Short-period waves in the vertical wind using the Indian MST radar

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The Indian Mesosphere-Stratosphere-Troposphere (MST) radar, installed at Gadanki (13.47°N, 79.18°E), near Tirupati, Andhra Pradesh, was operated in the ST mode during February-March 1992. One of the objectives of this operation was to study the short period waves in the vertical wind velocity in the tropo-stratosphere regime. The direction of the antenna beam was pointed vertically toward zenith and the observations were taken with 150 m range resolution for two hours (1430-1630 hrs IST) of radar time daily for five days (24-26 February and 23-24 March 1992). The data were stored on the magnetic tape for off-line processing. A quick fit algorithm was developed on VAX 11/780 computer to analyse the stored data for obtaining vertical wind velocity from the Doppler shift. Spectral analysis of the time series of vertical wind velocity showed that the peak of the short period waves vary between 4 and 24 min in the lower troposphere (3.15-10.0 km). Mostly, the dominant period lies in 4-8 min or 14-24 min. However, in the upper troposphere (14.0-19.0 km), waves with 4-7 min periodicities are dominant. The region between 10.0 and 14.0 km could not be studied due to very weak echoes. The Brunt-Vaisala (BV) period was also computed using the radiosonde data taken from Madras, a nearby IMD station. The BV period in the lower troposphere shows wide fluctuations, varying between 5 and 18 min. However, in the upper troposphere, it is between 4 and 7 min and in good agreement with the radar measurement.

1 Introduction

The Mesosphere-Stratosphere-Troposphere (MST) radar technique, pioneered by Woodman and Guillen, has provided the capability of direct measurement of small vertical velocities in the middle atmosphere. Such measurements are vitally important for an improved understanding of many dynamical processes, including troposphere/stratosphere exchange and the vertical transport of heat, energy and momentum by waves. It has several other applications in a number of problems in the atmospheric sciences, ranging from short-term weather forecasting to long-term vertical transport of trace constituents. Several MST/ST radars are now operating at different places in the world, but these are mostly located at mid- and high latitudes. However, the atmospheric dynamical processes near the equator are quite different from those at mid- and high latitudes. For example, a number of vertically propagating long-period-wave modes are theoretically permitted only at near-equatorial latitudes. An additional unique feature of the low latitude atmosphere involves the vertical transport properties associated with the intertropical convergence zone (ITCZ) and large scale Hadley cell circulation. The macroscopic circulation associated with tropical monsoons is still another low latitude phenomenon that requires extensive study. In view of these challenging research problems an MST radar has been installed in Gadanki (13.47°N, 79.18°E) near Tirupati, Andhra Pradesh. The radar operates at a frequency of 53 MHz and with a peak power aperture product $3 \times 10^{10}$ Wm$^2$, which is quite adequate for the above mentioned study. The radar has five beams, namely, zenith, $\pm 20^\circ$ off zenith in N-S directions and $\pm 20^\circ$ off zenith in E-W directions. With these five beams it is possible to check the assumption of spatial homogeneity. In addition to these beams, an additional sixth beam is provided by pointing the antenna beam northward with zenith angles of $14^\circ$. It is possible to achieve or-

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thogonal intersection with geomagnetic field lines and, hence, to measure characteristics of field-aligned irregularities in both the E- and F-regions. The Scientific Advisory Council of the MST radar made an announcement in September 1991 to utilize the radar in the ST mode and invited proposals from different laboratories, universities and institutions for conducting experiments. In response to this announcement, a proposal was submitted to study short period waves in the tropostratosphere regime by measuring the vertical wind velocity with the antenna beam directed vertically towards zenith. This proposal was approved and the experiment was conducted in the afternoon of five days during February-March 1992. In this paper, the results of these experiments are presented.

2 Experimental set-up
The radar was used in the ST mode with an average power aperture product of \(4.8 \times 10^6\) Wm\(^2\) and beam width of 4.6\(^\circ\). The radar has a phased array with 256 crossed Yagi elements. The same antenna was used for transmitting and receiving the pulses. Its recovery time was about 8 \(\mu\)s, which sets the lowest usable radar range to about 1.20 km. Only the vertical beam data were gathered in this study.

The observations were taken for two hours (1430-1630 hrs IST) of radar time for five days (24-26 Feb. and 23-24 Mar. 1992). The transmitted pulses of 16 \(\mu\)s were coded with baud length of 1 \(\mu\)s and a duty ratio of 1.6\%. The specifications of the experiment are given in Table 1. These sampling rates were sufficiently fast to discriminate the most rapid wave motions. The data were stored on magnetic tapes for off-line processing.

3 Method of analysis
The above measurements recorded power spectrum of the echoes returned to the radar as a function of range. The spectrum (relative echo power density versus Doppler shift) contains information on various parameters, including the total received power, the mean Doppler shift of the signal, and the distribution of velocities about the mean value (spectral width). A sample power spectrum obtained from the radar in the ST mode, indicating the positive Doppler shift, is shown in Fig. 1. The power spectrum showed a Gaussian distribution.

For off-line processing, a quick fit algorithm was developed on VAX 11/780 computer at the National Physical Laboratory, New Delhi.\(^7\) The procedure for parametrization of the spectrum in terms of the first three moments adopted is similar to the one for the Poker Flat radar\(^8\). The first three moments (zeroth, first and second) of the spectra are directly related to the echo power, the mean Doppler shift of the signal and the spectral width, respectively.\(^1\) It also gives signal-to-noise ratio (SNR). Figure 2 contains the height profiles of each parameter, namely, echo power, Doppler shift, spectral width and SNR. In addition, 2d1 plot software was also developed. In this software, the peak amplitude of power spectrum at every

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**Table 1 – Specifications of the experiment**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam used</td>
<td>Z, (Z_r)</td>
</tr>
<tr>
<td>Spectra</td>
<td>Doppler power</td>
</tr>
<tr>
<td>Observation interval from one beam to another beam</td>
<td>36 s</td>
</tr>
<tr>
<td>Transmitted pulse</td>
<td>16 (\mu)s (coded)</td>
</tr>
<tr>
<td>Inter-pulse period</td>
<td>1000 (\mu)s</td>
</tr>
<tr>
<td>Coherent integration</td>
<td>256</td>
</tr>
<tr>
<td>No. of FFT</td>
<td>128</td>
</tr>
<tr>
<td>Range resolution</td>
<td>150 m</td>
</tr>
<tr>
<td>Height coverage</td>
<td>3.6-22.8 km</td>
</tr>
<tr>
<td>Nyquist frequency</td>
<td>1.953 Hz</td>
</tr>
<tr>
<td>Doppler frequency resolution</td>
<td>0.0305 Hz</td>
</tr>
<tr>
<td>Maximum velocity</td>
<td>5.52 ms(^{-1})</td>
</tr>
<tr>
<td>Radial velocity resolution</td>
<td>0.086 ms(^{-1})</td>
</tr>
<tr>
<td>Duration of observation</td>
<td>2 h</td>
</tr>
</tbody>
</table>

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![Figure 1 – Sample of power spectrum obtained at 4.20 km from the MST radar in the ST mode on 23 Mar. 1992 at 14:32:07 hrs IST [The antenna was pointed at zenith (x-polarization).]](image-url)
range bin was normalized, as demonstrated in Fig. 3. The Doppler shift variation with altitude can be noticed from Fig. 3.

Using this algorithm, the mean Doppler shift of the received signal (which is directly related to the line-of-sight velocity of the medium) was estimated as the first moment of the power spectrum. It was converted to the vertical velocity of wind by multiplying with one half wavelength of the transmitted frequency. The data were recorded as function of radar range which was converted to height above mean sea level (m.s.l.) using the equation:

\[ h = (r - r_b) \cos \psi + h_s \]

where \( h \) is the height from m.s.l., \( r \) the range, \( r_b \) the range bias (\( = 1.0 \) km), \( \psi \) the zenith angle and \( h_s \) the height of the radar site above m.s.l. (\( = 0.40 \) km). The height mentioned in the text hereafter is to be taken as the height above the mean sea level.

Time series of the vertical wind velocity were obtained from mean Doppler shift. Two regions were selected for the analysis, one between 3.15 and 10.00 km and the other between 14.00 and 19.00 km. The region between 10.00 and 14.00 km could not be studied due to very weak signal in this range. In the regions studied, if a range bin had an SNR of less than \(-10\) dB, then that range bin was discarded. The data gaps were filled by interpolation (using Lagrangian formula) around the missing point using a five degree polynomial. Before taking the Fast Fourier Transformation (FFT) analysis, the time series of the vertical wind velocity are reduced to zero mean to eliminate linear trend. To lessen the effect of discontinuities, the end regions were made to have smooth transition to the mean of the measured value by multiplying the sequence of the vertical wind data with the 'weights' of a suitable data window. The adopted window is called a 'Cosine Bell' window applied to the first and last 10% of the data. The weights are defined by:
Fig. 3 - Doppler shift versus altitude measured by MST radar in the ST mode on 23 Mar. 1992.
[Antenna was pointed at zenith (x-polarization). The numbers on LHS of the graph are altitudes in
km from radar site.]
where, \( L \) is the length of the data and \( f \) the desired fraction (usually 0.1).

The tapered series are extended by adding zeros towards the end to bring the number of data points equal to \( 2^k \), where, \( k \) is an integer whose magnitude depends on the length of the data series. Then the FFT analysis is applied to obtain the spectrum of this time series. A final smooth estimate of the spectra may now be found by further frequency smoothing with a procedure called 'Hanning' as follows:

\[
\hat{G}_k = 0.25 G_{k-1} + 0.5 G_k + 0.25 G_{k+1} \quad \text{ ... (2)}
\]

where, \( k = 1, 2, \ldots, (m-1) \) and \( \hat{G}_k \) represents a smooth estimate at harmonic \( k \) to reduce the error due to truncation.

### 4 Results

The vertical wind velocity versus time plots at different altitudes in lower and upper troposphere are shown in Figs 4 and 5. In the upper troposphere between 14.0 and 19.0 km, only those range bins were analysed where the SNR was more than \(-10\) dB and had almost continuous data. One or more range bins were used to get an averaged time series of vertical wind velocity. This number is mentioned in the bracket on y-axis of Figs 4 and 5. The purpose of taking an average of these range bins, was to see the consistency in the wave periodicity. The amplitude spectra obtained from FFT for the above mentioned time series are shown in Figs 6 and 7 for the lower and the upper troposphere, respectively. From Fig. 6, it can be noticed that the peak of the spectrum lies at about 18 min in the first two ranges (4.20 and 4.95 km). Above that the peaks of the spectra shift towards lower periods. Again above 7.20 km, the peak of the spectra shifts towards higher periods. From Fig. 7, the peak of the spectra can be noted to be at about 4-7 min in the upper troposphere.

Figures 8-11 show the wave period profiles, obtained by applying FFT at every range bin (without averaging any range bin), with a 150-m altitude resolution. It is observed from the Figs 8-11 that the peak period of the waves varies between 4 and 24 min in the lower troposphere (3.15-10.0 km) but most of the time it lies between 4 and 8 min or 14 and 24 min. In the upper troposphere, the waves of 4-7 min period are dominant.

We have compared the above periodicities with the Brunt-Vaisala (BV) period. This is the period at which a parcel of air displaced vertically will oscillate under the influence of gravity neglecting the effect of viscosity. This is also the short-period cut-off for internal gravity waves. The BV frequency, \( N \), in radians per second is given as

\[
N^2 = g/\theta(d\theta/dz) \quad \text{ ... (3)}
\]

where, \( \theta \) is the potential temperature [\( \theta = \gamma(1000/\text{ALT}) \)].
\( P^{2/7} \), where, \( P \) is the atmospheric pressure in mbar and \( T \) the absolute temperature; \( g \) the gravitational acceleration and \( z \) the vertical coordinate. All the above parameters can be obtained from the radiosonde data. In the present calculation, the radiosonde data of four days taken at every 1 min interval from Madras, a nearby IMD station, are used to get the profiles of the temperature and the potential temperature as shown in Figs 12-15. It gave height resolution of 300 m in the lower troposphere and about 400 m in the upper troposphere. The computed frequency, \( N \), is converted into BV period. The BV period profiles are also shown in Figs 8-11. It is to be noted from Figs 8-11 that the BV periodicities of 5-18 min with wide fluctuations are seen in the lower troposphere, while, in the upper troposphere, 4-7 min periodicities of the waves are seen. In the middle troposphere (between 10.0 and 14.0 km), the BV periodicities of about 10-20 min are noticed (Figs 8-11). This region could not be studied by the radar as mentioned earlier.

![Fig. 6 - Amplitude spectra obtained after FFT of the averaged time series of vertical wind velocity in the lower troposphere.](image)

![Fig. 7 - Same as Fig. 6, but for upper troposphere.](image)

![Fig. 8 - Short period waves-height profiles obtained from MST radar in the ST mode and radiosonde data at Madras on 23 Mar. 1992.](image)
The short period waves obtained from the MST radar and radiosonde data show good agreement in the upper troposphere. However, in the lower troposphere, the periodicities of the waves are not matching at specific heights. The nature of the short period waves profile is, however, nearly the same for both the measurements, except in the region 3.15-5.55 km. In the region of 3.15-5.55 km, the periodicity of the short period wave is larger as compared to the radiosonde measurements.

The cross-correlation technique has been also applied to the averaged time series of vertical wind velocity at several altitudes. Figure 16 shows the cross-correlation seen between 4.20 km altitude time series of the vertical wind velocity and other time series at higher altitudes. This altitude is mentioned on the y-axis of the left hand side of the plots. From Fig. 16, it can be seen that the periods of the vertical wind velocity have significant correlation at neighbouring altitudes. This correlation vanishes as the range between the two altitudes increases.

5 Discussion
Observations of vertical wind velocity by VHF radars have also been made in the past at several locations. Rottger, for example, took continuous measurements of vertical wind, with the SOUSY-VHF-Radar for a 50-min period, around noon on

Fig. 9 - Same as Fig. 8, but for 24 Mar. 1992

Fig. 10 - Same as Fig. 8, but for 24 Feb. 1992

Fig. 11 - Same as Fig. 8, but for 25 Feb. 1992.

Fig. 12 - Temperature and potential temperature profiles obtained from the radiosonde data taken at every 1 min interval from Madras, a nearby IMD station.
20 June 1978. A marginal jet stream above the radar site was then present. He noticed that waves with periods near 5-10 min occur at levels between 9.0 and 11.0 km, but below 9.0 km, the velocity fluctuations showed no distinct periodicities. Observations of the vertical winds in the altitude range 3.9-19.7 km were taken by Ecklund et al.\textsuperscript{12} over a 30-day period using the MST radar at Poker Flat, Alaska. They noted that the short period waves in the vertical wind velocity occasionally show very regular sinusoidal oscillations with periods varying from 5 to 30 min. Typically the vertical velocity fluctuations are irregular with no well-defined oscillation. Ecklund et al.\textsuperscript{12} have also presented the results of vertical motions during the Alpex experiments under very quiet conditions. Their observations represent temporal intervals of 2-3 days and spatial intervals between 3.9 and 6.1 km in the troposphere and between 10.6 and 12.9 km in the stratosphere. They have found that the spectra have a pronounced peak near 13 min on tropospheric spectrum and at \( \sim \) 5 min on the stratospheric spectrum. Cornish\textsuperscript{13} discussed the vertical wind velocity measurements...
taken with the Arecibo 430 MHz radar. He noted that the waves with periods in the range of 5-10 min are evident in the region of 15-22 km which covers the upper troposphere and the lower stratosphere. He also calculated the BV period from radiosonde data measured at San Juan, located 90 km east-northeast of Arecibo and found 4-6 min periodicities for the same region. Pandey and Mahajan\(^1\) analysed the data taken from Poker Flat MST radar covering 4-day period from 31 Jan.-3 Feb. 1982. The study was restricted only to four heights, namely, 10.3, 12.5, 14.7 and 16.9 km. It was noticed that there was some evidence of occasional sinusoidal oscillation ranging from about 5 min to 15 min. The present results are found to be in good agreement with those observed with other radars for the upper tropospheric heights. However, in the lower troposphere, the agreement is only fair.

6 Summary

Spectral analysis of radar measurements at Gadanki have shown that the peak period of the waves varies between 4 and 24 min in the lower troposphere (3.15-10.0 km) but most of the time it lies between 4 and 8 or 14 and 24 min. However, in the upper troposphere, the waves with periodicities of 4-7 min are dominant. The BV periods computed from the radiosonde data taken at Madras, a nearby station of IMD, show that the periodicities of 5-18 min are found with wide fluctuations in the lower troposphere, while, in the upper troposphere, 4-7 min periodicities are noticed. In the middle troposphere (a region between 10.0 and 14.0 km), the BV periods are noticed of about 10-20 min computed from radiosonde measurement. The short period waves obtained from radar are found to be in good agreement with the BV period computed from radiosonde data in the upper troposphere.

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References