5.8A STRATOSPHERE AND TROPOSPHERE (S-T) STUDIES AT MILLSTONE HILL RECENT RESULTS, CAPABILITIES AND LIMITATIONS

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ABSTRACT

The 440-MHz incoherent-scatter radar at Millstone Hill has been used in recent years for studies of the troposphere and lower stratosphere with a fully steerable 150' antenna. The configuration of the radar system is briefly outlined. Clear-air returns are received over an altitude range 4-25 km. The power spectra of these returns can be measured with a range resolution of up to 300 m and a Doppler resolution of up to 4 cm/sec. Due to the lack of a natural shield around the radar, the ground clutter at Millstone is more severe than at other installations. With the use of a fine Doppler resolution, however, the atmospheric returns are readily discriminated from the clutter. Recent observations of turbulence structures, spatial inhomogeneity of turbulence, and enhanced turbulence associated with convective phenomena are described. Capabilities and limitations of the Millstone S-T radar are pointed out.

THE MILLSTONE HILL RADAR

For close to two decades, the 440-MHz UHF radar at Millstone Hill has been used for ionospheric studies with the incoherent-scatter technique (EVANS 1969). These studies initially were carried out with a 220' fixed antenna pointed 2° off zenith towards the south. A fully steerable 150' diameter antenna was added to the radar in 1977. The radar system was upgraded during 1981 with a CAMAC system for radar control and a Harris H-100A minicomputer in conjunction with a Floating Point Systems FPS-120B array processor (AP) for real-time data acquisition and processing. In the past, the UHF radar shared parts of its transmitter system with an L-band satellite-tracking radar. Recent upgrading efforts also have involved considerable modification to the transmitter system (EVANS and REID 1982) that make the operation of the UHF radar independent of the satellite tracking radar. The UHF radar system is used in several different experimental modes for studies of the ionosphere (HOLT et al., 1983), and in recent years also of the stratosphere and troposphere (S-T) region. A brief technical description of the radar is included in the Appendix. A list of publications related to the S-T work at Millstone Hill is appended to the references.

THE S-T EXPERIMENTS AT MILLSTONE HILL

For studies of the stratosphere and troposphere, the 440-MHz radar is used as a pulsed Doppler radar, with either of the two antennas, at a peak power of 1.4 MW and a pulse repetition interval of 2 msec. Two experimental modes designated "I" and "M" have been utilized thus far. The I-mode is used at low elevation angles with an effective altitude resolution of 1 km. The M-mode obtains a finer altitude resolution (300 m), especially at high elevation angles, with the use of phase codes.

In the I-mode, pulses of 10 μs width are transmitted. The atmospheric returns are detected coherently with a receiver system of 100 kHz bandwidth (matched to the transmitted pulse width), sampled in range, digitized to a

12-bit accuracy and temporarily stored in the array processor. When a preset number of pulses has been transmitted, the array processor computes the periodogram of the samples for each range from the stored values. The periodograms are averaged over a time duration of 0.5 to 1 min to obtain a reasonable estimate of the power spectrum of the atmospheric returns. These power spectrum estimates, together with the radar-system parameters in effect, are added periodically to records on a disc file.

Owing to the radar location on a hilltop, the power-spectrum estimates contain a strong contribution due to ground clutter at the radar frequency. This contribution is smeared in frequency since samples taken over a finite duration only are used for computing the periodogram. As a consequence of this smearing, the clutter contribution falls off inversely as the square of the Doppler shift. The atmospheric returns are several orders of magnitude weaker than the ground clutter and are detected solely on the basis of their Doppler shift. For this reason, the I mode is used to cover the region (4-25 km) over which useful atmospheric returns can be obtained, at low elevation angles (10°-30°). This provides a viable experiment when the coarse altitude resolution (1 km) imposed by the pulse length and the beamwidth is acceptable.

The M-mode uses a longer sequence of atmospheric returns to compute the periodogram -- thus reducing the smearing of the ground clutter, and employs phase codes to achieve a better range resolution (300 m). To make full use of the fine range resolution available in this mode, use of high elevation angles (> 75°) is desirable.

In the M-mode, the transmitted pulses are of 32 μs width, and are successively phase modulated with a 16-baud complementary code pair. The receiver system has a 500-kHz bandwidth matched to the 2 μs baud length. The signals received following each pulse are decoded (i.e., correlated) with the code that is used to modulate the pulse. The complementary codes have the desirable property that, when the decoded returns due to the two codes in the pair are added, the contributions in the range sidelobes cancel. Complementary codes have been used in earlier experiments with the SOUSY (SCHMIDT et al., 1979) and the Arecibo radars (WOODMAN, 1980). At Millstone Hill, the decoding scheme has been implemented in software using the array processor.

The slow fading rates and smaller Doppler shifts of the atmospheric returns obtained at high elevation angles can be exploited to reduce the data-input rate to the processor with the use of coherent integration (WOODMAN, 1980). Thus the atmospheric returns for a code can be summed coherently over several successively transmitted pulses prior to the decoding operation. Further, the dc or zero-frequency contribution can be reduced by transmitting the alternate code pairs with a 180° phase shift and then correcting the received signal for this phase shift. Following the coherent integration and decoding operations, the power spectrum estimates are obtained as in the I-mode.

At present the altitude coverage in the M-mode is limited to 5 km by the size of the AP memory (32 kilo words). Efforts are underway to double the AP memory to 64 kilo words. This will provide a 10-km altitude coverage with a 300-m altitude resolution. The entire S-T region below 30 km then can be covered in two 10-km segments with a time resolution of 1-2 min for a fixed antenna pointing direction.

Table 1 summarizes the parameters of the S-T experiments used at Millstone Hill. Figure 1 shows a typical example of power spectra obtained at Millstone Hill with the I-mode. Examples of M-mode spectra are discussed in the following section.

Table 1. Parameters of the Millstone Hill radar for ST studies

		I-mode	M-mode
Radar frequency	f_o	440 MHz	440 MHz
Peak power	P_T	1.4 Mw	1.4 Mw
Pulse repetition interval	T	2 ms	2 ms
Pulse width	τ	10 μs	32 μs
Phase code		none	16 baud complementary
Baud rate		none	2 μs
Receiver bandwidth		100 KHz	500 KHz
Range resolution	Δr	1.5 km	300 m
Typical elevation angle	θ	15°-30°	> 75°
Altitude resolution	Δz	~ 1 km	~ 300 m
*Doppler window	$\pm f_{max}$	± 250 Hz	± 62.5 Hz
Points in spectra	N	256	512
*Doppler resolution	Δf	2 Hz	0.24 Hz
*Maximum radial velocity	$\pm v_{max}$	± 85.2 ms^{-1}	21.3 ms^{-1}
*Radial velocity resolution	Δv	0.66 ms^{-1}	0.08 ms^{-1}
†Number of range bins	N_h	38	17
Lowest altitude	Z_{min}	~ 4 km	~ 9 km
†Altitude coverage		~ 20 km	~ 5 km
§Antenna		150'	150' or 220'
System temperature		150 K	150 K

Notes: * These parameters can be scaled down by coherent integration. The I-mode usually is run without coherent integration. In M-mode, the coherent-integration interval is a multiple of 4 T.

† The number of range bins is constrained by the Array-processor memory (currently 32 K words) for given number of points (N) in the spectra. The choice of N indicated is dictated by the extent of ground-clutter smearing that can be tolerated. Efforts are underway to double the AP memory to 64 K, to increase the altitude coverage for the M-mode.

§ The 150-foot antenna is fully steerable. It can be moved in azimuth at 1° per second. It provides a beamwidth of 1°. The 220-foot antenna is pointed permanently at an elevation angle 88° due south and provides a beamwidth of 0.7°.

RECENT RESULTS

The data acquisition programs for the upgraded Millstone Hill radar were developed and tested by R. H. Wand in June, 1981. These programs were used in a month-long campaign, jointly with the Air Force Geophysics Laboratory, to measure the refractive-index structure parameter (C_n^2) simultaneously by the radar, radiosondes and an optical scintillometer (GOOD et al., 1982).

In a series of observations during July - November 1981, the Doppler structure of atmospheric returns from regions of strong wind shear was observed at low elevation angles with a frequency resolution of 0.125 Hz, or a radial velocity resolution of 4 cm/sec. These experiments revealed a variety of thin turbulent structures, often dominated by breaking gravity-wave events and attributable, in one case, to Kelvin-Helmholtz instability. A comparison with radiosonde data indicates that the onset of one clear-air turbulence feature seen in the vicinity of the tropopause covered a horizontal extent of several hundred km (WAND et al., 1983).

During the remaining parts of 1981-82, over 400 hr of observations were made in several different configurations, primarily with the I mode. These configurations include observations along a fixed pointing direction for detecting short-period gravity-wave fluctuations, and observations along two

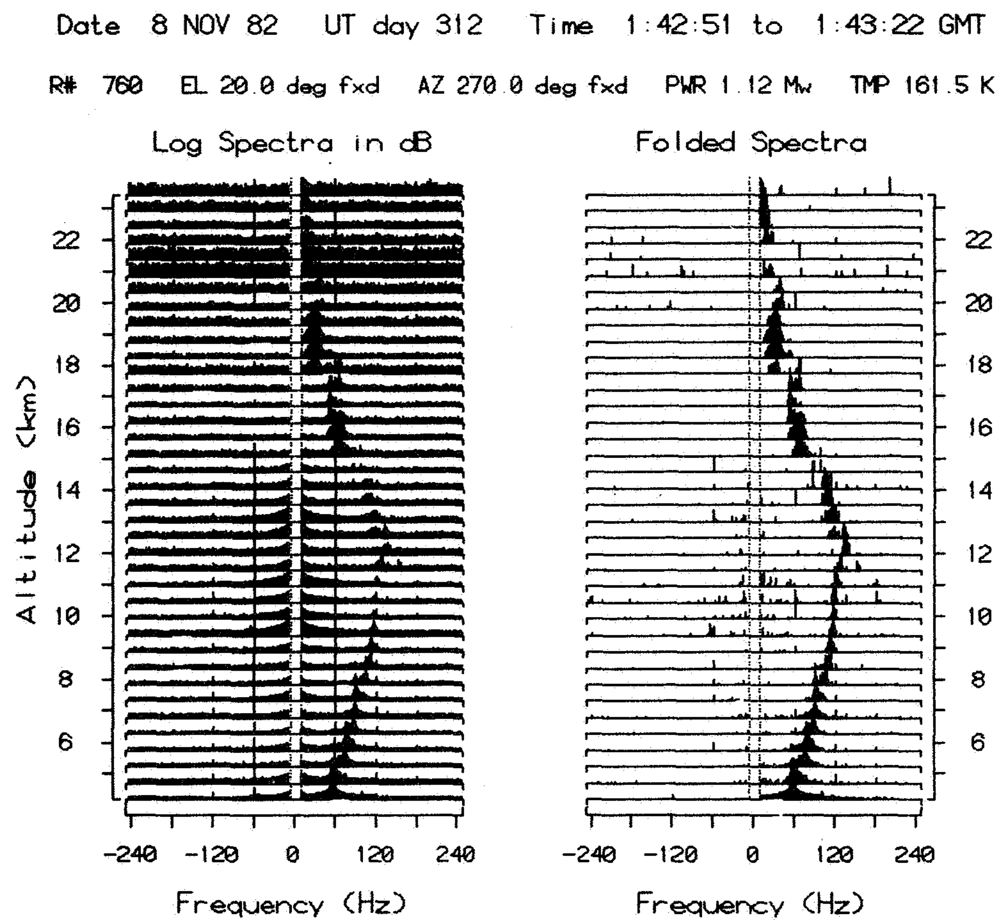

Figure 1. An example of power spectra obtained with the I mode. A narrow band of frequencies near the center has been suppressed. Spectra on the left show unusually strong clutter at 9-14 km. Spectra on the right are obtained by removing the part symmetric about the zero Doppler shift. A Doppler shift of + 60 Hz corresponds roughly to an eastward wind of 22 m/s in this case.

or more fixed azimuths to obtain the parameters of the horizontal wind field and turbulence. Limited observations (about 100 hr) also were made with the M mode on both the antennas. Most of these observations still are being analyzed. Preliminary results are described below.

Figure 2 shows the profiles of horizontal wind and signal power from measurements along two orthogonal azimuth directions at an elevation angle of 20°. The large difference of signal power along the two azimuth directions is indicative of patches of clear-air turbulence in the vicinity of the tropopause. Often, this difference persists for several hours. Enhanced turbulence appears to occur in regions of strong shear in the horizontal wind. Further analysis of these observations shows that the correlations between wind or wind shear and signal power are typically 0.5 to 0.7. At selected heights, these correlations can be even better for short intervals (3 hr or less).

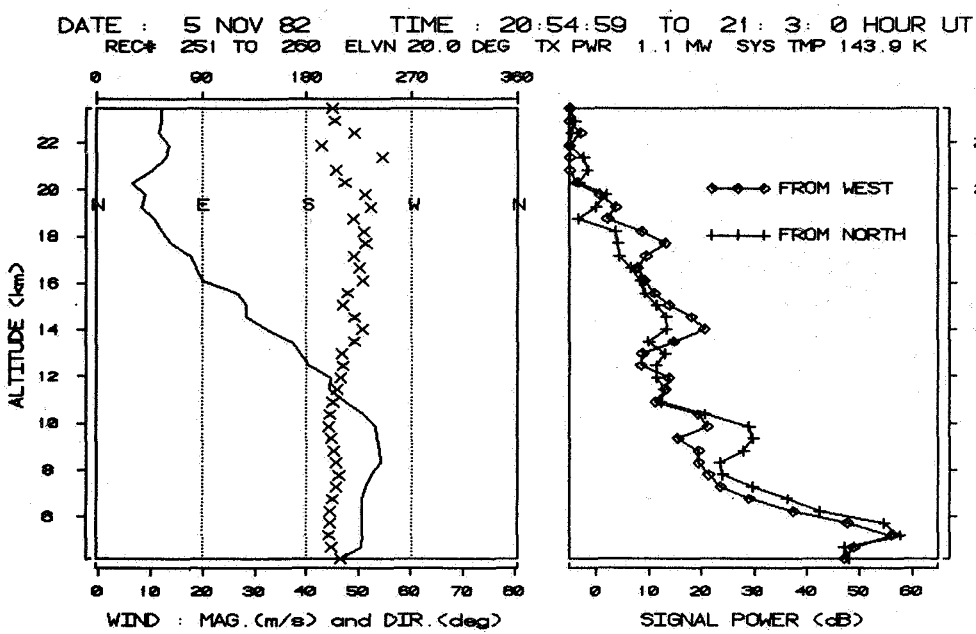

Figure 2. Profiles of horizontal wind and its direction (left) inferred from measurements along east and north at an elevation of 20°. Intensities of signals received along the two directions are shown on the right.

During one run on 8-9 September 1981, a moderate thunderstorm associated with the westerly passage of a cold front traversed Westford. The effect of this thunderstorm on the intensity of the signals received along twelve equispaced azimuths is shown in the series of plots in Figure 3. The asymmetric enhancement of the tropospheric signals corresponds roughly to the passage of the storm from the west to southeast. Enhanced echoes above the tropopause appear first to the north, then to the southeast as the storm moves away. These observations suggest that the turbulence in the lower stratosphere can be enhanced in the vicinity of a thunderstorm, probably as a consequence of the decay of short-period gravity waves that are generated by convection forced below the tropopause (LARSEN et al., 1982).

Figure 4 shows a plot of contours of constant signal power for a two-day interval on 17-19 July 1982. Throughout this interval the antenna was pointed towards east at a 20° elevation. A variable but persistent layer of turbulence at 14 km, in proximity of the tropopause level, is clearly visible. During the middle of this interval, two plume-like structures of turbulence can be seen that penetrate across the tropopause to heights of 19-20 km. Scattered precipipation was reported over southern New Hampshire on this day. It is possible that the observed plume-like structures are related to tropospheric convection associated with these precipipation events.

The modifications to the data-taking program for a 300-m altitude resolution, and the development of the software for decoding was completed by G. B. Loriot in November 1982. Observations with the 220' antenna during a day-long run in December 1982 indicate that stratospheric echoes can be received from altitudes as high as 25-26 km (as opposed to 28-29 km for Arecibo). Figure 5

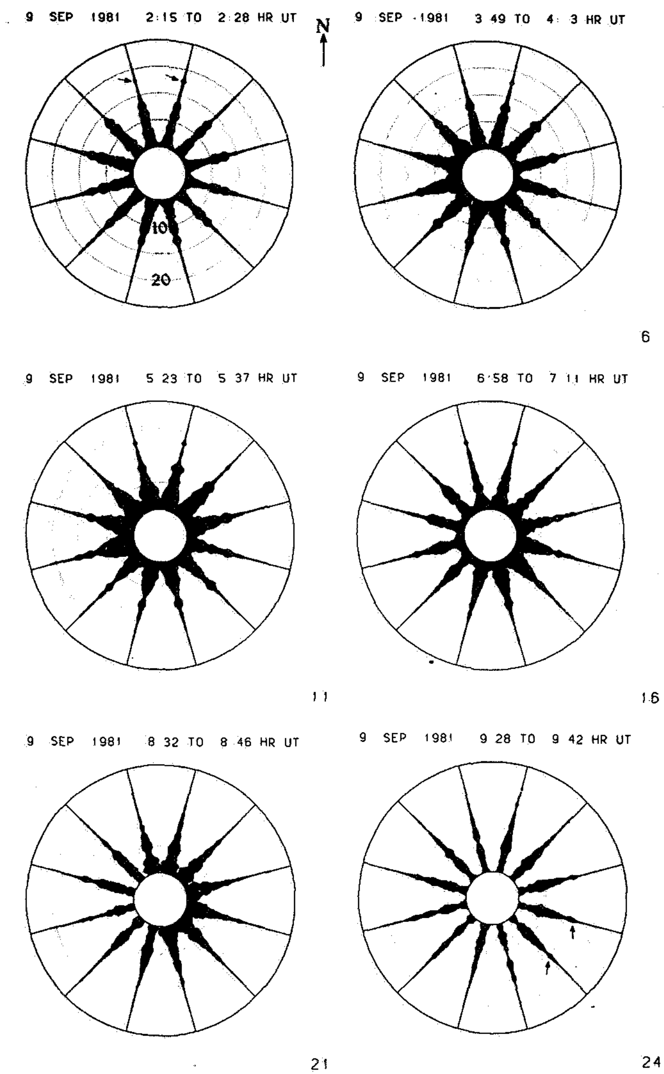

Figure 3. A sequence of plots (a through f) showing the log intensity of the received signals in a 12 position azimuth scan during the passage of a thunderstorm over Millstone Hill. Dotted circles are at a 5-km altitude interval and are spaced 17.5 km horizontally. The storm moves from the west towards the southeast. Stratospheric echoes enhanced by about 10 dB are marked with arrows and appear first to the north, then to the southeast.

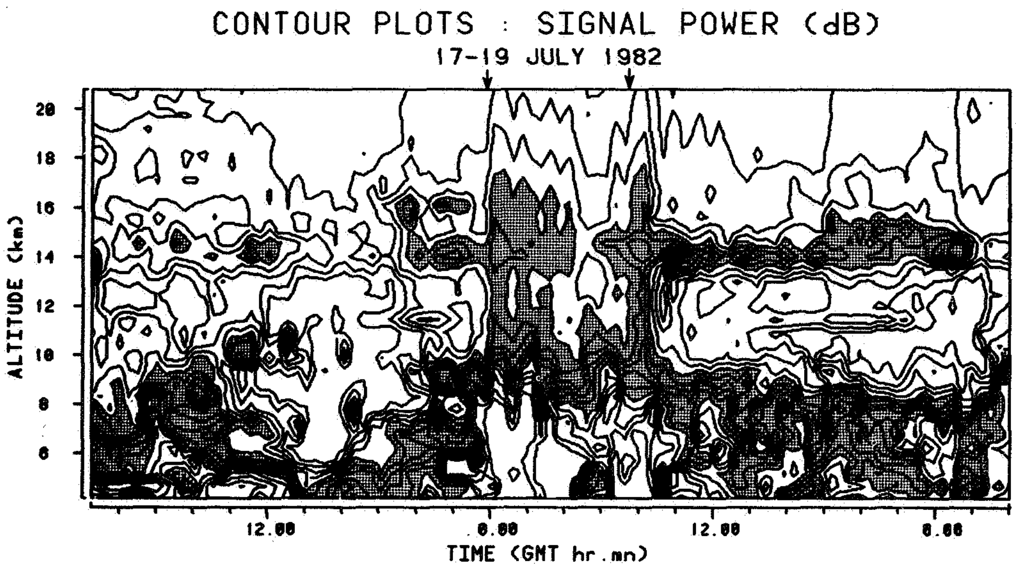

Figure 4. A plot showing the evolution of turbulence during a two-day period in the vicinity of the Millstone Hill radar. Contours are plotted at 2-dB intervals for detrended signal power. Shaded regions show signals that are 10-20 dB above the base power. A persistent layer is seen at 14 km. Arrows show the onset of two plume-like events that, probably, are related to convective activity to the north of the radar.

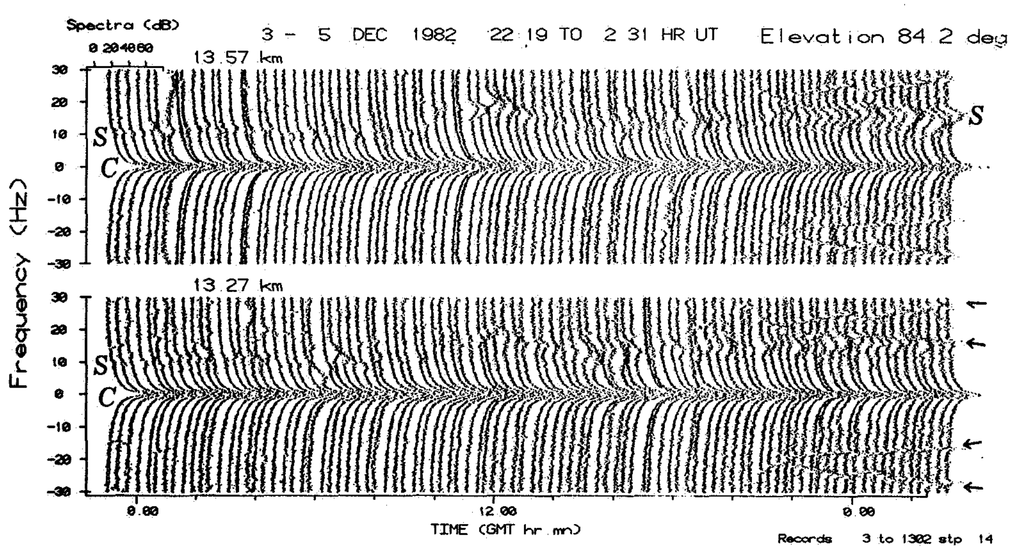

Figure 5. Time evolution of signal spectra for a 30-hr period at two heights and constant elevation in an elevation scan with 300-m altitude resolution (M mode). Each spectrum has 512 points. The ground clutter (C) and the Doppler-shifted signal peaks (S) are identified. Arrows show persistent external interference that complicates the task of inferring the spectral moments.

shows a sequence of spectra observed with the 150 antenna in the vicinity of the tropopause for a 30-hr interval. A program for obtaining wind and turbulence parameters from these spectra is under development.

CAPABILITIES AND LIMITATIONS

The availability of two antennas at the Millstone Hill radar -- one pointed close to the vertical and the other fully steerable -- gives it a unique capability for studies of the dynamic phenomena in the troposphere and lower stratosphere. Its location is quite favorable for studying phenomena related to the polar-front jet stream.

Perhaps the most serious limitation of the radar is the lack of a natural shield around it. For this reason the radar suffers strong ground clutter at close ranges. Contamination of the atmospheric returns by the ground clutter is minimized, however, with the use of 12-bit analog-to-digital converters and by using a sufficiently large number of points (typically 512) in the spectra. This latter step provides better accuracy in estimating the spectral width of the atmospheric returns, and offers the possibility of obtaining improved estimates of the energy-dissipation rate due to turbulence (see e.g. SATO 1981). Due to the constraint of the finite processor memory, the number of range cells for which the spectra can be measured simultaneously at 512 points is reduced, however. Efforts currently underway to increase the array processor memory from 32 k words to 64 k words, and possibly to 256 k words, will circumvent this problem.

Further modifications to the transmitter to provide a 1 msec pulse repetition interval have recently been successful [W. A. REID, personal communication], albeit with a lower (1 MW) peak power. These modifications, if implemented for routine operation, will improve the detectability of signals above 25-km altitude.

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

PUBLICATIONS RELATED TO S-T WORK AT MILLSTONE HILL

The early observations of clear-air turbulence using the L-band radar at Millstone Hill have been reported by :

Crane, R. K. (1970), Measurements of clear-air turbulence in the lower stratosphere using the Millstone-Hill L-band radar, preprints, 14th Radar Meteor. Conf., pp. 101-106, AMS, Boston, MA.

Crane, R. K. (1980), A review of radar observations of turbulence in the lower stratosphere, Radio Sci., 15, 177-193.

The first observations with the UHF radar at Millstone Hill have been reported by :

Watkins, B. J. and R. H. Wand (1981), Observations of clear air turbulence and winds with the Millstone Hill radar, J. Geophys. Res., 86, 9605-9614.

Recent modifications and upgrading of the Millstone Hill UHF radar are described in :

Holt, J. M., J. V. Evans, W. L. Oliver and R. H. Wand (1983), The upgraded Millstone-Hill radar, Radio Sci., in press.

A comparison or refractivity-structure parameter measured at optical and UHF frequencies is made by :

Good, R. E., B. J. Watkins, A. F. Quesada, J. H. Brown and G. B. Loriot (1982), Radar and optical measurements of C_n^2, Appl. Optics, 21, 3373-3376.

Observations of thin structures of turbulence generated by wind shear have been reported by :

Wand, R. H., P. K. Rastogi, B. J. Watkins and G. B. Loriot (1983), Fine Doppler resolution observations of thin turbulence structures in the tropo-stratosphere at Millstone Hill, J. Geophys. Res., 88, 3851-3857.

APPENDIX

THE RADAR AT MILLSTONE HILL FOR S-T STUDIES

A block diagram of the 440-MHz UHF radar at Millstone Hill, as presently configured for S-T studies is shown in Figure A.1. Two antennas may be used in conjunction with the UHF transmitter: a fixed 220-foot antenna pointed due south at an elevation angle of 88 degrees, and a 150-foot fully steerable antenna. The transmitter normally is operated at a 1.4 to 1.6 MW peak power with either coded or uncoded pulses at a 2 ms pulse repetition interval. Three experimental modes, designated I, K and M, are used to S-T work. The I and K modes use uncoded pulses of 10 and 5 μs (2 μs in some cases), respectively. In the M mode, 32 μs pulses, phase coded with a 16-baud complementary code at a 2 μs baud rate, are used, Only the I and M modes are used routinely. Each of the two antennas is equipped with a low noise parametric amplifier, though the rest of the receiver is common. The overall system noise temperature typically is 150 K. The received signals are successively down converted to a 30-MHz intermediate frequency (IF) for the M mode, and to a 2 MHz IF for the I and K modes. Following the IF stage, bandlimiting is applied to match the receiver to the pulse length (for I and K modes), or the baud rate (for the M mode).

The receiver IF is detected coherently with a pair of quadrature phase detectors to obtain the inphase and quadrature (or the sine and cosine) components of the complex received signal. These components are sampled through a "comb" at range intervals corresponding to the pulse length (for I and K modes) or the baud rate (for the M mode), and digitized by 12-bit A-D converters. The Formatter is a locally built unit that sign-extends the 12-bit samples to 16 bits, and packs them pairwise into 32-bit words.

The GPIOP (General Purpose Input Output Processor) is a programmable controller that runs in parallel with the Array Processor (AP). It has two independently programmable processors: a Control Processor (CPROC) and a Formatting Processor (FPROC). The Formatting Processor unpacks the 32-bit words supplied by the Formatter, converts them to a 38-bit floating point format required by the Array Processor, and then transfers these 38-bit words to the Array Processor by a direct memory access channel. The Control Processor initiates transfer of blocks of radar data from the formatter in response to interrupts from the radar timer.

In the Array Processor are performed all the computation-intensive tasks, viz., coherent integration, decoding, Fourier transforms (FT) and the power spectrum estimation. The Array Processor runs as a peripheral to the H-100 computer, connected to it as a UBC (Universal Block Controller) channel. The processed results from the Array Processor, usually in the form of the time-averaged periodograms, are transferred to the H-100 computer. These results are stored on a disk file and saved later on magnetic tape. Current or past spectra on this disk file can be examined on a fast vector display (256 kHz rate).

The H-100 computer controls and monitors the various radar functions through a CAMAC (Computer Automated Measurement and Control) system that utilizes the same UBC as the Array Processor for an input-output path. The radar information input to the H-100 includes the antenna azimuth and elevation, peak transmitter power, a refractometer reading, day number, time and other radar status parameters. Settings of 24 operator-selectable sense switches also are input to the H-100, and provide a ready means of controlling the various program functions.

Program output commands via the CAMAC channel are used to supply the

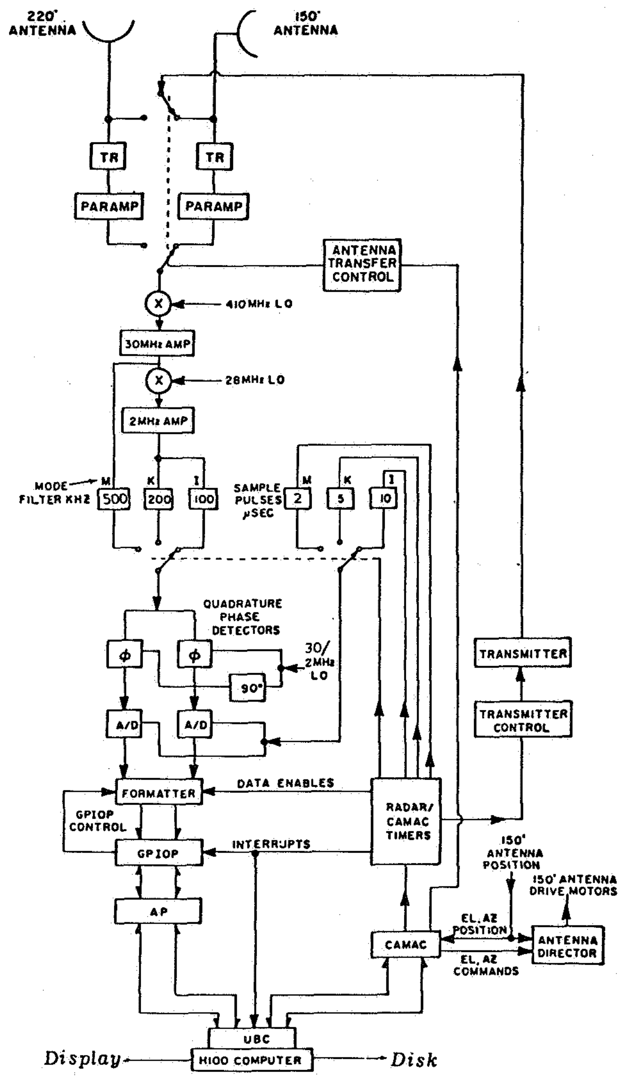

Figure A.1. A block diagram of the 440-MHz radar system at Millstone Hill.

azimuth and elevation commands to the 150-foot antenna director, to select one of the several radar timer modes, to select either the 150-foot or the 220-foot antenna, and to control various other radar functions. The CAMAC elevation and azimuth commands are sent directly to the Antenna Director which uses the difference between the command and true position to steer the antenna through elevation and azimuth servos.

A number of adjustable parameters for each mode, set usually through an input parameter file for the H-100, allow considerable control over the experiments. The most important of these are the range spacing, the number of ranges, the number of pulses to be coherently integrated, the number of Fourier-transform points and the number of periodograms to be added incoherently to obtain the power-spectrum estimates. The current 32-kilo word limitation on the Array Processor memory restricts the selection of the number of ranges and the number of Fourier-transform points. Typically, the I mode is used with 256 point Fourier transforms for 39 ranges, and the M mode with 512 point Fourier transforms for 18 ranges. One range usually is reserved for monitoring the system noise sampled at a distant range. Efforts presently underway to double the memory size of the Array Processor to 64 kilo words will allow 36 ranges for the M mode with a $\sim$10-km altitude coverage for the 2 μs baud rate. A wider altitude coverage over 8-25 km, say, in 5 or 10 km steps is possible with cycle times of 1-2 minutes.