8.2A DECODING: SOFTWARE IMPLEMENTATIONS

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ABSTRACT

The motivation to use phase-coded observations for the stratosphere-troposphere region is briefly discussed. Previous work using hardware correlators to decode the received signal is referenced. An alternative technique using software to decode the signal samples is described in detail, and results of this implementation are presented.

INTRODUCTION

High-power sensitive Doppler radars have been shown to be feasible probes of clear air turbulence in the troposphere and stratosphere (BALSLEY, 1981; RASTOGI, 1981). Typically, a 10-20 μs pulse is transmitted with a peak power of 1-2 MW, and the backscattered signal is sampled at or near the pulse length. Several range gates are simultaneously sampled to cover a desired altitude span, and the samples are stored in a processor. Coherent integration (presuming) may be employed to narrow the bandwidth, and the range resolution is determined by half the pulse length (1.5-3.0 km). After a sufficient number of radar sweeps have been stored, power spectra are estimated from the time series of samples at each range gate. Spectral moments yield estimates of properties of turbulence in the medium as a function of range, with the spatial resolution as set by the pulse length. Routine observations of this type have been carried out by several groups during the past decade (WATKINS and WAND, 1981; ROTTGER, 1981). Observations of the development, organization, and decay of these structures may lead to an understanding of their role in the dissipation of short period motions and in their effect on vertical transport.

However, turbulent structures in the strato- troposphere (ST) are known to exist in layers as thin as tens of meters. Many of the details of these structures would be obscured if a resolution of 1-2 km were used (SATO and FUKAO, 1982). If short pulses (1-2 μs) were used to increase the resolution, the peak power limitations of ~1-2 MW would severely degrade the signal-to-noise ratio (SNR) of the received signals, and many regions of weak turbulence would not be observed. In order to resolve these structures with radar, pulse compression by phase coding has been employed by several investigators, and has proven to be effective in increasing the SNR while maintaining a fine range resolution (WOODMAN, 1980; WOODMAN et al., 1980; SCHMIDT et al., 1979; SATO and WOODMAN, 1982a).

The phase-coded method comprises transmitting a long pulse to obtain good SNR, but modulating the phase at the desired resolution (baud rate) according to a pseudo-random binary code. The backscattered signal is sampled at the baud rate and the samples are correlated (decoded) with a replica of the code. This yields pulse compressed samples with the resolution set by the baud length. For an arbitrary code, the zero lag correlation will always give a maximum value, but lags further along the pulse will also contain significant values. There are many finite length codes in which this effect may be minimized, that is, the correlation sidelobes will be much smaller than the zero lag peak; Barker codes and some codes due to Turyn are two such examples (see Table 1). Signals from one range will still contaminate another range within the code length, but at a much reduced level. For ST studies, where the atmospheric signal is phase coherent over more than one radar sweep, special codes called "complementary

Table 1 Phase codes available at Millstone Hill

CODE	BIT PATTERN	DESCRIPTION
A	11101101111000101110110100011101 11101101111000100001001011100010	32-bit complementary code pair
A1	11101101111000101110110100011101 11101101111000100001001011100010 00010010000111010001001011100010 00010010000111011110110100011101	32-bit complementary code pair, followed by pair of negatives
B	1110110111100010 1110110100011101	16-bit complementary code pair
B1	1110110111100010 1110110100011101 0001001000011101 0001001011100010	16-bit complementary code pair, followed by pair of negatives
C	1111100110101	13-bit Barker code
D	1101101001000100010001111000	28-bit code (TURYN, 1968)
E	1110011100000010101001001001	28-bit code (TURYN, 1968)

NOTES: (A) and (B) autocorrelation sidelobes are equal and opposite in sign, yielding zero when summed. Requires coherence over 2 radar sweeps.

(A1) and (B1) are identical to (A) and (B) respectively, but their complements follow them in this sequence. Allows use of dc subtraction. Requires coherence over 4 radar sweeps.

(C) has low correlation sidelobes. Intended for D-region observations.

(D) and (E) have low correlation sidelobes.

codes" may be used to reduce this effect still further. Complementary codes are pairs of codes having very desirable sidelobe properties: the sidelobes of one code are complements of the other's, so that they cancel when summed together, leaving an enhanced contribution only at the zero lag peak. This is taken as the pulse compressed signal for a range cell with resolution set by the baud length.

In the studies referenced above, the raw samples from the radar receiver are decoded by a high-speed hardware digital correlator before transfer to either the processor or to magnetic tape for spectral processing. The radar facility at Millstone Hill has recently been modified to operate with phase coding (including complementary codes), but the implementation uses a programmable array processor to presume, decode, and spectrally process the raw samples in real time. No hardware correlator is required in this approach. The next section describes this system in more detail.

IMPLEMENTATION AT MILLSTONE HILL

(a) General Description

A phase-coded mode of operation for ST experiments has been implemented at the 440-MHz Millstone Hill radar using a Floating Point Systems AP-120B array processor to decode the samples and perform spectral calculations in real time. This mode has been implemented as an option for the real-time data-collection system recently developed (WAND et al., 1983; HOLT et al., 1983). Figure 1 is an overall diagram of this system, including antenna, transmitter, receiver and processors (see p. 357, this volume, by P. K. Rastogi). A control and formatting program runs in the Harris H100A host computer. The CAMAC interface controls and monitors radar timing, transmitter modulation, antenna selection and motion, and various ancillary functions. The array processor performs all signal processing tasks on the detected samples; all functions are under program control from the host computer. Rapid switching of experimental modes is easily

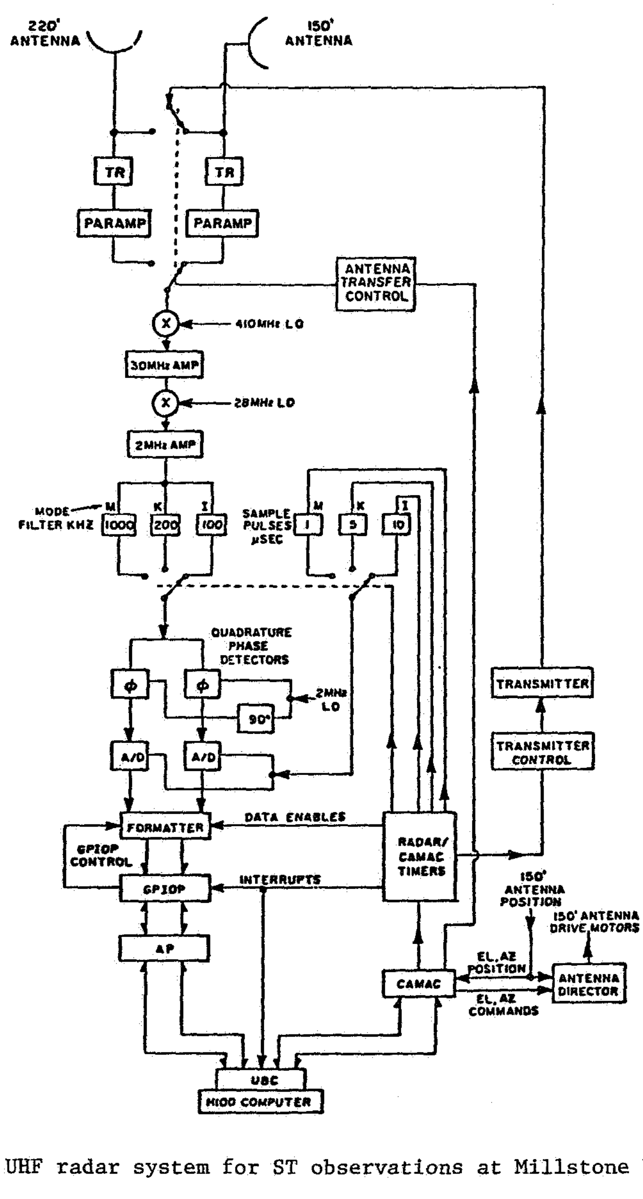

Figure 1. UHF radar system for ST observations at Millstone Hill.

achieved; a sequence of operations is specified at program initiation, and the Harris computer cycles through any mixture of coded or uncoded ST and/or incoherent scatter observations. This section concentrates on the special modes using complementary codes for ST observations.

Typically, a four-pulse sequence of 16- or 32-bit complementary codes has been used; the bit patterns are stored in PROMs and the specified code is selected under program control to modulate the transmitted pulse. The received signal is sampled at the baud rate (usually 2 μs), digitized, and transferred to the array processor (AP). Special purpose subroutines in the AP integrate the samples and decode them according to the transmitted code. Vendor-supplied routines estimate power spectra for each range gate from the time series of demodulated samples, and average these spectra for a specified integration period. At the end of this period, the time-averaged spectra are written to disc as formatted data records for real-time graphic display and subsequent off-line processing.

(b) Transmitter Modulation and Receiver Details

Table 1 lists the phase codes selectable for ST observations. Codes A, A1, B, and B1 are complementary codes having desirable sidelobe properties as described in the introduction. Codes C, D, and E have low correlation sidelobes. Selection of the code and its baud length is via computer control, through the CAMAC interface to the coded pulse generator (CPG). Each code's bit pattern is stored in PROMs in the CPG whose output is hardwired to the 30-MHz radar exciter. On initiation of the transmitted pulse, the selected code is clocked serially out to the exciter, where the 30-MHz phase is modulated. The clock rate (and thus the baud length) is determined by the CPG clock, which may have a period from 1.0 μs to 3.2 μs, in increments of 200 ns. The modulated 30-MHz signal is upconverted to 440 MHz and applied to the driver amplifier.

The complex envelope of the backscattered signal is received at a low-noise parametric amplifier, down converted to 30 MHz IF, bandlimited, and quadrature detected in a linear detector. The detected complex signal is digitized by a pair ot 12-bit A/D converters, sampled at a programmable rate corresponding to the baud length, and transferred to the signal processor (array processor).

Figure 2 shows details of the Radar Timing Control. The CAMAC timers output 14 pulses for gating the transmitter, receiver and a calibrated noise source, and for data input to the array processor. Two banks of registers contain setpoints for the timers and the CPG; only one bank can control the radar at any one time, leaving the other free to receive new setpoints. After the new values are written and verified, the Bank Select Logic will switch register banks to select the new mode. All operations are under program control; to avoid timing errors, the setpoints are calculated in advance from input parameters during program initiation and verified for consistency.

(c) Signal Processing Details

All processing of the real and imaginary digitized radar samples is performed in the AP-120B array processor in real time. The inputs to the AP are raw digitized samples; one complex sample per range gate plus additional samples for decoding are input each radar sweep. The outputs of the AP to the host computer are time-averaged power spectra, (square of the complex DFT of a time series), one for each range gate. Processing in the AP may be subdivided into pre-processing (coherent integration and decoding) and spectral estimation (calculation of power spectra). Figure 3 is a diagram of the software implementation.

The AP contains a programmable I/O processor (GPIOP) which receives the

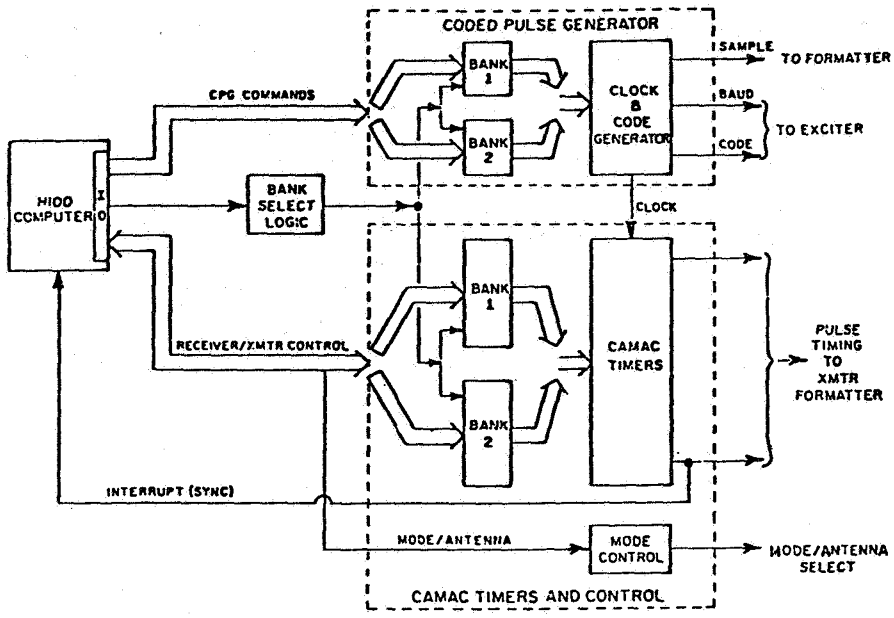

Figure 2. Radar control details showing control paths between H100 computer and radar transmitter and receiver. Clock rates for input samples and for baud length are output by CPG; timing pulses are output by CAMAC timers, and ancillary functions are selected by mode control.

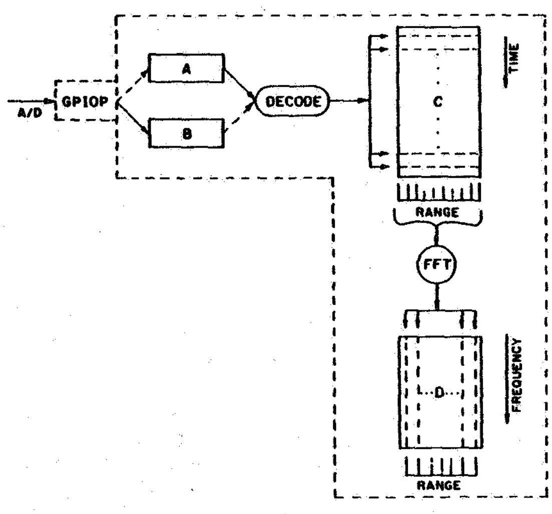

Figure 3. Signal processing.

digitized complex samples from a locally built "formatter" module in response to interrupts from the radar timers. As received, the 2 12-bit integers are packed into a 32-bit word. The GPIOP processor unpacks the samples and converts the integers to 38-bit AP floating point numbers. These are then transferred to input buffers in AP main memory; a separate processor in the GPIOP controls the word count and buffer addresses. Samples are pre-processed in blocks of 4 radar sweeps, in order to provide adequate time to decode. Two AP memory input buffers are defined (A and B in Figure 3), and pre-processing proceeds in parallel with input, in a double-buffered mode. The GPIOP fills one input buffer with samples from 4 consecutive radar sweeps. During this time, the AP: (1) integrates the samples in the other buffer, (2) decodes the resulting 2 sweeps of samples according to the appropriate complementary code, (3) adds the resulting decoded sweeps of samples to cancel their autocorrelation sidelobes, and (4) transfers the result to intermediate buffer C. This process presume and decodes 4 sweeps of data, with one set of samples as a result. If additional coherent integration (modulo 4) is specified, the transfer process ("4" above) sums the results to previous samples in buffer C. The pre-processing then switches to the other input buffer, and continues until buffer C has been filled.

Pre-processing in this manner requires considerable computation speed, and is beyond the capabilities of a general purpose computer. For this reason, previous phase-coded implementations have used a hardware correlator to decode the radar samples. The computational speed of the AP microcode has allowed us to eliminate the need for a hardware correlator; an additional benefit is the flexibility of the processor to operate in various modes of signal processing. The 6-MHz rate of computations and the fact that decoding is simply a one-bit-multi-bit correlation allows these processes to be carried out in real time for the codes used and for a sufficient number of signal heights. Although the AP cannot process as fast as hardware decoders, it is adequate for the number of heights required for typical ST observations. The typical interpulse period used at Millstone Hill is 2 ms, leaving 4x2 ms = 8 ms for the AP to complete its tasks. Table 2a gives some timing limitations of the pre-processor. These limits depend only on the specific code and the number of ranges specified, and are independent of the number of coherent integrations or the number of spectral points. These are timing limits for the pre-processor only. More stringent limits are imposed by the memory size (32 k at present) of the AP, and Table 2b gives some overall limits of the processor with this memory configuration. Efforts are presently underway to increase the memory size to 64 k, and the limits for this configuration are also listed in the table.

Following the pre-processing of a specified number of radar sweeps to fill buffer C, input is suspended and power spectra are estimated for each range. A vendor-supplied FFT routine computes a complex DFT, which is then squared and summed to previous spectra in output buffer D. Total power and dc levels are also calculated and stored in buffer D. Input of samples is then resumed, and the process repeats for a specified number of cycles. Note that although samples are input in a double buffered mode, the overall processor runs single buffered. This leads to a "dead time", when input is suspended, of ~1-2% of the total integration time for typical experimental parameters.

At the end of the integration period, the processor halts and the time-averaged spectra, power and dc levels are transferred to the host computer and written to disc as formatted data records for subsequent tape storage and off-line processing. If desired, the raw spectra and simply processed spectra may be displayed on a fast vector display in real time. The host computer downloads the next set of experimental parameters to the radar system, and processing resumes. The flexibility and rapid switching capabilities of the system allow one observation to differ in any or all aspects from the previous one. In particular, the start range can be changed to the last range observed in the

Table 2a. Pre-processing limits imposed by AP computation speed

CODE	NUMBER OF RANGES
16-bit complementary	450
32-bit complementary	250

Table 2b. Processing limits imposed by AP memory size

SPECTRUM LENGTH	NUMBER OF RANGES 32k Memory	64k Memory
32	340	681*
256	38	84
512	18	42
4096	1	5

*Although this exceeds the number of ranges given in Table 2a, a minor software change can permit such operation. In this case, the number of coherent integration must be a multiple of 8 rather than 4.

previous record, to compensate for the height limitation imposed by AP memory size. At a sacrifice in time resolution, heights from ~8 to 30 km can be scanned in short order, typically 3-4 minutes. As explained in the next section, the smearing of FFT processing can be reduced by increasing the time series, and spectra with 512 FFT points are typically used at Millstone Hill. The 32-k memory size of the AP restricts the number of ranges to 17 (plus 1 noise range). Using 300 m resolution, about 5 km of range can be observed simultaneously, and a radial velocity resolution of ~4 cm/sec is obtained. To cover the total range of ~20 km (from 8 to 28 km) four successive records will suffice. An integration time of ~40 sec per record provides a good SNR, yielding a cycle time of ~3.5 minutes.

(d) System Tests

A series of tests were conducted to estimate the overall system performance for the complementary code mode of observations. The method employed was to inject a coded 440-MHz signal into the receiver, and then run the data collection program as in an actual experiment. The code was synchronized with the radar sweep interrupt (T0) and repeated continuously along the time base. A complementary code and its partner were interchanged as in an actual experiment. This technique exercises all receiver and processing components: IF mixing, sampling, bandlimiting, signal processing, formatting, range tags, etc. In the absence of noise, and with complete sidelobe cancellation, a strong power peak will appear at zero frequency every N-th range gate for an N-element code. The first peak will occur at an integral multiple of (NxBaud) microseconds after T0. For a perfectly matched input filter, no spillover of power to adjoining range gates will occur. Furthermore, the peak at zero frequency will be very narrow in frequency, and no signal will be present in other frequency bins.

In practice, the sharpness of the peak and its amplitude above the noise will give a measure of system performance. Figure 4 is an example of such a test. Here, a 16-bit complementary code was used; eight coherent integrations were employed, yielding a frequency bandwidth of 60 Hz (18 m/s), and 512-point power spectra were estimated at 18 range gates (the top spectrum is the noise gate). The log of the raw spectra is shown on the left; the right plot is a log plot of the relative power at each range. Frequency resolution here is ~.11 Hz (velocity resolution ~3.3 cm/sec). The sharp peak at one range gate, with an amplitude ~25 dB above the noise, indicates good performance. This peak reappears every 16 range gates as the receiver window is moved along the time base.

OBSERVATIONS USING COMPLEMENTARY CODES

The received signal from ST observations at Millstone Hill comprises ground clutter, system noise, interference, and atmospheric signal. The ranges of interest are severely contaminated by ground clutter, with power levels often 60 dB above the signal. If this clutter were confined to a single (zero) frequency, it could easily be removed and spectral moments estimated after filtering interference and noise. However, the clutter is fading clutter, with a finite width about zero frequency. This effect is exacerbated by the "spill-over" effect of FFT processing, and complicates spectral moment estimation, especially when the atmospheric signal has a small Doppler shift. At Arecibo Observatory (SATO and WOODMAN, 1982b) this effect is handled by a nonlinear least squares fit of a parameterized function which includes the clutter. At Millstone, the clutter is much more intense than at Arecibo, due to the lack of natural sheilding. Although a fitting technique will be employed to estimate moments, this task is simplified by computing spectra from long time series, thus collapsing the clutter to nearly its intrinsic width. If the number of spectral points is increased to 2048 or 4096, the clutter width is extremely narrow, and signals with very small Doppler shifts can be clearly identified (WAND et al., 1983). However, due to limited AP memory size, a compromise must be made, since the number of range gates that may be observed decreases with increased in spectral length (see Table 2b). A spectral length of 512 points yields a fairly narrow clutter width, and 17 signal ranges plus 1 noise range may be observed at present (32k AP memory). With a baud length of 2 μs (300 m

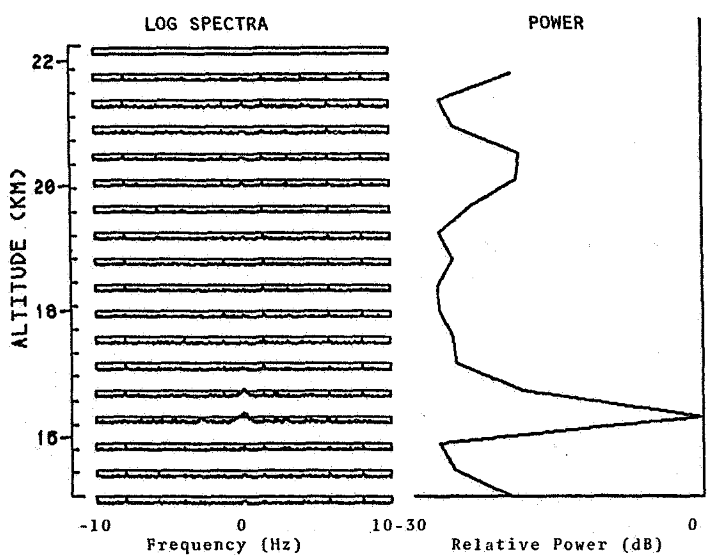

Figure 4. Test signal. (See text for details.)

resolution), a total range of ~5 km is covered at once. This alone is insufficient for ST observations, which should cover the altitude range of ~8-~30 km. This can be rectified, at a sacrifice in time resolution, by moving the start range to successively higher altitudes for 3 to 4 successive records. (Alternatively, the AP memory size may be increased to 128k, giving adequate storage for the full ST range.)

Figure 5 shows the raw spectra for such an experiment. Here, 3 successive records are merged, with altitude coverage from 12 to 29 km and altitude resolution of 300 m. Twelve of the 51 signal ranges are shown. Each spectral plot is a superposition of 6 observations, so that a total of 18 integration periods is represented. The variance of the signal seen in these plots is a measure of the variability of turbulence at each height over this period of ~1 hour. The frequency bandwidth is 20 Hz, velocity bandwidth 6 m/s, and velocity resolution ~1.5 cm/sec. Signals can clearly be seen up to 20 km, and again at 24-25 km altitude. The clutter still has a wide frequency spread, even with a 512-point power spectra, but is manageable and appears to be a good candidate for removal using fitting techniques.

Figure 6 shows a 30-hour time series of 2 selected heights from a similar experiment. These spectra were gathered on the steerable antenna at 5.8 deg from the zenith. The frequency bandwidth was increased to 60 Hz (18 m/s), and velocity resolution ~3 cm/sec. Atmospheric returns are seen with varying intensity and frequency (radial velocity) throughout this period.

SUMMARY

A phase-coded mode of ST observations has been successfully implemented at Millstone Hill, using a programmable array processor to perform signal processing in real time. Its capabilities are sufficient to gather spectral observations over an altitude range of 20 km in some 3-4 minutes, with a spatial resolution of 300 m and radial velocity resolution of ~2 cm/sec. Atmospheric returns from the UHF radar are observed up to 25 km.

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REFERENCES

Balsley, B. B. (1981), MST techniques - A brief review, J. Atmos. Terr. Phys., 43, 495-509.

Holt, J. M., J. V. Evans, W. L. Oliver and R. H. Wand (1980), The upgraded Millstone Hill radar, Radio Science (in press).

Rastogi, P. K. (1981), Radar studies of gravity waves and tides in the middle atmosphere: A review, J. Atmos. Terr. Phys., 43, 511-524.

Rottger, J. (1981), Investigations of lower and middle atmosphere dynamics with spaced antenna drifts radars, J. Atmos. Terr. Phys., 43, 277-292.

Sato, T. and S. Fukao (1982), Altitude smearing due to instrumental resolution

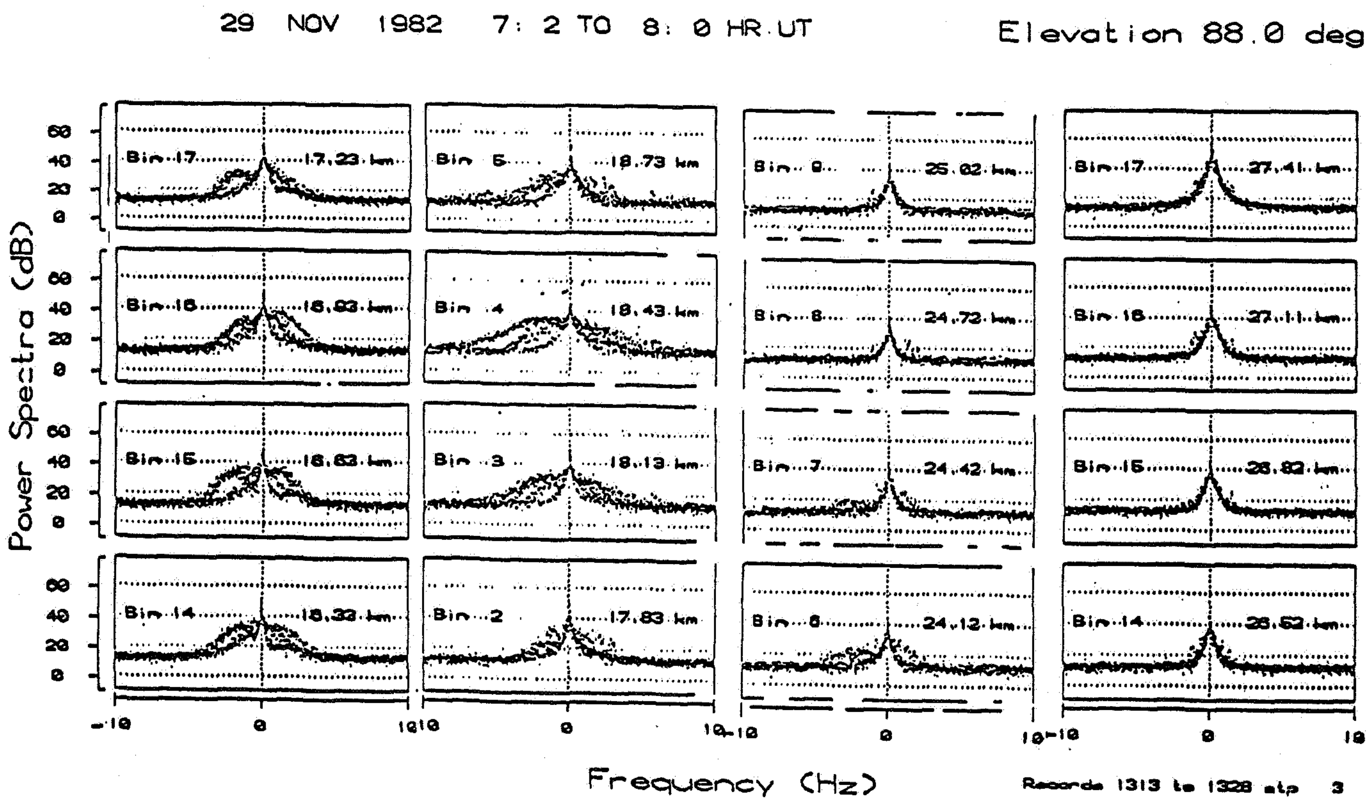

Figure 5. Raw spectra observed using complementary codes. Altitude coverage was 12 to 29 km, 300 m resolution. About 1/4 of the ranges are shown.

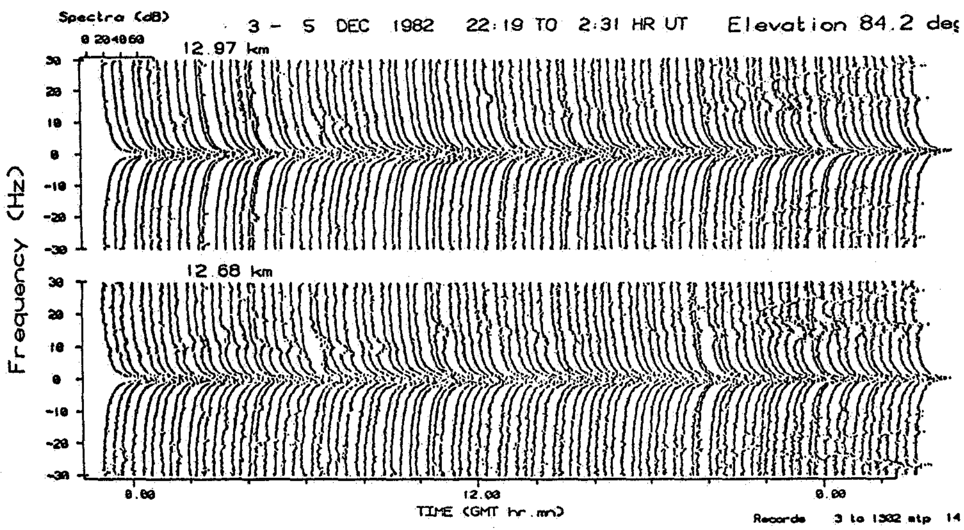

Figure 6. Time series of spectra. A 30-hour time series of phase-coded observations. Spectra at 2 heights are shown. Height resolution is 300 m, velocity resolution is 1.5 cm/sec.

in MST radar measurements, Geophys. Res. Lett., 9, 72-75.

Sato, T. and R. F. Woodman (1982a), Fine altitude resolution observations of stratospheric turbulent layers by the Arecibo 430 MHz radar, J. Atmos. Sci., 39, 2546-2552.

Sato, T. and R. F. Woodman (1982b), Spectral parameter estimation of CAT radar echoes in the presence of fading clutter, Radio Sci., 17, 817-826.

Schmidt, G., R. Ruster and P. Czechowsky (1979), Complementary codes and digital filtering for detection of weak UHF radar signals from the mesosphere, IEEE Trans. Geosci. El., GE-17, 154-161.

Turyn, R. (1968), Sequences with small correlation, in Error Correcting Codes, ed. H. Mann, 195-228, J. Wiley, New York.

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. (in press).

Watkins, B. J. and R. H. Wand (1981), Observations of clear air turbulence and winds with the Millstone Hill radar, J. Geophys. Res., 86, 9605-9611.

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

Woodman, R. F., R. P. Kugel and J. Rottger (1980), A coherent integrator-decoder for the SOUSY-VHF radar, Radio Sci., 15, 233-242.