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7. OVERVIEW OF ON-LINE DATA PROCESSING FOR MST RADARS
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INTRODUCTION

The most important aspects of the processing of MST radar data were discussed in considerable detail at the URSI/SCOSTEP Workshop of Technical Aspects of MST Radar which was held at the University of Illinois in May 1983. The papers presented at that Workshop have been published recently in the Handbook for MAP, Volume 9 (BOWHILL and EDWARDS, 1983). The concepts and conclusions presented in the many papers in this Handbook are still quite up to date, and so the aim of this paper is simply to briefly review and summarize the important points.

The analysis of the data can be divided usually into on-line and off-line portions. The on-line processing significantly compresses the data via time averages and usually produces power spectra or autocorrelation functions (ACFs). The off-line processing involves curve fitting and parameter extraction. The details of the latter depend upon the experiment, the facilities of the observatory, the types of interference that must be coped with, etc., and hence are quite variable. The goals and techniques of the on-line processing are less variable and better established, and it is these that this paper will focus on. Further details of the subjects to be discussed below are given in papers in the MAP Handbook just mentioned.

The goals of the on-line and now almost exclusively digital processing, procedures are to achieve good altitude resolution and coverage, good frequency (Doppler shift) resolution, and good time resolution, while avoiding, insofar as possible, the problems of range and frequency ambiguity (aliasing), ground clutter, and interference. Some of these goals are in conflict, of course, and compromises are necessary. In almost all cases, however, achieving optimum results requires some sort of pulse compression (or perhaps frequency stepping) and some coherent integration (voltage averaging). The first allows full utilization of the average power capability of the transmitter and the second reduces the computing requirements.

PULSE COMPRESSION BY PHASE CODING

It is easy to show that when proper processing is done, the effective signal-to-noise ratio for power, power spectrum, ACF, etc. measurements is proportional to $P_{av}\tau n^{1/2}$, where P_{av} is the average transmitter power, τ is the pulse length (or baud length for a phase coded pulse) or the inverse of the total pulse bandwidth for a chirped pulse) and the inverse of the receiver bandwidth (matched filtering), and n is the number of independent samples averaged (incoherently). For most radars the most practical way to achieve good range resolution (small τ) and still use the full power capabilities of the transmitter is through pulse compression obtained with binary phase codes. A relatively long pulse is divided up into n shorter bauds of equal length, some of which are shifted in phase by 180°. If the target remains phase coherent for a sufficiently long time, the radar echoes can be processed (decoded) in such a way that they are nearly equivalent to echoes received from a pulse of one baud length but n times the actual transmitted peak power. The compression is usually not quite perfect; the echo from a single point target would consist of weak range "sidelobes" as well as the main echo. The decoding process consists of passing the received signal through a matched filter whose impulse response is the time inverse of the transmitted pulse. This amounts to cross-correlating the signal with a replica of the transmitted pulse. The codes in general use fall into a number of general classes.

(a) Barker Codes

These were first discussed by BARKER (1953) and are used extensively in incoherent-scatter measurements. The distinguishing feature of these codes is that the range sidelobes have a uniform amplitude of unity. For example, the phase coding sequence and the ACF (the voltage pattern of the decoded echo from a stationary point target) for a 5-baud Barker code are

$$\begin{array}{c} + \; + \; + \; - \; + \\ \ldots 0\;0\;1\;0\;1\;0\;5\;0\;1\;0\;1\;0\;0 \ldots \end{array}$$

If the compression were perfect, only the 5 would be present in the ACF; the 1s are the unwanted range sidelobes. The maximum value of n for Barker codes, which all have this same ACF pattern, is 13. The signal-to-noise ratio in the central peak is increased by a factor n (not n^2), since the noise in each decoded sample is the sum of n independent samples.

The compression process only works if the correlation time of the scattering medium is substantially longer than the full uncompressed length of the transmitted pulse. The decoding involves adding and subtracting voltages, not powers; if the scattering centers move a significant fraction of a radar wavelength between the time of arrival of the first and last baud of the pulse, the compression process will fail. This is never a problem in practice in MST observations, but can be a problem in ionospheric studies. In fact, the correlation times in the troposphere and stratosphere are usually so long (the order of tenths of a second or longer) that more powerful compression codes can be used.

(b) Complementary Code Pairs

Although the range sidelobes for Barker codes are small, they can still cause problems in MST work because the scattering cross section decreases so rapidly with altitude (2-3 dB per kilometer). Comlementary codes completely eliminate this problem, at least in principle; they have no range sidelobes at all. The existence of these codes was first pointed out by GOLAY (1961) and is mentioned in some radar literature (RABINER and GOLD, 1975), but they are impractical for most radar applications because the targets must have very long correlation times. It was Woodman who first noticed their potential for MST work and his suggestion led to their first use in studies at SOUSY (SCHMIDT et al., 1979) and Arecibo (WOODMAN, 1980a) with 32-baud codes and 2 and 1 μs baud lengths, respectively (300 and 150 m resolution).

Complementary codes come in pairs, and the ACFs of the two pulses have the property that their range sidelobes are equal in magnitude but opposite in sign, so that if the medium stays coherent over the interpulse period (IPP), the output voltages from the pair of echoes can be added, giving complete cancellation of the sidelobes, or perfect compression. One can easily verify that the 2-baud pair (++, +−) has this property. Representing such a pair as (A, B) it is also easily shown that (AB, A$\bar{B}$), where $\bar{B}$ is the complement of B, is also a complementary pair. Hence code lengths that are any power of 2 can be constructed, and also 10 times any power of 2, it turns out. The main practical limitation on the code length is ground clutter; the lowest altitude from which useful data can be received becomes higher as the code becomes longer. The computing requirements become greater too, of course, but this is usually not a serious problem because of the availability of coherent integration, as discussed below.

(c) Complementary Sequences of Complementary Codes

If the correlation time of the medium is many times longer than the IPP, more complicated sequences with complementary properties can be devised that can reduce range ambiguity (aliasing) problems quite dramatically. Ordinarily, if the IPP is T, echoes from the altitudes h, h + cT/2, etc. are mixed together. From another point of view, the ACF of the pulse sequence has identical peaks at delays or 0, T, 2T, etc. But by transmitting cyclicly a four-pulse sequence such as A, B, A, $\overline{B}$, ... and decoding by cross correlating with A, B, A, $\overline{B}$, the first undesired peak can be pushed from T out to 2T. With longer sequences it can be pushed still farther. GONZALES and WOODMAN (1984) have used this idea in HF probing of the mesosphere with an 8-pulse sequence to eliminate problems caused by multiple reflections from the ionosphere.

(d) Quasi-Complementary Code Sets

In the real world complementary codes do not, of course, work quite as ideally as described in the previous two sections, largely because transmitters do not transmit exactly the desired waveform. So in practice there will still be range sidelobes, and some of them may be serious, but just which ones depends on the actual code used and how the transmitter happens to distort it. To cope with these practical difficulties, SULZER and WOODMAN (1984) generated a set or 48 different 32-baud codes (the computer search required some 350 hours using an FPS 120 B Array Processor!) that, when used in sequence, had substantially better sidelobe properties in actual use with the Arecibo 430-MHz radar than a simple 32-baud complementary pair. The 48-code set is also less affected by the code truncation which occurs at the lowest altitudes sampled. Unfortunately, with such a scheme there are no decoding shortcuts; each pulse must be decoded in real time as it comes in, and so only observatories with very powerful digital hardware, such as Arecibo with its assorted radio astronomy devices, can take advantage of this technique.

(e) Cyclic Codes

These are sometimes also called maximal length sequences and are a well known class of codes that repeat at intervals of $N = 2^n-1$ bauds (i.e., CW transmission) and can be generated by an n-bit shift register. The ACFs of these sequences have periodic peaks of amplitude N at intervals of N times the baud length, but are unity everywhere else. If the periodic peaks cause no range ambiguity problems, and ground clutter associated with the CW transmission is unimportant, very high compression ratios can be achieved. These requirements are often met in radar astronomy applications, where such codes are widely used, but for MST studies these codes are only useful with bistatic radar systems. WOODMAN (1980b) describes the use of cyclic codes to achieve an altitude resolution of 30 m in a bistatic measurement with the 2380 MHz radar at Arecibo, and soon 15 m resolution will be possible.

FREQUENCY STEPPING

It is possible to achieve the goals of pulse compression by manipulating the frequency rather than the phase of the transmitted signal, and it is now fairly easy to do this with a computer-driven frequency synthesizer. One can either change the frequency rapidly within a long pulse or transmit a series of short pulses at a high pulse repetition rate (PRF) with the frequency stepped cyclicly. Stepping within the pulse and suitably processing the data is just "chirping", which can also be done with analog techniques. In MST applications, however, the phase coding techniques are generally more convenient. On the other hand, using short pulses and a very high PRF to raise the average power, with frequency stepping to avoid range aliasing, can be quite useful for studies at low altitudes, where pulse compression cannot be used because of ground clutter problems. To fully utilize the technique one may need to use several receivers.

COHERENT INTEGRATION

This is very simple and easy to implement digital filtering processes that was first applied to MST radar data by WOODMAN and GUILLEN (1974). It is a crude filter, but it often leads to an enormous reduction in subsequent computer processing requirements. Coherent integration consists of replacing N consecutive voltage samples from a given altitude by their sum, thereby reducing the number of samples which need to be processed in all subsequent operations by this factor N, which may be as large as a few hundred. Since this operation is linear it can be done before any decoding of compressed pulses is carried out (except for very long sequences of differently coded pulses; see above). Hence, as long as one can perform these additions fast enough, using special purpose hardware if necessary, the decoding and FFT or similar processing can be done with fairly inexpensive computers. Coherent integration is obviously most useful when the coherent time of the medium is at least an order of magnitude longer than the IPP.

The question that naturally arises is how large can N be? To analyze how coherent integration affects the signal, it is simplest to consider it to be made up of two separate operations: (1) filtering via a running average (a filter with a unit impulse response of duration T, where T is N times the IPP), followed by (2) sampling at intervals of T, which of course represents a drastic undersampling of the original unfiltered signal. The first operation multiplies the power spectrum of the original signal by $\sin^2 x/x^2$, where $x = \pi fT$ and f is the frequency in Hz. The sampling operation then leads to frequency aliasing, with signal power at frequencies f and $f \pm n/T$, where n is any integer, summed together. Somewhat surprisingly, perhaps, a signal spectrum which is flat before coherent integration will still be flat afterwards; the filtering and aliasing balance each other and white noise still looks white, with no tapering at the window edges. Upon reflection this result is not surprising, since the sum of n random noise samples is itself just random noise. On the other hand, a narrow signal peak with a Doppler shift of 0.44/T Hz, near the edge of the aliasing window, will be attenuated by 3 dB by the filter function, whereas a peak near the center of the spectrum will be unaffected. In other words, one should be conservative in the use of coherent integration and make sure that all signals of interest are in the central portion of the post-integration spectrum. Finally, it is perhaps worth reiterating that coherent integration is only a filtering procedure, a fairly crude one in fact. Exactly the same result (a slightly better result, actually) would be achieved (but at greater cost) by Fourier transforming the full original time series and retaining only the interesting part.

OTHER POINTS

For completeness, it may be worth including a few brief remarks about coarse quantization and spectral moments. It is possible to derive all the useful statistical information (except the total power in some cases) about the scattered signal (a Gaussian random variable) even if the quantization is very crude, e.g., determines only the sign bit in the most extreme case. With such quantization very high processing speeds are possible, particularly with special purpose hardward. A number of possible schemes and their associated correction factors and statistical efficiencies are discussed by HAGEN and FARLEY (1973). The use of coarse quantization has become less necessary as digital hardware has become faster and less expensive, but for some applications it is still necessary.

Turning to the question of spectral moments, it is well known from Fourier transform theory that the derivatives of the ACF at the origin (zero lag) give the moments of the power spectrum. Hence from a power measurement and a complex lagged product measurement at a single short lag, it is possible to obtain the first two moments of the power spectrum as well as the total power. If the spectrum is nicely shaped, with a single fairly symmetrical peak, these moments alone give all the important information. If the spectrum is more complicated, however, as is often the case, the full spectrum is needed.

REFERENCES

Barker, R. H. (1953), Group synchronizing of binary digital systems, in Communications Theory, W. Jackson (ed.), 273-287, Academic Press, New York.

Bowhill, S. A. and B. Edwards (1983) (Editors), Handbook for MAP, Vol. 9, SCOSTEP Secretariat, Dep. Elec. Eng., Univ. Il, Urbana.

Golay, M. J. E. (1961), Complementary series, IRE Trans. Info. Theory. IT-7, 82-87.

Gonzales, C. A. and R. F. Woodman (1984), Digital correlation techniques in radio science, Radio Sci., 8, 775-784.

Rabiner, L. R. and B. Gold (1975), Theory and Application of Digital Signal Processing, Prentice-Hall.

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

Sulzer, M. P. and R. F. Woodman (1984), Quasi-complementary codes: A new techniques for MST radar sounding, Radio Sci., 19, 337-344.

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

Woodman, R. F. (1980b), High-altitude resolution stratospheric measurements with the Arecibo 2380-MHz radar, Radio Sci., 15, 423-430.

Woodman, R. F. and A. Guillen (1974), Radar observations of winds and turbulence in the stratosphere and mesosphere, J. Atmos. Sci., 31, 493-505.

SESSION SUMMARY AND RECOMMENDATIONS

A number of the points made in the 1983 Workshop were reiterated. The theory, advantages, and disadvantages of various data-processing techniques, particularly those used on line, are now pretty well agreed upon; there seem to be no serious controversies. Nevertheless, there were a number of interesting points brought out in the papers and the ensuing discussion that seem worth summarizing here.

1) J. L. Green pointed out that there may be advantages to decoding schemes that are not equivalent to matched filtering. Such schemes can substantially reduce the range sidelobes associated with Barker codes, for example, at the cost of slightly reducing the compression ratio. Of course, Barker codes are not used too much for MST radar work, but perhaps similar ideas would work with complementary codes or quasi-complementary sets? Or perhaps such procedures might eliminate the need for the quasi-complementary sets, which can only be implemented if very powerful decoding hardware is available?

2) S. A. Bowhill discussed the concept of pulse compression via frequency chirping and pointed out that in MST applications, in which the medium has a very long coherence time, it is possible to chirp by varying the frequency on a pulse-to-pulse basis, rather than within the pulse. This is like frequency stepping, except that voltages, not powers, are added after incorporating appropriate phase factors. The advantages over conventional chirping are a reduction in ground clutter and possibly better transmitter performance. The same concepts apply to phase coding also, of course, as discussed in the overview and the paper by R. G. Strauch. One must carefully compare the range

sidelobes, etc. in both cases and the ability of the transmitter to actually generate the desired pulse shape.

3) D. V. Sarwate described algorithms for generating a wide variety of sets of complementary sequences such as, for example, 8 sequences of length 7 which have the property that the sum of the 8 ACFs has no range sidelobes.

4) M. Petitdidier and J. W. Brosnahan described new high performance preprocessing hardware which is in the advance design stage and should be relatively inexpensive. Prices of digital hardware continue to drop and performance continues to rise. The biggest problem right now seems to be long delivery times for some of the crucial chips. G. Stitt and S. A. Bowhill compared various FFT device possibilities.

5) P. K. Rastogi, S. K. Avery and C. E. Meek discussed offline analysis procedures used in extracting physical parameters from conventional MST Doppler radar data, meteor radar data, and partial-reflection drift data. The problems and solutions vary considerably from technique to technique.

Turning to RECOMMENDATIONS, it was the consensus of the group that it was worth reemphasizing the recommendation of last year. Although many observatories perform quite advanced data processing, there is still room for improvement. As the cost of hardware preprocessors and small computers declines and their power increases, it is increasingly cost effective to utilize the most sophisticated techniques. As much processing as possible should be done online in order to compress the data and reduce the tape handling and delays associated with subsequent off-line processing.

Finally, the group urged that all spaced antenna drift (SAD) measurements should be done coherently. Forming auto- and cross correlations using only the signal power or amplitudes is considerably less effective than using full complex voltage products.