere in detail. Some of the basic parameters of the planned Indian MST radar are given in Table 2. In view of quick commencement of scientific observational programme and easy maintenance, modular system design will be followed in the fabrication of this radar facility.

Table 2—Basic Parameters of the Planned Indian MST Radar

Location	: Vicinity of Tirupati (13°38′N;79°24′E)
Type	: VHF pulsed Doppler
Transmitter	
Frequency	: 53 MHz
Bandwidth	: 1 MHz
Peak power	: 2.5 MW
Average power	: 60 KW
Pulse width	: 1-32 μsec (in steps of 1 μsec)
Pulse repetition frequency	: 256 Hz-8 kHz (binary steps)
Duty ratio	: 2.5% (maximum)
Antenna	
Array configuration	: Rectangular
Element	: Coaxial-collinear
Aperture	: 21,000 m^2
Beamwidth	: $\simeq$2-3°
Polarizations	: Linear ×2
Beam directions (zenith angle)	: 0/±20°EW/±20°NS
Average power aperture	: 1.3×10^9 Wm^2

4 Principle and Mechanism of MST Radar Returns

All radar echoes in the 1-100 km height region may be thought of as arising from fluctuations of the refractive index in the spatial volume defined by the transmitted pulse width and the antenna beam. The factors causing these fluctuations include variations in humidity, temperature (and/or air density) and electron density.

The echo power at VHF, above the stratopause level, is from intermittent neutral turbulent fluctuations and is due to the presence of free electrons during the daytime whereas the echo power at UHF is due to only Thomson scatter from the free electrons. The enhanced VHF echoes that arise from stable, horizontally stratified atmospheric structure, when the radar beam is directed vertically, offer a means of studying atmospheric stability[20].

The Coherent radar echoes of the MST system are considered normally to be due to (i) the refractive index inhomogeneities in the troposphere mainly due to humidity and to some extent due to temperature variations, (ii) a variety of hydrometeors, (iii) quasi-specular reflections from stable layers, (iv) temperature fluctuations in the stratosphere and (v) ambient electron-density-induced refractivity gradients above 60 km. Analysis of the Doppler spectra of the scattered signals provides information on the dynamic properties of the atmosphere. The quantitative retrieval of the other meteorological information, such as, vertical wind, potential temperature gradients (which control atmospheric stability) are also possible.

There are three mechanisms which give rise to the signals observed on MST radars. These are (i) turbulent (non-thermal) scatter, (ii) Fresnal (partial or specular) reflection and (iii) thermal (incoherent or Thomson) scatter. Out of these, the turbulent scatter has a dominant role in the continuous measurement of winds, waves and turbulent structures at all heights. According to Rottger[20], the refractive index (n) of the atmosphere up to 100 km for VHF radar is given by

$$(n-1)=\frac{3.7\times 10^{-1}e}{T^2}+\frac{77.6\times 10^{-6}p}{T}-\frac{40.3\,Ne}{f^2}$$

where p is the atmospheric pressure in mbar, e is the partial pressure of water vapour (humidity) in mbar, Ne is the number density of electrons per m^3, and f is the frequency in Hz. The first two terms are due to the bound electrons inherent in the density variations of water vapour and dry air, respectively, whereas the third term is due to the presence of free electrons. Because of high humidity, the first term is more important from mid-troposphere up to the stratopause ($\simeq 50$ km). The third term plays an important role above 50 km from where the electron density increases with height.

5 Application to Cloud Physics

VHF MST radar has its use in cloud physics research and its related micro-and meso-scale meteorological studies[21]. It is known recently that feedback mechanisms exist between cloud microphysics and cloud dynamics and these mechanisms influence directly the chain of events leading to the developments of precipitation[22,23]. It should be possible with the help of VHF MST radar to study the interactions between cloud dynamics and its microphysics—an aspect which has been recognized to have a prominent role in the development of precipitation from clouds. Some of the important applications of this radar in this regard are outlined here.

5.1 Turbulence

The backscattered signal arises from irregularities in the refractive index of length equal to one half of the order of wave length. The amplitude distribution of the Doppler spectrum gives the measure of $\overline{Cn^2}$, i.e mean refractivity turbulent structure constant. The vertical profile of received power can be converted to a vertical profile of Cn^2. Satisfactory agreement has been reported between the vertical profile of Cn^2 as obtained with a VHF MST radar and the theoretical profile based on the rawinsonde observations[24]. It should be possible with such radar to obtain information on the dissipation rate, ε_d, and the diffusion coefficient, k_H, within and outside a jet stream or thunderstorm.

The microstructure of the atmospheric turbulence has been studied with the high sensitive SOUSY-VHF-radar, and is found to consist of sheets and layers of thickness 150 m between 15,400 and 15,700 m (Ref. 20).

5.2 Meso-scale Wind

5.2.1 *MST Radar Wind-Measurement Technique*—Doppler radars have been in use for about two decades as a research tool to study meso-scale atmospheric winds and associated phenomena. Most of these radars operate at microwave frequencies where they are sensitive to hydrometeors[16]. MST observing techniques vary with frequency. Radars which operate at UHF involve the use of steerable dishes (or fixed dishes with steerable feeds), and a number of scanning modes can be employed depending on the equipment. At VHF the use of steerable dishes becomes impracticable owing to the large aperture necessary to produce a beam width comparable to that of the UHF system. At these frequencies phased arrays consisting of either collinear arrays or Yagi-Uda antenna, become much more attractive. Steering is typically accomplished by electrically phasing the array elements. In some instances, fixed beams are used, since only three components of the radial motion of the irregularity structure are necessary to fully define the wind vector.

5.2.2 *Wind Variability*—Since MST radars are almost of continuously monitoring type, they provide very useful data for studying meso-scale wind variations in the atmospheric wind field. Many workers tested the accuracy of the MST radar measurements by comparing the vertical profiles of the radar-deduced horizontal wind in the troposphere and in the lower stratosphere with concurrent wind profiles from balloon sounding techniques and found fairly good agreement[10,14,15,25-29]. Recently, an extensive series of such comparison was made by Fukao *et al.*[30] between vertical profiles of horizontal winds measured with MST Doppler radar at Arecibo and rawinsonde-derived winds measured at some 80 km east of Arecibo. Fairly good agreement was noticed between these measurements. Also, studies recently reported[31] have shown that VHF MST radars are suitable tools for investigating and studying middle atmospheric dynamics during stratospheric warmings. The importance of the MST radar technique lies in providing information with greater frequency and accuracy over the conventional rawinsondes.

5.3 Vertical Air Motion

VHF MST radars are capable of measuring vertical velocities instantaneously and accurately by means of vertical pointing antenna. Contour plots of vertical velocities suggesting the occurrence of gravity wave oscillations, with a peak-to-peak amplitude of 0.4 m sec^{-1} and with periods near 5-10 min at levels up to about 11 km (tropopause level), have been reported[20] when a marginal jet stream was above the radar site.

It is possible to study the horizontal and vertical wind behaviour within and outside the convective clouds and storms. Time-height contour plots of vertical velocities, during a thunderstorm period, showing coincidence between the largest vertical air motion and thunderstorm active time have been reported[22]. Information regarding vertical air motions facilitates a more detailed understanding of the development in cloud microstructure.

5.4 Drop Size Distribution

The most exciting potential application of the MST radar technique is the simultaneous measurements of vertical air motions and hydrometeor fall rates, which are an index of drop size distribution, with VHF radar or VHF radar in combination with a conventional microwave radar. These measurements would be helpful in testing the results of various conventional Doppler measurements of precipitation fall rates. Under some atmospheric conditions like convective storms or clouds, the VHF MST radar alone would give the simultaneous measurement of vertical air motions and hydrometeor velocities. Such results have been reported[32]. There is a strong suggestion that VHF MST radar could portray echoes from precipitation also[21]. This aspect has to be fully explored to enable the VHF MST radar being used as a potential tool for the study of the physics and dynamics of clouds.

6 Conclusion

The different scattering and reflection mechanisms involved in the MST radar returns that help the understanding of turbulence, wind and stability characteristics of free atmosphere in the 1-100 km altitude region have been briefly discussed. Some important cloud physics applications of VHF MST radar are outlined. Studies reported in the field of cloud physics using such radar are limited. Currently, plans are in progress to have a VHF MST radar facility in India (Indian MST radar) also. With this sensitive radar facility in the offing, some of the crucial measurements like three-dimensional wind velocity vector, that are vital in the field of cloud physics research, would be possible. Such facility has the potentiality to generate data for the study of the interactions between cloud dynamics and cloud microphysics. The importance of this facility to the study of cloud physics should not, therefore, be lost sight of.

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