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8.0 AN OVERVIEW OF DATA ACQUISITION, SIGNAL CODING AND DATA ANALYSIS TECHNIQUES FOR MST RADARS

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INTRODUCTION

In this paper, I will attempt to give an overview of the data-acquisition, signal-processing, and data-analysis techniques that are currently in use with high-power MST and ST radars. Many of the topics discussed here have also been the subject of papers presented at the two previous MAP Workshops on MST Radars, and have been reviewed by RASTOGI (1983) and FARLEY (1984). This review supplements, and hopefully augments, the work discussed in these papers. An additional useful reference is the comprehensive review of the MST technique by ROTTGER (1984).

We begin with a general description of data-acquisition and signal-processing operations and attempt to characterize these on the basis of their disparate time scales. Then signal-coding techniques, a brief description of frequently used codes, and their limitations are discussed, and finally, several aspects of statistical data-processing such as signal statistics, power-spectrum and autocovariance analysis, outlier-removal techniques, etc. are discussed.

DATA-ACQUISITION AND SIGNAL-PROCESSING OPERATIONS

It is interesting to note that although all the signal-processing operations in MST radars are carried out in time, these operations can be conveniently divided into three different categories on the basis of their time scales as shown in Figure 1.

The operations that proceed most rapidly, at scales of the order of a μsec , take place along the T_z axis. Time measured along this axis scales directly to radar range z through $z = 0.5 cT_z$. The total span of the T_z axis is of the order of 1 msec corresponding to a maximum range of 150 km. The operations along this axis include transmitter pulse shaping, receiver impulse response, range gating, signal coding, and decoding. Each point along this axis represents a complex sample, with an in-phase and a quadrature component, corresponding to a range cell. The samples are usually digitized to an accuracy of 8-12 bits. The time-resolution along the T_z axis should correspond to the most rapid modulation imposed on the transmitted pulse, and the duration of the receiver impulse response should be closely matched to it. In the simplest MST radar experiments this resolution is the duration of the transmitted pulse, typically 10 μsec . In coded-pulse experiments, the scale along the T_z axis corresponds to the duration of a code element, typically 1 μsec . The only operation that proceeds more rapidly than the time-scale along the T_z axis is that of analog to digital (A/D) conversion of the received signal. For using signal coding, not only should the A/D converters be fast with a conversion time of only a fraction of a μsec , they should also be linear over a wide dynamic range (about 60 dB) that includes low-level noise as well as the strong ground clutter and interference.

The time scale along the T_y axis is measured in units of the interpulse period (IPP), that is typically of the order of a msec, and it extends for times of the order of 10-100 sec. For each channel or range cell, a digitized complex sample is obtained every IPP. The operations along the T_y axis

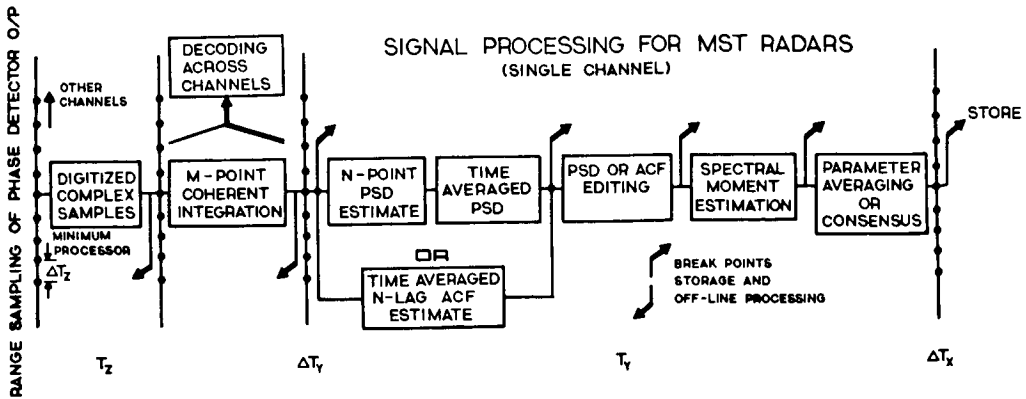


Figure 1. Signal-processing operations in MST radars can be decomposed on the basis of three different time scales as shown above. The specific operations that proceed at these time scales are shown in the boxes. In some cases, decoding is carried out after coherent integration.

include coherent integration of the digitized complex samples, estimation of averaged power spectral density (PSD) of the integrated samples, automated editing of the spectral estimates, and finally estimation of the basic spectral-moment parameters. An equivalent amount of information can be obtained through autocovariance function (ACF) of the coherently integrated samples.

In most MST radar experiments, the received signals have a small bandwidth with fading times of the order of 0.1 sec. A sufficiently large number M of digitized complex samples can therefore be added together, thus resulting in a substantial reduction in data rate. When a coding scheme is used during transmission, the operation of signal decoding can often be relegated until after coherent integration for slowly fading signals, with a remarkable saving in computational effort. For a linear system, the operations of coherent integration and decoding are commutable. The estimation of PSD or ACF of the received signal is carried out on finite blocks (of length N) of coherently integrated samples. Usually some time-averaging of these estimates is desirable. Estimates of averaged spectra for all the channels are supposed to be available at the far end of T_y axis, at intervals of the order of 0.1 to 1 min. The final operations along the T_x axis involve spectral editing and spectral-moment estimation. The averaged PSD estimates often are contaminated with undesired signatures due to ground clutter, aircraft echoes, and ducted returns. Algorithms for removing the effect of these signatures tend to be ad-hoc in nature and are often implemented in post-processing. Algorithms for obtaining low-order spectral moments of the averaged PSD estimates vary in their sophistication from evaluation by definition, to rigorous least-square fits to idealized spectral shapes.

The time-scale along the T_x axis is of the order of 1 min. The operations carried out along this axis can be classified under statistical data analysis. These operations include post-processing of averaged PSD estimates to obtain time-series of physical parameters for all range cells and for all antenna pointing directions.

Even though all of the signal-processing operations mentioned above have become reasonably standardized, the details of their implementation differ

considerably from one radar to another. Figure 2 shows the sequence in which these operations are usually carried out. An important decision in the overall organization of these operations pertains to their division into real-time (or on-line) and off-line (or post-) processing. Processing in real time requires synchronization of all the data acquisition, housekeeping, and processing modules -- usually through access to additional fast processors. The data input rate to a real-time processor is typically 0.5 Mbyte/sec for a 256-channel radar. If the processor obtains averaged 128-point spectra for all channels in the form of 4-byte integers at intervals of 1-min, then the data output rate is only about 131 kbyte/min. To provide this near 250-fold reduction in data rate, the processor needs the ability to carry out over a million multiplications per sec. The numbers on which the processor operates are, of course, irretrievably lost and the processing scheme is relatively inflexible. A 'minimum processor' on the other hand would merely transfer raw data samples to a storage medium, relegating the major computational tasks to an off-line processor for a later time. Off-line processing allows the experimenter total flexibility in examining and reducing the data. There is, however, a serious limitation in terms of storage requirements. Due to the very high data-input rates, a standard 9-track, 2400; 1600 bpi tape can accommodate only 1-2 min worth of raw data samples. Most MST radars tend to make a compromise between these two extremes, depending on the available storage and real-time processing facilities.

Figure 2 shows several other breakpoints for dividing up the processing effort into real-time and off-line. At the breakpoint chosen, the partially processed data are transferred to a storage medium. The most common breakpoints are either after coherent integration (before or after decoding), or

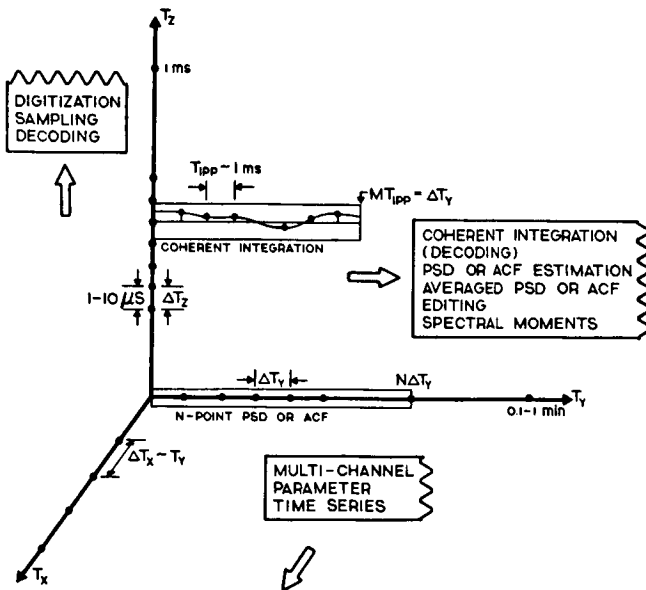


Figure 2. Sequence of signal-processing operations for a single channel is shown above. Sampling and digitization of phase-detector output provides a time sequence of complex samples for each channel. Decoding is carried out across channels. Oblique arrows show possible breakpoints for on-line and off-line processing. PSD estimation may be replaced by an equivalent ACF estimation.

after averaged PSD estimates have been formed. Editing of averaged PSD estimates and spectral-moment estimation is invariably carried out off-line. When the alternative method of obtaining spectral moments through the ACF estimates is followed, it can be very simply implemented in on-line processing. It suffers from a serious limitation, however, that no subsequent correction can be applied for external interference.

Some form of display routines are essential for monitoring the progress of experiments. When PSD estimation is not carried out in real time, ACF estimation for a small number of time lags can still be implemented on-line to provide a display of the low-order moments for a few representative ranges. At MST radar installations with more sophisticated processing and display facilities, it is usual to display averaged PSD estimates for all ranges. Such displays allow experimenters to take crucial real-time decisions.

In the simplest data-acquisition schemes, the input data stream is directed to a memory buffer. Data acquisition is halted once the buffer is full, and at the same time the processor starts working on the numbers in the buffer and updates the processed results. Such single-buffer schemes are simple to implement, but work with only a fraction of raw data that could be handled with improved data-acquisition schemes. Most data-acquisition systems have a direct memory access (DMA) channel, which permits transfer of data to a memory buffer. As long as the DMA channel and the processor do not share the same memory buffer at the same time, data transfer and processing can proceed concurrently. The DMA channel can interrupt the processor but the converse is not true. If sufficient memory is available, then data-throughput can be increased by adopting a dual-buffer scheme in which two data-acquisition and processing paths are maintained in parallel, all the way from input to output. One buffer is processed while the other is being replenished, and vice versa. There is a trade-off between available memory, processor speed and data throughput. This permits the use of one or several slow-processors in a multibuffer scheme. With the declining cost of microprocessors and large-scale memory chips, such schemes have become a viable alternative to large, dedicated processors for MST radar applications.

In large processors that allow several programs to run concurrently at different priorities, on-line processing tasks can be broken up into modules in such a way that time-critical operations, e.g., range gating and digitization, PSD of ACF estimation etc., run at the highest priorities. Operations such as display can be run on a very low priority. To ensure proper synchronization of these operations, a high-speed processor or an auxiliary parallel processor is usually required.

SIGNAL CODING AND DECODING

The atmosphere behaves as a diffused random medium for radio waves. The objectives of radar experiments are to probe it with as fine a range resolution as possible, and to measure its velocity precisely. To attain a fine range resolution, the radar must send an infinitely narrow pulse. For precise velocity measurements, it must send a pure sinusoidal waveform. The two objectives are clearly contradictory. For a slowly moving medium, a compromise is effected by sending a modulated pulse train in which pulse duration is T_t , PRI is T_p , and the duration of pulse train is T_D . In this scheme, often called the single-pulse technique, the range resolution is $0.5 c T_t$ and the radial velocity resolution is $c/2f_0 T_D$, for a radar frequency f_0 . This is a standard mode of operation for many MST radars.

An obvious way to improve the range resolution, i.e., to decrease it, is to reduce the pulse duration. This is actually the approach followed in a few

tropospheric radar experiments, but it has the following disadvantage. Since practical transmitters have both a peak power and an average power limitation, sending narrow pulses at a given PRI reduces the average power that in turn degrades the received signal power and detectability of Doppler shifts. Since the range is aliased beyond $0.5 cT_p$, the PRI cannot be very much reduced below about 1 msec.

An alternative method is to transmit a broad pulse, but to modulate the phase of the radio frequency carrier in accordance with a code. Successive parts of the scattering volume are now illuminated with different phases, but this can be undone through an inverse operation called decoding on the received signal. To provide a fine range resolution, a phase code should have an almost impulse-like ACF. The decoding operation then merely involves correlating the received signal with a delayed replica of the code. For two-level or binary phase codes, the decoding operation can be implemented without actual multiplications, using additions only. For this reason, and because of technical limitations in applying multi-level phase modulation to radar transmitters, binary phase codes have been widely used in MST radar experiments.

A binary phase code is simply a sequence of 0's and 1's (or + and -), where a 0 or + denotes a reference phase and a 1 or -, a phase shift of 180 deg. The time T_B corresponding to the duration of a 1 or 0 is called a baud or baud length, a term derived from telegraphy. The code length can be expressed either in bauds or in time units. Phase codes that achieve an impulse-like autocorrelation function provide a range resolution of the order of $0.5 cT_B$, corresponding to the baud length. Some examples of the most commonly used binary phase codes are given below.

Barker codes. These codes are known for several lengths $n \leq 13$. The value of autocorrelation function is n at zero lag, but 0 or 1 at all non-zero lags. This code is useful when the scattered signal has a large bandwidth or a large Doppler shift, e.g., in D-region incoherent-scatter experiments (where these codes were first applied), and low-elevation ST experiments. The codes for several values of n are given below (GOLOMB and SCHOLTZ, 1965).

$n = 1$	+	1
$n = 2$	++	2
$n = 3$	++ -	2,1
$n = 4$	+++ -	3,1
$n = 5$	+++ - +	3,1,1
$n = 7$	+++ -- + -	3,2,1,1
$n = 11$	+++ --- + -- + -	3,3,1,2,1,1
$n = 13$	+++++ -- ++ - + - +	5,2,2,1,1,1,1

Complementary code pairs and sets. These codes form pairs, or more generally sets, with a very interesting property. The autocorrelation functions for the individual codes have sidelobes that exactly cancel each other upon addition. For complementary codes of length n , the sum of the two autocorrelation functions is $2n$ at zero lag and zero at all other lags. This behavior is near ideal. In order that perfect sidelobe cancellation may occur, it is imperative that the scattering medium should remain unchanged during illumination by the two codes in the pair, i.e., over at least two p.r.i.'s. In the most commonly used form of MST radar experiments, this happens to be true for several (tens to hundreds) p.r.i.'s. An interesting application of linear system theory provides a great saving in computations required for decoding complementary code pairs. If the signals corresponding to each code are separately and coherently integrated, then decoding can be done after coherent integration. Several complementary code pairs, adapted from RABINER and GOLD (1975), are given below.

```

n = 2      ++
           + -
n = 4      +++ -
           ++ - +
n = 8      +++ - ++ - +
           +++ --- + -
n = 16     +++ - ++ - ++++ --- + -
           +++ - ++ - + --- +++ - +
n = 32     +++ - ++ - ++++ --- + - +++ - ++ - + --- +++ - +
           +++ - ++ - ++++ --- + ---- + -- + - +++ --- + -

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The basic property of complementary code pairs, that the sidelobes in their ACFs cancel each other when the ACFs are added, can be extended to sets of codes. In his original paper, GOLAY (1961), discusses methods of forming complementary code sets from code pairs of lengths $n = 2^k$ as well as for a few other values of n . SARWATE (1983, 1984) discusses methods of forming feedback shift-register sequences with complementary property. For integer values of k , 2^k sequences of length $2^k - 1$ exist. For MST radar applications, complementary code sets for $n \leq 6$ should be useful. In using such code sets, some of the simplicity of decoding with complementary code pairs is lost since it is no longer possible to use coherent integration due to limitations on fading time of signals, and on the number of separate memory buffers that can be maintained. Use of fast pulse-by-pulse decoders becomes essential in this case.

Quasi-Complementary Code Sets. For a baud length T_B μ sec, the transmitter should have a nominal bandwidth of $(1/T_B)$ MHz. For this finite bandwidth of the transmitter, abrupt phase transitions required for ideal phase codes cannot be faithfully reproduced. A desired phase relation may only be attained after many cycles of the carrier have elapsed. For this reason, the ideal performance of binary phase codes is rarely achieved, even if the signals returned from the atmosphere remain perfectly coherent. It is feasible to carry out a selective Brute-Force search for code sets that are quasi-complementary at a specified ACF sidelobe level. An exhaustive search of this kind is impossible even for short code lengths, e.g., 32 (SULZER and WOODMAN, 1984). When the ACFs for the entire code sets are added together, the sidelobes are at a finite though small level. The sidelobe levels tend to become randomized and even smaller when quasi-complementary code sets are used with a transmitter of finite bandwidth $1/T_B$ for probing a slowly fluctuating medium.

An empirical search for quasi-complementary code sets has been made by SULZER and WOODMAN (1984). The search was made through 0.7 billion codes of length 32 using about 350 hr of computations on an array processor connected to a host minicomputer, to first screen about 300 codes with acceptable sidelobe properties. From these a set of 48 codes was selected to give an acceptable collective sidelobe performance. In actual tests, the performance of this code set was indeed found to be superior to a complementary code pair.

Due to their inherent complexity, the use of sophisticated coding and decoding schemes is likely to be limited to only a few research facilities, most notably the Arecibo Observatory where a planetary radar decoder has been available for MST work. With the development of alternative decoding hardware (SULZER and WOODMAN, 1983; PETITDIDIER et al., 1985) it is certain that these schemes will find wider application.

Two additional limitations of coding schemes should be stressed at this point. The first one pertains to ground-clutter performance. Since a wide transmitted pulse is used, the average transmitter power in coded-pulse experiments is frequently larger than without signal coding. The ground-

clutter problem thus becomes more severe at larger ranges. The second limitation pertains to the length of the code. Since decoding is implemented as a correlation in range, a total number of range cells corresponding to the code length is wasted. In a 256-channel experiments using a 32-baud code, only 224 channels are available after decoding. Long codes are therefore not very useful for standard monostatic radar experiments. They are, however, quite useful for bistatic experiments.

ASPECTS OF STATISTICAL SIGNAL AND DATA ANALYSIS

In this section, we consider aspects of signal and data analysis with application to MST radars.

Signal statistics. In recent years, two distinct scattering mechanisms have been identified, viz. volume scattering from refractivity fluctuations and specular reflections from sharp refractivity gradients. Evidence for these mechanisms comes from observations of aspect sensitivity and spectral characteristics of scattered signals. An alternative method of discriminating between the two mechanisms is on the basis of signal statistics, in terms of their moments, probability density function, and higher-order spectra. Since the emphasis in most MST radar experiments is to obtain the PSD or ACF of the signals, there is very little direct information available on their statistics. The necessary observations for this type of analysis can be obtained by using the 'minimum processor' mentioned earlier for a small number of range cells.

PSD and ACF estimation. The PSD of the received signals is estimated as their time averaged periodogram using the discrete Fourier transform (DFT) methods. Essentially, a block of n coherently integrated complex samples is transformed, and the squared magnitude of the transform is averaged in time. The averaged PSD estimate thus obtained gives only a distorted and aliased estimate of the ACF when Fourier transformed. The direct ACF estimates obtained by an averaged lagged-product method do not have this restriction and are clearly superior. The DFT method, despite its serious drawback, has become the standard procedure for estimating the PSD. The PSD estimates can be improved by padding the sample block with n zeros and transforming the resulting $2n$ points at a time.

Data smoothing and outliers. Radar data are frequently contaminated with data points of dubious validity. Visual inspection of almost any time series will show a few points that clearly do not belong. Such points are usually called outliers. Manual editing of outliers is impractical for large data sets. Direct averaging of data points is likely to yield a biased and even meaningless average. The following procedures based on median and order statistics reduce the effect of outliers on averages.

The median of a given data set is a more realistic indicator of its average than the mean. For a long data sequence, a 7-point running median (e.g.) performs better smoothing than a 7-point running mean and is robust with respect to outliers. Mean is obtained as a linear combination of data points, whereas median does not possess any such properties. When some smoothing is to be performed on data contaminated with outliers, a very acceptable smoothing procedure is to consider a block of n data points, sort them in ascending order, discard $x\%$ of the highest and lowest values and average over the remaining points. It is necessary to sort out only a few highest and lowest values. This scheme discriminates between data points and outliers on the basis of their magnitudes. If more is known of outlier statistics, better algorithms can be devised. No rejection scheme can be perfect, however, for some good data points may be rejected and some outliers may be accepted. A good scheme will tend to minimize these errors.

Data-analysis techniques based on median and order statistics provide a quantitative basis for handling noisy data. Recently, these methods have been successfully applied to editing and analysis of ST spectra at Millstone Hill. D-region incoherent-scatter data from Arecibo (GERMAN, 1985; YING, 1985), and power-law analysis of mesoscale winds from Poker Flat (BEMRA, 1985). Potential MST applications include improved interference rejection algorithms for spectral moment estimation, and improved filtering schemes for automated analysis of large data sets.

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SUMMARY

The keynote paper on this topic reviewed salient aspects of data acquisition, use of phase codes and decoding techniques, estimation of ACF and PSD, and data-processing methods used in MST radar probing of the atmosphere. Additional papers on this topic focussed on three important areas. These papers were followed by brief invited reviews of points that would be generally useful but are often overlooked.

CODING AND OTHER TECHNIQUES FOR IMPROVING RANGE RESOLUTION

SULZER and WOODMAN described a practical approach for implementing optimum codes for which decoding is done through "inverse" codes that correct for non-ideal behavior of high-power transmitters.

STITT and BOWHILL presented a frequency-hopping scheme within the coherence time of signals, that provides improved range resolution. This technique is equivalent to a digital frequency chirp within the signal coherence time, and is potentially useful for very slowly fading signals e.g., in HF radar experiments.

HARDWARE DEVELOPMENTS

STITT and JOHNSON described a variable frequency local oscillator, using computer controlled phase-lock loops, for de-chirping in the frequency-hopping scheme mentioned above.

BOWHILL and RENNIER described an inexpensive but versatile data-taking system using an Apple microcomputer and Forth language. This system is used in ST experiments with the Urbana radar to obtain spectral moments in real time and to display velocities up to 29 km altitude. The system cost is about \$5000.

CARTER et al. described an inexpensive preprocessor and pulse-generator card for coherent integration.

DATA PROCESSING

ROTTGER described a matched-filter algorithm for enhancing signal spectra. GREEN, YING et al., and BOWHILL discussed the application of median and related statistics for spectral and data editing. GREEN described the use of a 3-spectra median statistic, with smoothing and peak tracking, for reducing the effect of interference echoes. YING et al. presented methods based on median and percentiles for forming templates that are effective in rejecting interference in routine processing of D-region incoherent-scatter spectra. BOWHILL described a three-point median filtering algorithm due to Tukey, and discussed its effectiveness in removing single outliers.

INVITED DISCUSSIONS

ROTTGER described an on-line technique for removing the instrumental dc effects in which the phase of transmitted pulse is alternately switched between 0 and 180 deg, and the receiver output corresponding to the latter is inverted in sign. When the receiver output for successive pulses is accumulated, it is virtually devoid of instrumental dc effects. This method has been in use at Jicamarca for almost 25 years and deserves the attention of groups designing new MST radars.

SATO summarized the distortions introduced in the PSD estimates through the method of averaged periodograms using the DFT algorithms. These distortions are introduced through the aliasing of the ACF, and are most significant in the presence of a very slowly fading near dc component. The effect of these distortions is frequently apparent in UHF radar spectra contaminated by slowly fading and slightly Doppler-shifted strong ground clutter. These distortions also become very important in the analysis of meso-scale wind fluctuations with a power-law spectrum.

WOODMAN commented on the computational and SNR advantages of using coding and decoding techniques in MST radar experiments, especially when the operations of decoding and coherent integration can be commuted with little extra storage, e.g., with the use of complementary code pairs.

CONCLUDING REMARKS

It appears that an awareness of signal-processing and data analysis methods that have been developed through research use of MST radars over the last 15 years would be of benefit to groups currently involved in designing and constructing new radars. Most of the on-line signal processing tasks can be implemented inexpensively through modules using microprocessors and signal-processing chips. Median and related filtering schemes provide an effective means for automated editing of radar spectra and derived parameters contaminated with interference or other outliers. These schemes deserve further examination.