5.7A THE URBANA MST RADAR, CAPABILITIES AND LIMITATIONS

O. Royrvik and L. D. Goss

Aeronomy Laboratory, Department of Electrical Engineering
University of Illinois, Urbana, Illinois 61801

ABSTRACT

The 41-MHz coherent-scatter radar located northeast of the University of Illinois at Urbana, Illinois has been used during the last five years for studies of the troposphere, stratosphere and mesosphere regions. The antenna consists of 1008 halfwave dipoles with a physical aperture of 11000 m^2. Transmitted peak power is about 750 kW. Clear-air returns may be received from 6 km to 90 km altitude. Autocorrelation functions of the scattered signal are calculated on-line. From the autocorrelation functions the scattered power, line-of-sight velocity and signal correlation time are calculated. Some aspects of the troposphere/stratosphere and the mesosphere observations are described. Capabilities and limitations of the Urbana MST radar are pointed out, and recent and planned improvements to the radar are described.

THE URBANA MST RADAR

The Urbana monostatic VHF radar has been in operation since 1978 (MILLER et al., 1978). It is located at the Aeronomy Laboratory Field Station approximately 10 km northeast of the University of Illinois at Urbana (40° 10'N, 88°10'W). Transmitted frequency is 40.92 MHz and peak transmitted power is, at the present, approximately 750 kW. The antenna consists of 1008 half-wavelength dipole elements divided into three parallel sections. This arrangement allows for limited steerability of the antenna by inserting different lengths of cable in the feedline to each of the three sections. The ground where the antenna is located slopes 1.5° to the to the southeast (36° south of east) so that the on-axis antenna position is off-vertical by the same amount. In addition, off-vertical antenna beam positions pointing approximately 2.5° off-vertical to the east and south, can be obtained by changing the relative phasing of the three antenna sections. The change of the antenna beam direction is done manually and is therefore not very practical for day-to-day operation. Both transmitter and receiver are connected to the antenna via a transmit/receive switch which consists of a set of gas-filled tubes. Due to recovery time of the switch only signals from above 9 km altitude can be received.

The receiver system consists of a low noise, broad band preamplifier, a filter and a single conversion receiver with a bandwidth of 230 kHz centered around 40.92 MHz (Figure 1). A toggle-switch attenuator is located between the mixer and the IF section to provide control of the 5.5 MHz IF frequency. The signal is quadrature phase detected, and the two components fed through a multiplexer and a 10-bit analog-to-digital converter with a conversion time of 10 μs. Data processing has until recently been done on a Digital Equipment Corporation PDP-15 minicomputer with 32 k of core memory. Data collection is under the control of a radar director that allows the pulse repetition frequency, number of samples, and altitude of first sample to be preset. Pulse repetition frequency is normally 400 Hz and due to computer limitations only 20 altitudes can be sampled. Samples of the returned signal can be taken anywhere from the upper part of the troposphere through the mesosphere, however, only a 30 km altitude range can be sampled at any one time. Fifty consecutive samples from each altitude range are coherently integrated so as to give an integrated sample each 1/8 s. Autocorrelation functions are calculated on line with 12 lags 1/8 s each. The correlation functions are

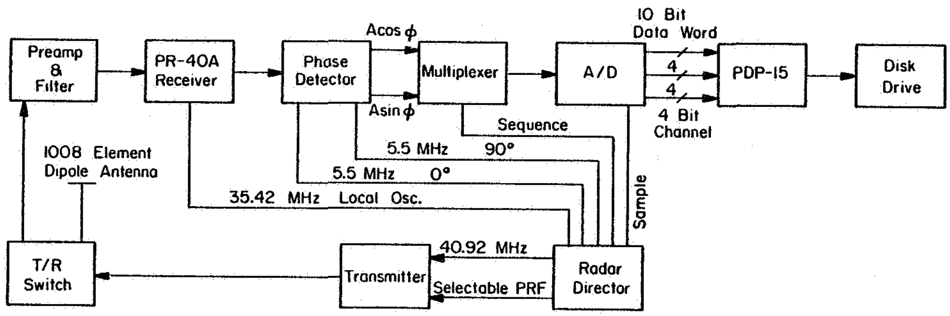

Figure 1. Block diagram of the Urbana MST radar in its most used configuration.

then incoherently integrated for one minute. The one-minute averaged autocorrelation functions are stored on magnetic tape for later processing. Scattered power, line-of-sight velocity and signal half-correlation time are calculated from the autocorrelation function. Hourly averages of power and velocity are also calculated. The radar parameters are summarized in Table 1.

MESOSPHERIC EXPERIMENT

The mesosphere between about 60 and 90 km has been probed on a regular basis approximately once a week since the spring of 1978. Twenty μs Gaussian-shaped transmitted pulses have been used for the mesosphere in order to obtain maximum transmitted power. The resulting 3-km transmitted pulse has been sampled every 1.5 km, thus allowing some improvement in height resolution deconvoluting the returned signal. This technique, however, is not used on a regular basis. Data are normally taken in two-hour blocks during daylight hours and it is rare to find a day of no mesospheric scattered signal large enough to be detected above the noise level. Usually the scattering occurs in one or more layers that are stable in altitude. On a few occasions mesospheric data have been obtained under nighttime conditions, and the signal in those instances are believed to be due to meteor precipitation or high-energy particle precipitation from solar flares.

An example of a data set from the mesosphere is seen in Figures 2-4. The data were obtained on May 12, 1982 between 13:15 and 15:15 CST. The scattered power in Figure 2 shows a moderately disturbed day with a strong scattering layer in the region between 80- and 86-km altitude, and some scattered signal in most of the range gates below 80 km. Figure 3 shows the line-of-sight velocity for the same time period. The short period (5-15 min) velocity oscillations have relatively large amplitudes (2-5 m/s) and are likely to be the vertical velocity component of internal gravity waves. Since the antenna beam is off-vertical by 1.5° the line-of-sight velocity includes a small but important component of the horizontal velocity that has been reduced by a factor sin 1.5° $\approx$ 1/38. By averaging the line-of-sight velocity for one hour, and assuming that the one-hour-average of the vertical velocity component is zero, we can multiply the resulting averaged velocity by a factor of 38 and obtain the horizontal velocity in the southeast direction.

One may consider further the assumption of zero averaged vertical velocity. Any oscillation with periods shorter than one hour will not systematically contribute to the averaged hourly velocity; however they will

Table 1. Parameters of the Urbana MST radar

	Mesosphere	Stratosphere/Troposphere
Radar frequency	40.92 MHz	40.92 MHz
Peak power	750 kW	750 kW
Pulse repetition frequency	400 Hz	400 Hz
Pulse width	20 s	10 μs 20 μs
Receiver system bandwidth	100 kHz	100 kHz
Range resolution	3 km	1.5 km
Antenna	1008 dipole	
Antenna efficiency	-7.6 dB	
Physical aperture	11000 m^2	
Effective aperture	450 m^2	
Power gain	27 dB	
Data	12-lag ACF 1/8 sec lag	12-lag ACF 1/8 sec lag
Time resolution	1 min	1 min
Maximum radial velocity	$\pm$ 14 m/s	$\pm$ 14 m/s
Number of range gates	20	20
Lowest altitude	58 km	6 km

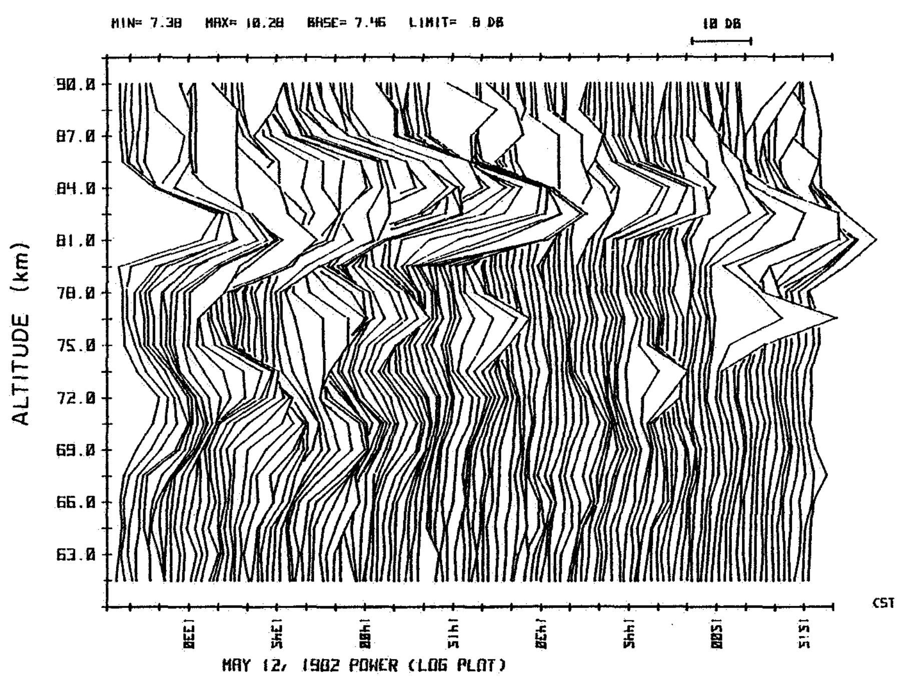

Figure 2. Scattered power map for May 12, 1982, 13:15 to 15:15 CST.

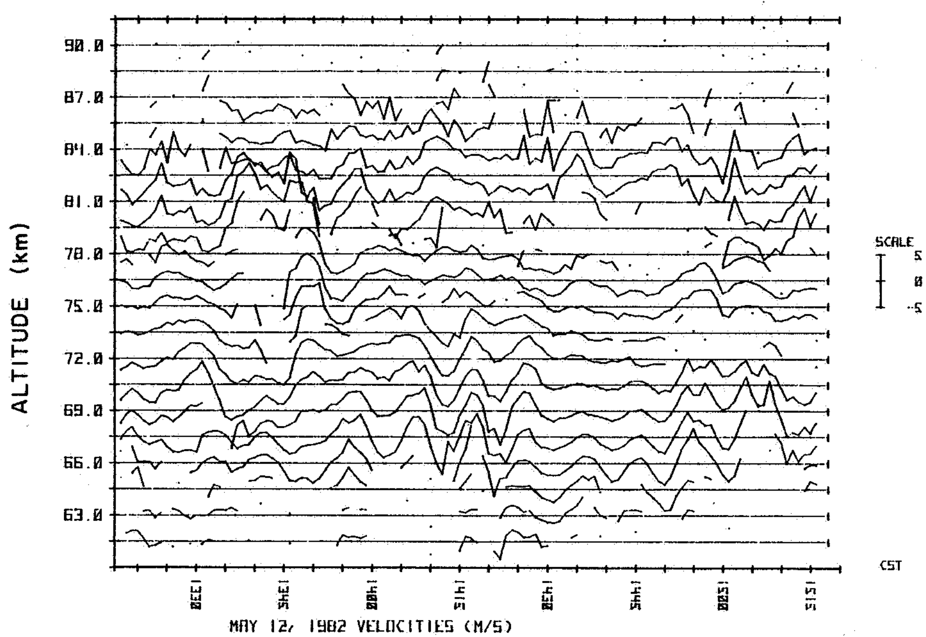

Figure 3. Line-of-sight velocities for May 12, 1982, 13:15 to 15:15 CST. The scale is 5 m/sec.

contribute to the uncertainty of the velocities. This contribution is considered to be geophysical noise. For velocity oscillations with periods larger than one hour we can apply the asymptotic relation that relates the velocities and periods; $\frac{\tau}{\tau_g} \approx \frac{V_x}{V_z}$ (HINES, 1960). Here τ_g is the Brunt-Vaisala period, τ the period of oscillation, and V_x and V_z the horizontal and vertical velocities, respectively. Solving for the relationship we find that any oscillation with periods less than three hours will contribute to the average mainly through the vertical velocity component while those with periods longer than three hours will contribute mainly with the horizontal component. Thus observed tidal oscillations with periods from 6-24 (48) hours can safely be assumed to yield horizontal velocity components in these observations. This makes it necessary to assume that oscillations with periods of one to six hours have velocity amplitudes considerably smaller than the tidal oscillations. That this appears to be the case is apparent from most of the mesospheric data.

Figure 4 shows two examples of hourly averages from the two-hour data set in Figure 3. The top two plates show the averaged line-of-sight velocity as a function of height for each of the two one-hour sections. The two curves show the limits of the standard deviation, thus the actual velocity profile has a high probability of lying mainly between these curves. As can be seen by comparison, the details of the velocity profile change from one hour to the next; however, the overall picture of a wave with a vertical wavelength of 14-16 km is obvious in this example. In a large fraction of the data this kind of wave profile persists throughout the day while slowly descending making it obvious that tidal components dominate the wind velocity, and that oscillations of 1-6 hours are not usually large enough to mask the presence of tidal components. It is thus concluded that it is possible to study some

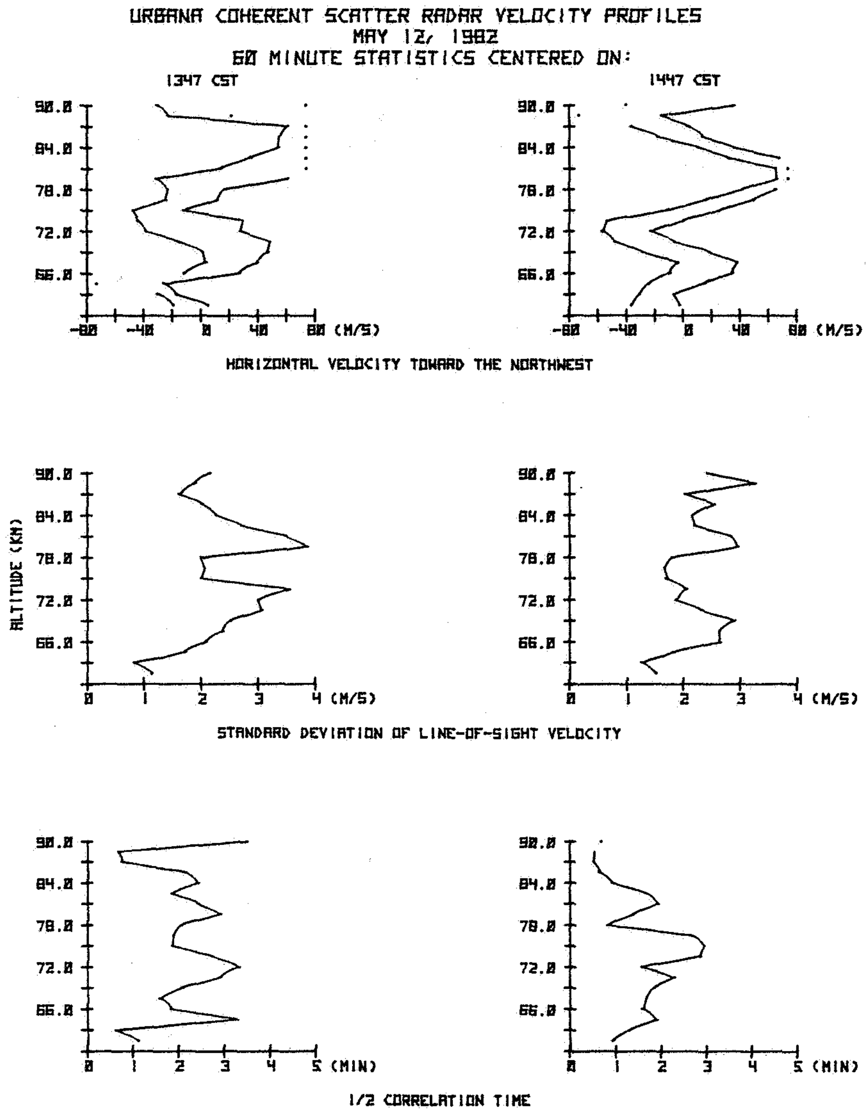

Figure 4. Diagram showing two one-hour averaged; (a) horizontal velocity towards the northwest; (b) standard deviation of the line-of-sight velocity; and (c) half-correlation time of the line-of-sight velocity oscillations. The data cover the two-hour period from 13:15 to 15:15 CST on May 12, 1982.

features of the long-period horizontal wind field using the Urbana radar although some care must be taken.

However, one complicating factor in interpreting these data is the aspect sensitivity of the scattered signal in the lower part of the mesosphere (FUKAO et al., 1980). The result of this aspect sensitivity is that the horizontal velocity is almost certainly being underestimated in the lower part of the mesosphere; however it is not a simple task to estimate by how much. A factor of two, however, seems like a reasonable upper limit.

The second set of plates in Figure 4 show the standard deviation of the line-of-sight velocity. This gives a good estimate of the amplitude of the velocity oscillations at any altitude averaged over one-hour periods. Thus a profile of gravity-wave activity is found. It can be seen that there is a slight tendency for an increase in amplitude with increasing altitude in both the hourly profiles. There are also two distinct peaks in the profiles at about 70 and 82 km. The reason for these peaks is not clear, however, they appear to be real since they are present in both profiles.

The last two plates in Figure 4 show the half-correlation time of the line-of-sight velocity time series. This gives a convenient estimate of the dominant frequency of the velocity oscillations. If a sinusoidal wave is assumed, a half-correlation time of 2 min is equivalent to a period of 12 min. Although there are substantial variations in the correlation time, it indicates that the dominant period is between 10 and 15 minutes for most altitudes especially during the first one-hour period.

TROPOSPHERE-STRATOSPHERE OBSERVATIONS

Some troposphere-stratosphere observations have been made using the Urbana MST radar. There have been two main problems with this study, however. First of all, the transmit/receive switch presently used limits the lowest observable altitude to about 10 km. Secondly, the altitude resolution is 1.5 km, corresponding to a transmitted pulse width at its lowest possible limit of 10 μs. Useful scattered power is received from 9 to approximately 24 km on most occasions. An attempt was made to lower the observable altitude by receiving separately on a single 13-element Yagi antenna pointing vertically. This allowed data to be obtained down to 6 km as the lower altitude. However, the upper limit on useful data was 18 km in this case and the data were not nearly as continuous as that obtained by the large antenna. Thus a smaller amount of useful data was obtained when using the Yagi as a receiving antenna.

It has been possible to compare calculated horizontal velocities in the southeast direction to data obtained by a rawinsonde released from Peoria, Illinois 168 km to the northwest of Urbana. Figure 5 shows two wind profiles from the Peoria rawinsonde on July 15, 1982 at 6:00 CST and 18:00 CST. As can be seen, the southeast wind profile has changed substantially during the 12 hours between the two profiles. In particular, a large shear region has developed between 13 and 14 km. Figure 6 shows four velocity profiles obtained by the Urbana radar between 9:41 CST and 12:45 CST for the same day of July 15, 1982. In this set of profiles it is apparent that the large shear region is developing over the two-hour time interval between 10:41 CST and 12:45 CST. It is also apparent that the radar profiles at 9:41 CST and 12:45 CST compare reasonably well to the rawinsonde profiles of 6:00 CST and 18:00 CST, respectively. The differences can easily be attributed to differences in time and distance separating the two sets of observations. It is suggested that the significant wind shift that occurred in the 12-14 km region was associated with a warm front that moved through during the morning hours on July 15, 1982.

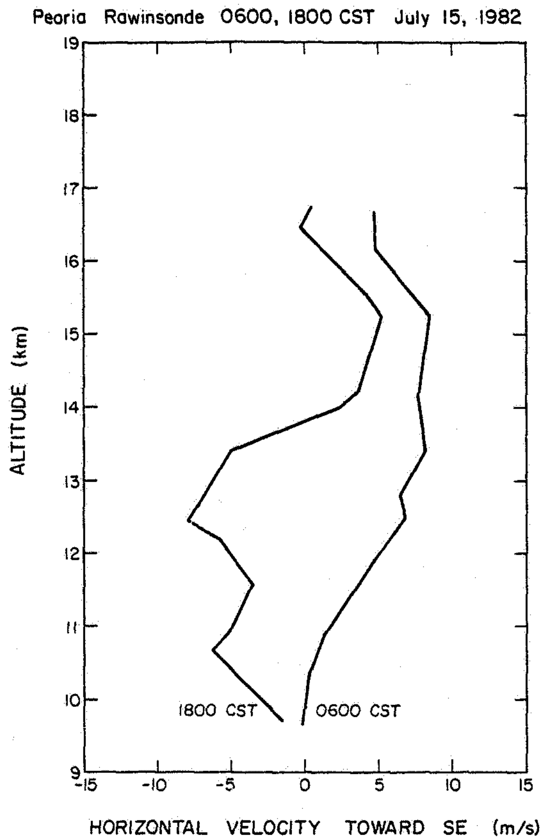

Figure 5. Profiles of horizontal velocity component towards the southeast from two Peoria rawinsonde releases on July 15, 1982. Times are 6:00 CST and 18:00 CST.

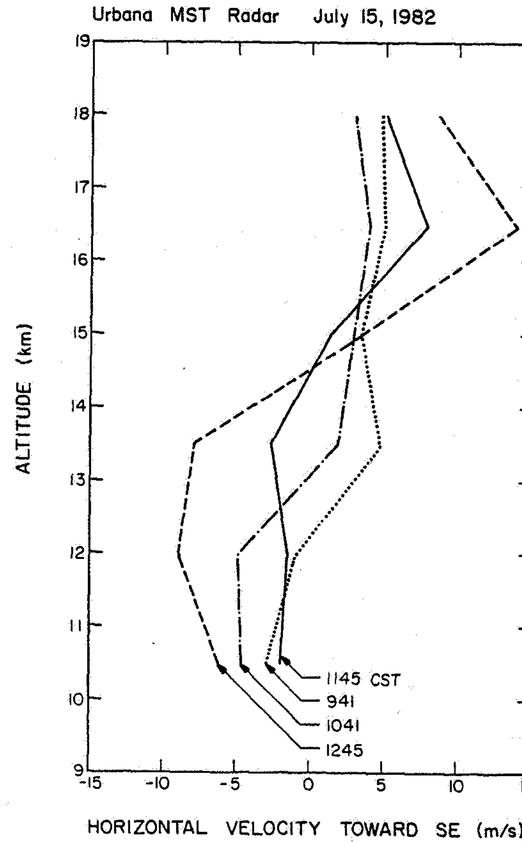

Figure 6. Profiles of horizontal velocity component towards the southeast from Urbana MST radar on July 15, 1982. Times are 9:41, 10:41, 11:45 and 12:45 CST.

Interesting data have also been taken in the vicinity of thunderstorms. One example of this is shown in Figure 7. On the evening of June 29, 1982 a severe thunderstorm passed from west-to-east over the Urbana radar. Data taking was started as the main part of the storm had just passed. The updraft region of the storm can easily be seen between 18:40 and 19:00 CST between 12 and 15 km. These observations are compared to the National Weather Service radar summary at 1735 CST, approximately 1 hour before data collection began. The summary shows cloud top heights of 55,000 feet or 16.7 km in an area just west of Urbana. Thus, the observation of an updraft at 15 km is entirely possible for this storm. Gravity-wave activity, possibly related to the storm, was very strong reaching amplitudes of several m/s. This is several times the amplitude of 0.2 m/s that is normal for the troposphere/stratosphere region over Urbana. A large increase in gravity wave activity has been encountered during all observations involving strong convective activity.

Many groups using VHF radars have reported enhanced radio returns at vertical incidence in the troposphere/stratosphere region. These returns are thought to be caused by specular reflection from horizontally stratified layers in the lower stratosphere as opposed to scattering from isotropic turbulence (GAGE and GREEN, 1978).

Figure 8 shows hourly averaged power levels from the radar data compared to changes in potential temperature ($d\theta/dz$) as a function of altitude for July 22, 1982. The potential temperature is calculated from data available from nearby National Weather Service balloon soundings at five altitudes common to the range probed by the radar. The potential temperature is a good measure of the stability and stratification of the atmosphere at any given altitude in the stratosphere. There is a rough agreement between stability as represented by the potential temperature changes and the power profile. In particular, a layer of enhanced stability (positive $d\theta/dz$) exist around 12 km and a corresponding layer of enhanced scattering is evident in the power profile. Similar agreements are seen in other profiles of potential temperature changes and scattered power.

POSSIBILITIES AND LIMITATIONS

It is clear that the Urbana MST radar has the capability to measure the line-of-sight velocities in parts of the troposphere/stratosphere and mesosphere regions. The slight off-vertical pointing direction of the antenna also allows a measurement of tidal and other long-period components of the horizontal wind in the southeast direction. Velocity measurements can be obtained from those altitude regions where the scattered signal exceeds the detection threshold set by the noise level. In order to increase the scattered signal level it is desirable to increase pulse length of the transmitted signal. However, this has the unfortunate side effect of decreasing the range resolution. One way of increasing transmitted power and still retaining high range resolution is to phase code the transmitted signal (WOODMAN, 1980). However, the Urbana transmitter has a narrow bandwidth so that the baud length has to be at least 6 μs, thus giving a 900 meter range resolution. This is not much better than the 1.5-km range resolution presently used in the troposphere/stratosphere region. Another way of increasing range resolution has been suggested by Bowhill (private communication) and will be implemented for the Urbana radar in the near future. In this scheme the radar will transmit a series of pulses at different but closely spaced frequencies. The signal phase values obtained from each of the different frequencies can then be combined to obtain a high altitude resolution (150 meters) while maintaining maximum transmitted power.

One problem that appears to be unique to the Urbana MST radar is oblique

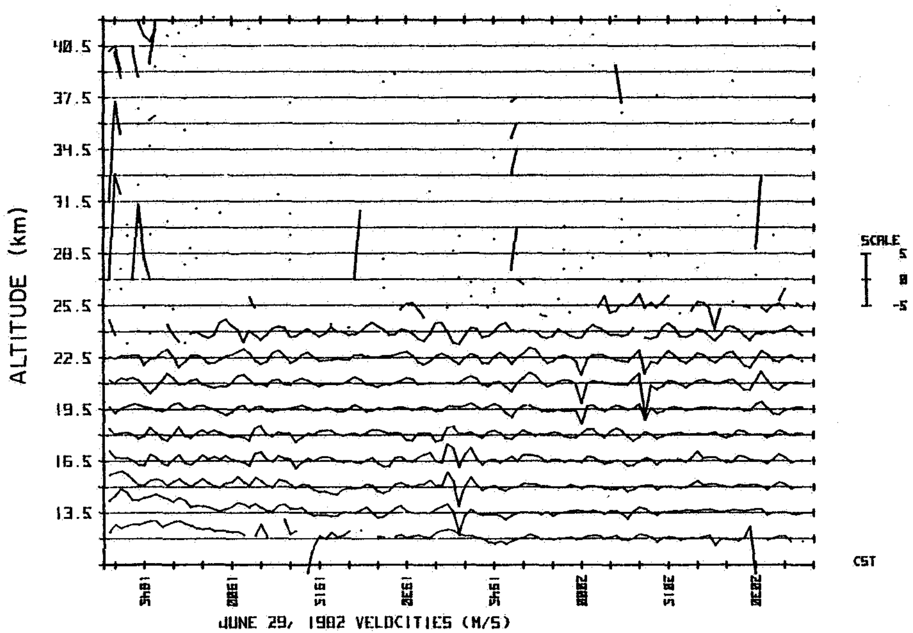

Figure 7. Line-of-sight velocity in the troposphere/stratosphere region between 18:40 and 20:40 CST on June 29, 1982.

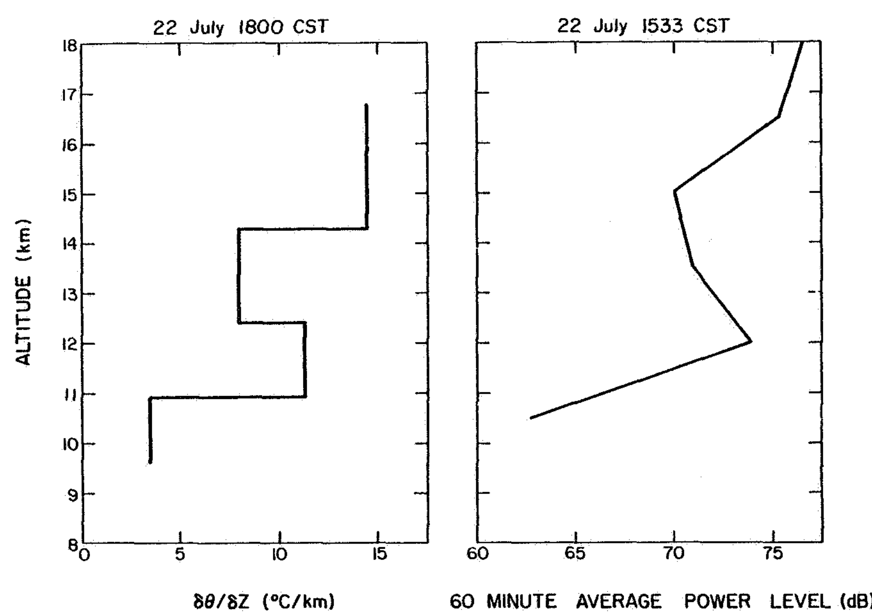

Figure 8. Profiles of potential temperature variations (dθ/dz) from Peoria rawinsonde July 22, 18:00 CST; and scattered power profiles from the Urbana MST radar at 15:33 CST, same date.

reflection and backscatter. At times, especially during the November to March period, we have observed quite strong scattered power at all altitudes from ground level and up. The calculated velocities are identical in all range gates and slowly changing with a period of the order of one hour. Line-of-sight velocities can reach as much as 3-4 m/sec. It is believed that this signal is over-the-horizon ground reflection where the signal is obliquely reflected off the F layer, and transmitted/received in low elevation sidelobes of the antenna. Thus the received signal is range aliased. By using a variable interpulse period (IPP) and coherently integrating, it has been possible to reduce the strength of the aliased signal relative to the real signal from the troposphere/stratosphere and mesosphere region. In order to generate a variable IPP, an Apple II microcomputer has been implemented as a radar director. This allows software control of all radar parameters except for transmitted power and transmitted pulse length. Sets of 50 pulses are transmitted all with different IPP, thus the aliased signal will be incoherent from pulse to pulse, and will contribute only to the noise level.

The PDP-15 minicomputer used for data taking has deteriorated significantly during the last few years, and as a backup and possible replacement, an Apple II-based data-taking system is being implemented. The number of range gates sampled by the Apple system has been limited to 20, and correlation functions are being calculated on-line although with somewhat less accuracy than that of the PDP-15 data. The Apple data-collection system uses separate analog-to-digital converters and can be run independently from the old computer. We therefore now have the capability to take both tropospheric/stratospheric and mesospheric data simultaneously.

The Urbana radar also has the advantage of being located on a site where there are other instruments for probing similar regions of the atmosphere. These are: an HF partial-reflection drifts radar operating at 2.6 MHz, a meteor radar (40.92 MHz), a sodium LIDAR, and an ionosonde. The ionosonde is at the present not operational, but could be made so if desired. Of the other experiments the partial-reflection drift radar is probably the most interesting support for the MST radar. It is totally independent of, and can be run in parallel with, the MST radar. A preliminary comparison between velocities in the two radars show reasonable agreement (RUGGERIO and BOWHILL, 1982). In addition, there are some indications that the scattered power profiles at both 40.92 and 2.66 MHz are very similar between 60 and 90 km altitude, a point awaiting further study. The meteor radar and the MST radar cannot be run simultaneously since they use the same transmitter and receiving system. However, alternating between the two will allow comparison of long-period waves in the altitude region where the two experiments overlap between 80 and 90 km. The LIDAR is mainly a nighttime experiment and not very well suited for daytime operation so comparison with the MST radar cannot be made simultaneously.

Presently, modifications to the transmitter are underway to allow an increase of transmitted power, hopefully by a factor of 2. However, the most desirable improvement to the Urbana MST radar is an upgrading of the present antenna system.

REFERENCES

Fukao, S., T. Sato, R. M. Harper and S. Kato (1980), Radio wave scattering from the tropical mesosphere observed with the Jicamarca radar, Radio Sci., 15, 447-457.

Gage, K. S. and J. L. Green (1978), Evidence for specular reflection from monostatic VHF radar observations of the stratosphere, Radio Sci., 13, 991-1001.

Hines, C. O. (1960), Internal atmospheric gravity waves at ionospheric heights, Can. J. Phys., 38, 1441-1481.

Miller, K. L., S. A. Bowhill, K. P. Gibbs and I. D. Countryman (1978), First measurements of mesospheric vertical velocity by VHF radar at temperate latitude, Geophys. Res. Lett., 5, 939-942.

Ruggerio, R. and S. A. Bowhill (1982), New advances in the partial-reflection drifts experiment using microprocessors, Aeronomy Rep. No. 106, Aeronomy Lab., Dept. Elec. Eng., Univ. Ill., Urbana-Champaign.

Woodman, R. F. (1980), High-altitude resolution stratospheric measurements with the Arecibo 430-MHz radar, Radio Sci., 15, 417-422.

PUBLICATIONS RELATING TO URBANA MST RADAR

Allman, M. E. and S. A. Bowhill, Feed system design for the Urbana incoherent-scatter radar antenna, Aeron. Rep. No. 71, Aeron. Lab., Dep. Elec. Eng., Univ. Ill., Urbana-Champaign, 1976.

Miller, K. L., S. A. Bowhill, K. P. Gibbs and I. D. Countryman (1978), First measurements of mesospheric vertical velocities by VHF radar at temperate latitudes, Geophys. Res. Lett., 5, 939-942.

Countryman, I. D. and S. A. Bowhill, Wind and wave ovservations in the mesosphere using coherent-scatter radar, Aeron. Rep. No. 89, Aeron. Lab., Dep. Elec. Eng., Univ. Ill., Urbana-Champaign, 1979.

Gibbs, K. P. and S. A. Bowhill, The Urbana coherent-scatter radar: Synthesis and first results, Aeron. Rep. No. 90, Aeron. Lab., Dep. Elec. Eng., Univ. Ill, Urbana-Champaign, 1979.

Royrvik, O., K. P. Gibbs and S. A. Bowhill (1982), VHF power scattered from the mesosphere at midlatitudes, J. Geophys. Res., 87, 2501-2508.

Zendt, F. L. and S. A. Bowhill, A preprocessor for the Urbana coherent-scatter radar, Aeron. Rep. No. 102, Aeron. Lab., Dep. Elec. Eng., Univ. Ill., Urbana-Champaign, 1982.

Loane, J. T., S. A. Bowhill and P. E. Mayes, Feed system design and experimental results in the UHF model study for the proposed Urbana phased array, Aeron. Rep. No. 107, Aeron. Lab., Dep. Elec. Engin., Univ. Ill., Urbana-Champaign, 1982.

Tanner, D. R., P. E. Mayes and S. A. Bowhill, Phased array design including consideration of mutual coupling with application to the Urbana coherent-scatter radar, Aeron. Rep. No. 108, Aeron. Lab., Dep. Elec. Eng., Univ. Ill., Urbana-Champaign, 1982.

Herrington, L. J., Jr. and S. A. Bowhill, Phase modulating the Urbana radar, Aeron. Rep. No. 109, Aeron. Lab., Dep Elec. Eng., Univ. Ill., Urbana-Champaign, 1983.

Gibbs, K. P. and S. A. Bowhill, An investigation of turbulent scatter from the mesosphere as observed by coherent-scatter radar, Aeron. Rep. No. 110, Aeron. Lab., Dep. Elec. Eng., Univ Ill., Urbana-Champaign, 1983.

Goss, L. D., and S. A. Bowhill, Observations of the upper troposphere and lower stratosphere using the Urbana coherent-scatter radar, Aeron. Rep. No. 111, Aeron. Lab., Dep. Elec. Eng., Univ. Ill., Urbana-Champaign, 1983.