Indian MST radar – Mesospheric studies

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The National MST (mesosphere–stratosphere– troposphere) Radar Facility (NMRF) has been set-up at Gadanki (13.5°N, 79.2°E) near Tirupati, with a primary objective to study the atmospheric dynamical phenomena in the height region between ~ 5 and 100 km. The technical capabilities of the radar are briefly mentioned. Mesospheric observations and preliminary results using the Indian MST radar are presented. It is seen that the mesospheric echoes of the radar signals arise from two distinct height regions of 67–70 km and 72–76 km, with the latter being predominantly present. The turbulence centres responsible for enhanced radar backscatter signals from the mesosphere grow and decay with time periods of a few tens of minutes and with the typical occurrence periods of ~ 1 h. The spectral width and signal-to-noise ratio (SNR) are in general directly correlated, except for certain echoes which are very sharp and with very high SNRs generated from very thin layers. Further data being gathered for mesospheric studies would help in detailed characterization of the mesospheric echoes and understanding their causative mechanisms.

THE atmospheric dynamical phenomena including that of turbulence in the height regions of the stratosphere (~ 16–50 km over the tropics), mesosphere (~ 50–85 km) and the lower thermosphere (~ 100–180 km) are relatively less understood. Gravity waves, planetary waves and tides pervade these regions of atmosphere. Propagating vertically and horizontally, these waves dissipate, interact nonlinearly and greatly influence the transport of momentum, energy and chemical constituents. For example, tropospheric gravity waves generated by airflow over topographic features can propagate vertically through the stratosphere and dissipate within the mesosphere[1]. Breaking of these waves alters the global thermal and wind structures, producing a large mesopause (~ 85 km) temperature anomaly (cold summer pole and warm winter pole). A more complete understanding of wave formation, propagation and dissipation is one of the major goals of present-day middle and upper atmospheric science. Also ionization irregularities in the mesosphere caused by neutral turbulence have been observed using rocket-borne techniques from Thumba (8.5°N, 70.8°E)[2,3].

The Mesosphere–Stratosphere–Troposphere (MST) radar is a powerful ground-based technique to study the three-dimensional characteristics of the atmospheric dynamics and turbulence phenomena[4]. Such radars have been particularly useful in delineating the characteristics of waves and wave dissipation in the Mesosphere–Lower Thermosphere (MLT). MLT acts as the key transition region between the lower atmosphere, associated with the weather phenomenon and the upper atmosphere associated with space flights. The complex dynamics and energetics of the MLT are controlled by coupling processes that are highly variable in both time and space. Large variability in the mesospheric radar signals has been observed by the MST radar facilities, distributed mainly over the polar and middle-latitude stations of the world[5–10]. Table 1 shows that apart from the Indian MST radar, the Jicamarca (12°S, 76.9°W) radar is the only facility situated over the low-latitude region and the data have been used to study the turbulence structure and dynamics of the mesosphere[11–13]. In order to establish the structure and variability of mesospheric turbulence and dynamic phenomena over the low-latitude region, there is a need for additional observational data from other low-latitude stations. The relatively new and highly sophisticated MST radar facility established at Gadanki near Tirupati (13.5°N, 79.2°E) provides an excellent opportunity to fill up this gap to a large extent and to investigate the features of low-latitude mesospheric turbulence and dynamical processes over the Indian region[14,15].

In this paper, preliminary results of the daytime observations of mesospheric back-scattered signals over Gadanki and their comparison with similar results obtained using MST radars over other parts of the world are presented, with special reference to the characteristics of turbulence in this region.

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MST radar at Gadanki

In the MST radar technique the Doppler power spectrum height profile of the radar backscattered signal from clear

Table 1. List of MST radars operating over low, middle and high latitude stations

Facility	Location	Frequency (MHz)	Power aperture (Wm^2)	Antenna configuration
Jicamarca, Peru	12°S, 72°W	50	3.26×10^{11}	Phased dipole array
Gadanki, Tirupati, India	13°N, 79°E	53	8.33×10^{8}	Crossed three-element Yagi
Arecibo, Pureturico	19°N, 67°W	47	2.5×10^{9}	Steerable dish/steerable feed
Shigaraki, Japan	35°N, 136°E	47	8.33×10^{8}	Circular phased array of crossed Yagi antennas
Aberystwyth, United Kingdom	52°N, 4°W	47	1.9×10^{9}	Phased array of four-element Yagi antennas
SOUSY, Germany	52°N, 10°E	54	1.92×10^{9}	Phased Yagi array
Poker Flat, Alaska	65°N, 147.5°W	50	5.1×10^{9}	Horizontal phased array of four quadrants of orthogonal coaxial–collinear dipoles

air provides vital information on the nature of radar scattering centres, atmospheric turbulence and atmospheric wind/wave patterns in the height range of ~ 5–100 km. In the absence of any signal echo, the main contribution to noise is the radio noise from our galaxy. Hence there is a threshold value of the noise level above which the signal fluctuations are considered for further analysis.

The average radar return echo power received from the mesosphere region is several orders of magnitude weaker compared to those from the troposphere and stratosphere. MST radar technique is not suitable to study the atmospheric height region between ~ 25 and 60 km due to near absence of radar backscatter signals, attributed mainly to the lack of presence of refractive index structures in this region. Such structures in refractive indices are prevalent in the troposphere (0–16 km) and remaining part of the middle atmosphere, i.e. between 16–25 km and 60–85 km, due to the influence of turbulence on atmospheric humidity, temperature or ionization. These variations are required to produce the radar backscatter signals. The radar return echoes from the mesosphere show considerable temporal and spatial variations, indicating the transient nature of the atmospheric turbulence in this region.

The MST radar at Gadanki is a pulsed Doppler radar operating at 53 MHz, with a peak transmitted power of 2.5 MW. The radar power aperture product of ~ 10^9 Wm^2, which is the measure of its sensitivity, is obtained by using a 32 × 32 array of 3-element Yagi antennas covering an area of 130 m × 130 m. The radar beam width is a narrow pencil beam of 3°, which through appropriate phasing of signal to different parts of the array, can be tilted from the zenith up to a maximum of ± 20° in the E–W and N–S planes.

The Inter Pulse Period (IPP) and the pulse width of the transmitted signals can be varied to cover different height ranges in the middle atmosphere and obtain different spatial (height) resolutions, for example, 150 m, 300 m, 600 m, 1.2 km and 2.4 km, corresponding to pulse widths of 1 μs, 2 μs, 4 μs, 8 μs and 16 μs, respectively. An IPP of 1 ms ensures covering the height region up to 100 km, without interference due to range aliasing. The IPP can be suitably altered to cover various height regions of the atmosphere. A complete description of radar specifications is given by Rao *et al.*[16]. A simplified and self-explanatory block diagram showing the MST radar system is given in Figure 1.

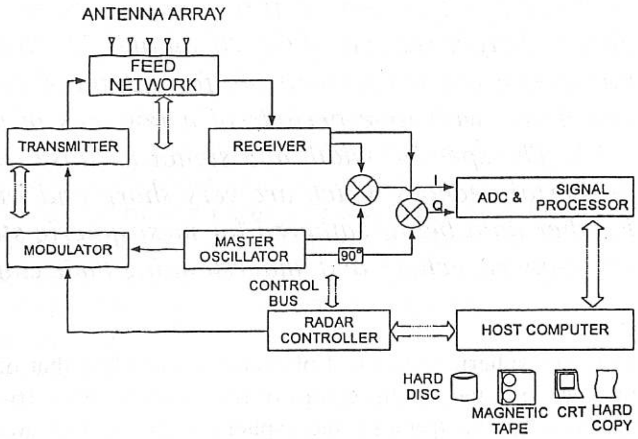

Figure 1. Simplified block diagram of the MST radar at Gadanki.

Mesospheric observations and analysis technique

The results presented in this paper are obtained by analysing the MST radar observations at Gadanki for 5 days during August–September 1995–1996 and hence are only indicative and preliminary. The observations were carried out so as to cover the mesospheric height range between 60 and 95 km, with varied height resolutions between 150 m and 1.2 km for zenith and 10° off-zenith N-S-E-W beam directions. The ranges for off-zenith signals are corrected to compare with range bins in the zenith direction. Each day's data spanned between ~ 1000 and 1600 h, with each cycle of observation lasting for about 100 to 180 s depending on the height resolution and the number of range bins. The Doppler spectra of each range bin of each cycle (raw data in this case) are scanned to select only those which have clear indications of detectable signal, which normally corresponds to a SNR better than – 14 dB. Hence computer-interactive selection of the useful Doppler spectra is carried out resulting in considerable compression of raw data. Finally, only a very small fraction of the total number of observation cycles is retained as a result of this screening of data and the remainder mainly contains noise.

Figure 2 shows two examples of Doppler spectra observed during August–September 1995–1996, over Gadanki in the mesosphere for the vertical radar beam direction. The abscissa shows the Doppler frequency and the ordinate, the return echo power in arbitrary units. The display indicates existence of narrow and broad frequency spectra occurring at different height regions. The characteristic width of the Doppler spectra can be determined and related to the type of turbulence.

The selected data sets mentioned above and separated for different beam directions are used for further analysis. The return echo power received by the radar from clear air turbulence is generally given by[17]

$$P_r = \frac{P_t A_e \pi \Delta r \alpha^2 L}{64 r^2} \eta,$$

where α denotes the efficiency factor, P_t the transmitted power, A_e the effective area of the antenna, r the range, Δr the range resolution, L the antenna loss factor, and η the radar scattering cross-section per unit volume of clear air. The Doppler power spectrum is used to compute the low-order spectral moments called as 0th, 1st and 2nd moments, respectively. The moments are expressed as[4,18]

$$m_0 = \int F(\omega)\, d\omega,$$

$$m_1 = \int \omega F(\omega)\, d\omega,$$

$$m_2 = \int \omega^2 F(\omega)\, d\omega,$$

where $F(\omega)$ is the Doppler power frequency spectrum of the linearly-detected scattered wave and ω is the radian frequency. The three important physical properties of the medium – the signal power, P_S, the mean Doppler frequency shift, Ω and the width of the frequency spectrum, σ, are directly related to the first three moments of the frequency spectrum as follows:

$$P_S = m_0,$$

$$\Omega = \frac{m_1}{m_0},$$

$$\sigma^2 = \frac{m_2}{m_0} - \frac{m_1^2}{m_0^2}.$$

The echo power obtained from the 0th moment is a measure of the strength of scattering/reflecting layer in the atmosphere, the Doppler frequency shift, i.e. the 1st moment provides the radial velocity of scatterers and the spectral width estimated from the 2nd moment is a measure of the magnitude of atmospheric turbulence. Broader spectral widths generally indicate presence of stronger turbulent scattering, whereas narrow spectral widths of intense signals indicate Fresnel reflection from sharp gradients of electron density[19]. The width of the Doppler spectrum gets obliterated by the horizontal motion of the scatterers. Hence necessary corrections are applied to determine the actual spectral width, by removing the variation in spectral width caused by horizontal motion of the scatterer[20,21].

Results

The observations on all the five days, i.e. 5–7 September 1995, 12 August 1996 and 20 September 1996 show the following common features:

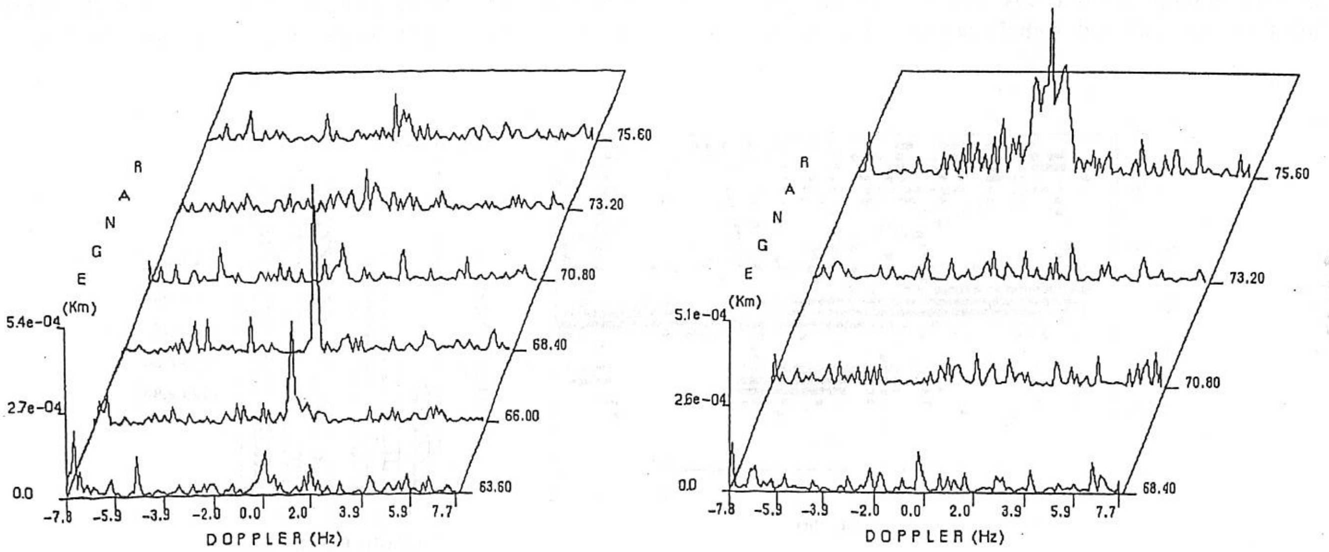

Figure 2. Examples of Doppler spectra as function of range in the zenith beam direction observed recently by the Indian MST radar at Gadanki (29 January 2001), at two different times.

- Above noise level, radar signals from the mesosphere are normally received only from a few of the total 25 range bins between 60 and 90 km, for a pulse width of 8 μs (1.2 km).
- The radar backscatter signals from a few range bins are observed intermittently. Out of about 530 scans of data during the above days of observation, only 48% had detectable echoes in some range bins in the mesosphere at least in one beam direction and about 5% detectable echoes were observed simultaneously in all beam directions.
- There is lack of correlation between returned signals received from different radar beams. For example, within the same radar scan of ~ 100 s duration, return signals are generally not received at all from the beam directions, indicating the common nature of intermittence of the low-latitude mesospheric echoes. Also returned signals often do not persist in successive radar cycles over the same beam directions. However, on some occasions the echoes may persist for longer periods in one beam direction.
- A marginally higher than unity value of aspect sensitivity (ratio of vertical to off-vertical return echo power) has been observed in the signals returned from the mesospheric heights, indicating a possible tilt in the horizontal layer of irregularity structures.

In order to get an idea of height distribution of the detectable returned echoes in the mesosphere, all such events irrespective of beam directions are collected for all the 5 days of observations and presented as a scatter plot in Figure 3. The radar signals from the mesosphere appear to be scattered in a random fashion, except that a major fraction of the echoes are generated from narrow height regions of 72–76 km and 67–70 km. The associated histograms show day-to-day distribution of these scattering regions. Except for one day, i.e. 12 August 1996, when most of the scattered signals originated from the lower mesosphere 67–70 km, the main scattering region is seen around 72–76 km on other days.

The contour diagrams of return echo power observed in the height range 65–85 km on 7 September 1995 for the vertical and one of the off-vertical (east) beams are shown in Figure 4. It can be seen that in both the beam directions, radar signals are mainly returned from 72 to 76 km altitude. From the continuous time series of radar backscatter data, it is also seen that these scattering regions develop, reach the peak and decay within a short period of ~ 15–20 min. Another scattering centre often develops with a periodicity of 30–50 min. It can also be seen that the scattering centres have a downward movement from morning towards evening, which is attributed to the downward shift of the *D*-region electron density structures with the progress of the sun's transit.

The broad features of the above-mentioned characteristics of mesospheric scattering of MST radar signals have been studied using the spectral width of the detectable radar echoes. The spectral widths for all significant echoes occurring between 67 and 77 km for zenith direction have been corrected, taking into account the beam-broadening effect. Figure 5 shows a plot of the SNR with corrected spectral widths for all the days of observation. In general, an increase in SNR with increasing spectral width is noticed. However, there are significant number of points with high SNR and narrow spectral widths. The direct correlation between SNR and spectral width indicates that the mesospheric echoes are affected by the neutral turbulence leading to enhanced scattering of radar waves, due to variations in the spatial structure of electron density irregularities. Presence of sharp electron density layer provides very strong return signals with narrow spectral widths, where this correlation breaks down. In the mesosphere, the collision frequency between the electrons and neutral atmospheric molecules is very high and hence the turbulence generated in the neutral atmosphere is manifested in the electron density distribution.

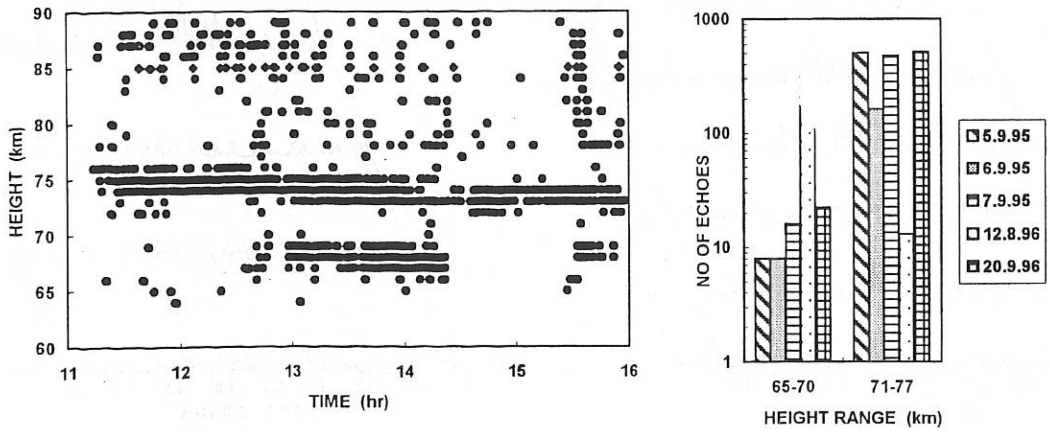

Figure 3. Scatter plot of detectable return echoes in the mesosphere for all observation days and histogram showing day-to-day distribution of the scattering regions.

Discussion

The characteristic features of the radar backscatter from the mesosphere observed over Gadanki are, in general, similar to those seen by the Jicamarca radar[4,11–13]. Both these low-latitude stations show intermittent signals from the mesosphere, with preferred height range around 72–76 km. On some occasions, Gadanki shows enhanced back-scattered signals from a lower height range around 67–70 km. The average aspect sensitivity (with respect to 10° beam angle in off-vertical direction) of the echoes from around 75 km is nearly equal to unity, indicating no significant preferred direction of turbulence for these beams or tilt in horizontal layers of turbulence being minimum. Dominant presence of thin layers of electron densities would otherwise have given a high value of aspect sensitivity. The results from Gadanki radar also shows periodic nature of generation and decay of scattering centres or irregularities governed by atmospheric turbulence. The periodicity of generation of these turbulence centres varies between 30 and 50 min. The vertically propagating gravity waves in the mesosphere also have similar periodicities[22] and these may dissipate in the mesosphere, producing the turbulence centres. From the intermittent nature of the return signals in spatial directions, it is inferred that in general, the turbulence-generated fields have horizontal scales less than ~ 25 km in the height range ~ 70–80 km. The results on the time scales of the scattering centres, i.e. their generation, decay and frequency are presented for a low-latitude station.

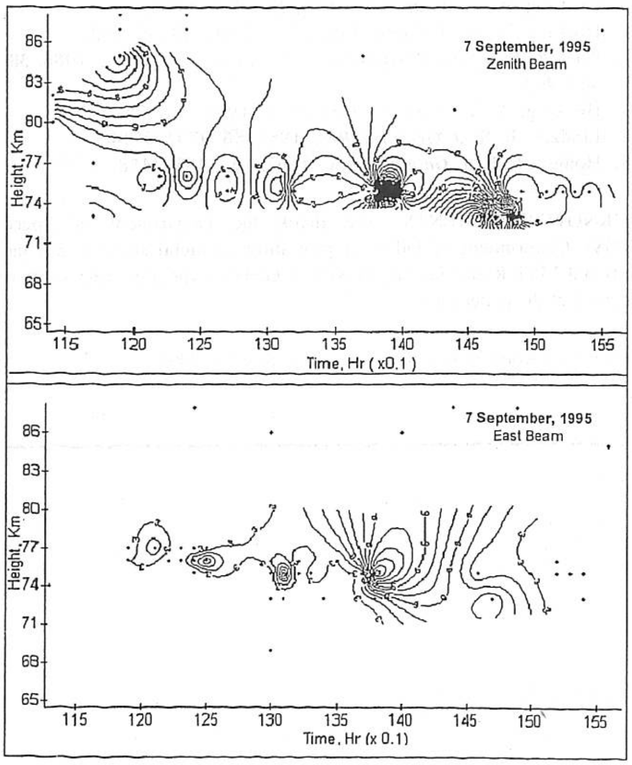

Figure 4. Contour diagrams of return echo power observed in the height range 65–85 km on 7 September 1995, for zenith and east beams.

At middle and high latitude regions, the MST radar observations of mesospheric backscatter signals have been made by using facilities in USA (Poker Flat radar)[5,6], Germany (SOUSY radar)[7], Japan (MU radar)[8,9], UK (Aberystwyth radar)[10], etc. In many of these stations, (i) strong spectrally narrow echoes owing to reflection from sharp and thin layers around 80–85 km are observed during summer months, called Polar Mesospheric Summer Echoes (PMSE); and (ii) spectrally broad and weaker echoes with characteristics consistent with isotropic turbulent scatter occur during other seasons at mesopause and lower mesospheric regions (as in the case of Gadanki radar). The PMSEs are very strong and continuous in nature and are associated with steep gradients of electron densities caused by a decrease in electron–ion recombination coefficient values. The decrease takes place mainly due to the fast reduction of water cluster heavy ions above ~ 80 km. Due to the very cold mesopause over the polar region in summer months, sharp gradients of electron densities are formed from water cluster heavy ions. In the absence of such cold mesopause over the tropics, PMSE type of echoes are rarely observed in the height range of 80–85 km located at Jicamarca or at Gadanki.

The gravity waves are generated in the troposphere due to various meteorological processes such as mountain lee waves, jet streams, weather fronts, convection, etc. The periods of these waves vary from a few minutes to about 8–10 h, depending on the variations governed by tropical convective systems, strong wind shears such as jet streams, etc. As the wave trains with different periodicities move in the horizontal direction, the vertical phase propagates downwards and energy, upwards. The height to which these waves penetrate into the mesosphere/thermosphere depends upon their vertical wavelengths. Larger the vertical wavelength greater is the penetration height[23]. The mesospheric radar echoes observed both at

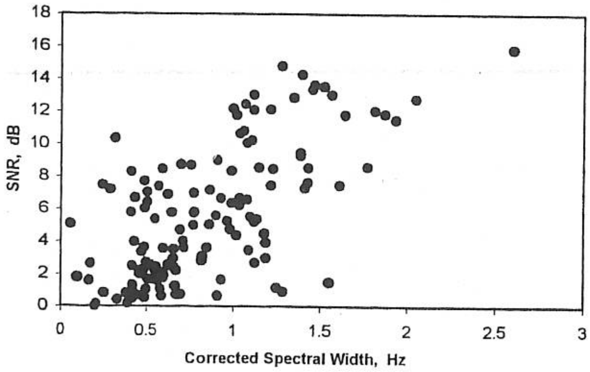

Figure 5. SNR of significant mesospheric echoes plotted as a function of spectral width covering the height range 67–77 km for the zenith beam for all observation days (5–7 September 1995, 12 August 1996 and 20 September 1996).

high and low-latitudes, i.e. PMSE at high latitudes during summer and the prominent ~ 75 km scattering layer seen over low-latitudes are produced due to the irregularities in the refractive index of the mesosphere at the half radar wavelength (~ 3 m), which is influenced by the dissipation of atmospheric turbulence resulting from wind shear or gravity wave breaking and the *D*-region electron density gradients[24,25].

Conclusion

Preliminary results of mesospheric echoes obtained using the Indian MST radar show the consistent presence of a lower mesospheric VHF scattering layer between 72 and 76 km. Sometimes, another significant layer at a lower height of 67–70 km is also observed. There is a considerable variation in the height of the maximum of radar backscatter in the mesosphere from one day to the other. The diurnal time series of SNR covering the strong echoing layer at 72–76 km shows periodic variations, which are attributed to the generation and decay of neutral turbulence leading to changes in refractive index of the medium at a spatial scale of half the radar wavelength. The neutral turbulence itself is intermittent, possibly due to the transient nature of gravity wave energy dissipation. These mesospheric results over Gadanki compare well with similar observations over Jicamarca, the only other low-latitude station in terms of the transient nature of mesospheric echoes and the height of occurrence of prominent scattering layer in the mesosphere. Further, analysis of voluminous data being collected over Gadanki may provide interesting insight on the low-latitude mesospheric turbulence and VHF scattering phenomena under different geophysical conditions.

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