6.2A PULSE COMPRESSION USING BINARY PHASE CODES

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INTRODUCTION

In most MST applications pulsed radars are peak power limited and have excess average power capacity. Short pulses are required for good range resolution, but the problem of range ambiguity (signals received simultaneously from more than one altitude) sets a minimum limit on the interpulse period (IPP). Pulse compression is a technique which allows more of the transmitter average power capacity to be used without sacrificing range resolution. As the name implies, a pulse of power P and duration T is in a certain sense converted into one of power nP and duration T/n. In the frequency domain, compression involves manipulating the phases of the different frequency components of the pulse. A short pulse consists of contributions from a wide band of frequencies, all of which are in phase at one point in space-time. Changing the phase relations on transmission lengthens the pulse, but it can be reassembled into a short pulse upon reception by proper processing _if_ the phases have not been perturbed in some unknown way in the meantime (i.e., by the scattering process). This is essentially the idea behind frequency 'chirping'.

Another way to compress a pulse is via phase coding, especially binary phase coding, a technique which is particularly amenable to digital processing techniques. This method has been used extensively in recent years in radar probing of the atmosphere and ionosphere, and it is the method we will discuss here. The general topic of pulse compression is dealt with in COOK and BERNFELD (1967), BARTON (1975), BROOKNER (1977), and other texts.

BARKER CODES

A class of codes known as Barker codes (BARKER, 1953) has been used extensively in ionospheric incoherent-scatter measurements. The Barker coded pulse is considered to be made up of n 'bauds', each of duration T, so the total duration is nT, with the maximum value of n being 13. The phase of each baud is 0 or 180 degrees (± 1), in a sequence that depends on n. The pulse is decoded upon reception by passing it through a 'filter' whose impulse response is the reverse in time of the transmitted pulse (the pulse 'played backwards', so to speak). Such a filter is said to be 'matched' to the pulse. In practice these matched filters are usually specially designed acoustic surface wave devices or conventional filters plus digitizers, digital delay lines, and some add/subtract circuitry or equivalent software.

From another point of view, the decoding process consists of cross-correlating the received signal with a replica of the transmitted pulse; hence, when an undistorted coded pulse is passed through such a decoder, the output is the autocorrelation function (ACF) of the pulse. As an example, the phase coding sequence and the ACF of a 5-baud Barker coded pulse are listed below.

+ + + − +

. . . 0 0 0 1 0 1 0 5 0 1 0 1 0 0 0 . . .

If the compression process were perfect, only the 5 would be present in the above ACF; the 1s represent undesired range 'sidelobes'. In Barker codes (n up to 13) the sidelobes are always unity and in the pattern above, and the central peak is n. For ionospheric applications the sidelobes are generally not a problem since, for n equal 13, say, the power corresponding to the central peak is 169 times greater than that in each of the 12 sidelobes. (Note that the signal-to-noise ratio in the central peak is increased by the compression by a factor of 13, not 169, since the noise is the sum of 13 independent samples.)

The above discussion is valid for scatter probing of the atmosphere as long as the correlation time of the scattering medium is long compared to the total (uncompressed) duration of the coded pulse. In practice this is always the case for MST applications but may not be true for incoherent scatter from the ionosphere, for example. Detailed calculations of what happens in the latter case are given by GRAY and FARLEY (1973), and a general discussion of the 'ambiguity function' of a Barker coded pulse as a function of target-induced Doppler shift is given in COOK and BERNFELD (1967). GRAY and FARLEY also discuss the use of multiple coded pulse sequences in the measurement of the ACF of the scattering medium. The effect of the coding is usually minimal; in typical situations the 'true' ACF is convolved with a function whose width is about one baud. Finally, although 13 bauds is the longest possible Barker sequence (unity sidelobes), there are many longer sequences with sidelobes that are only slightly larger. As an example, a 28-baud sequence with a maximum sidelobe level in the ACF of 2 is listed by GRAY and FARLEY and has been used by WOODMAN et al. (1980) for observations with the SOUSY radar.

COMPLEMENTARY CODE PAIRS

The codes discussed above have range sidelobes which are small, but which may still cause problems in MST applications. Ideally we wish to use high compression ratios (long codes) to get the best possible altitude resolution, but if we do so the 'wanted' signal from an altitude in the upper stratosphere, say, may be contaminated by range sidelobe returns from lower altitudes, since the scattered signal strength is a strong function of altitude, typically decreasing by 2-3 dB per kilometer. This problem can be completely eliminated, at least in principle, by the use of a special class of binary phase codes known as complementary codes.

The existence of complementary codes was first pointed out by GOLAY (1961) and has been mentioned in the radar literature (e.g., RABINER and GOLD, 1975), but the severe restriction on their use -- phase changes introduced by the target must vary only on a time scale much longer than the interpulse period (IPP) -- have prevented them from being utilized much in practice. The Doppler shifts encountered in military applications and in incoherent scatter from the ionosphere are much too large, for example, but the very small Doppler shifts associated with MST radar observations are entirely compatible with the use of such codes. The medium correlation time is typically tens or hundreds of times longer than the IPP.

Complementary codes are again binary phase codes and they come in pairs. They are decoded exactly as are Barker codes, by a 'matched' filter/delay line combination whose impulse response is the time reverse of the pulse. The range sidelobes of the resulting ACF output will generally be larger than for a Barker code of comparable length, but the two pulses in the complementary pair have the property that their sidelobes are equal in magnitude but opposite in sign, so that when the outputs are added the sidelobes exactly cancel, leaving only the central peak; i.e., the compression is perfect. As the simplest possible example, consider the 2-baud complementary pair below

Code:	+ +	(first pulse)
	+ −	(second pulse)
ACF:	0 +1 +2 +1 0	(first pulse)

0 -1 +2 -1 0 (second pulse)
0 0 +4 0 0 (sum)

Representing the above pair as (A, B) it is easy to show that the sequence (AB, A$\overline{B}$), where $\overline{B}$ is the complement of B, is also a complementary pair that is twice as long. Proceeding in this way one can obviously generate long n-baud code pairs, where n is any power of two. It turns out that n can also be ten, or ten times any power of two. Further properties of these sequencies are given by GOLAY (1961). In the first reported MST studies using these codes at SOUSY (SCHMIDT et al., 1979) and Arecibo (WOODMAN, 1980) n was 32 and the baud lengths were 2 μs and 1 μs, respectively (300 m and 150 m resolution).

There are two practical limitations on the maximum value of the compression rate n: (1) as n increases the effect of ground clutter extends to higher and higher altitudes; (2) the computing requirements for decoding increase with n. The first is the most serious limitation; the computing requirements can usually be handled one way or another. One process that often simplifies the computing is coherent integration (summing N successive voltage samples from a given altitude before doing any other processing). Since coherent integration and decoding linear operations they can be interchanged; e.g., samples from 100 pulses, say, can be coherently integrated and then decoded all at once. In dealing with the first limitation one must achieve some compromise between three competing goals: (1) the desire to confine strong ground clutter effects to the lowest possible range of altitudes (i.e., use short pulses); (2) the desire to avoid range ambiguity (use a long IPP); and (3) the desire to use the full average power capabilities of the transmitter to achieve maximum sensitivity.

MORE COMPLEX COMPLEMENTARY CODING SCHEMES

More complicated schemes can partly alleviate the ground clutter/range ambiguity problem. The cross correlation function (XCF) of the basic complementary transmitted sequency A, B, A, B, ... with the decoding function A, B is periodic with a period 2T, where T is the interpulse period (between A and B), but there are also substantial non-zero values of the XCF in the vicinity of T. For example, for the 4-baud pair (+++-, ++-+) the XCF is

... 0008000 ... 0040400 ... 0008000 ...

At delays near T from the 'wanted' return, in other words, the range sidelobes of the individual pulses add rather than cancel, whereas the main peak does cancel. The 4s in the above represent the most important source of range ambiguity. These can be eliminated by transmitting the more complex sequence A, B, A, $\overline{B}$, A, B, A, $\overline{B}$, ... and decoding by cross correlating with A, B, A, $\overline{B}$. The XCF for this scheme consists of single identical spikes at intervals of 2T; i.e., the first range sidelobes is pushed out to twice the interpulse spacing. By extending this idea the first sidelobe can be pushed out to even higher multiples of T. In this way a substantial range of altitudes could be probed at a very high pulse repetition frequency (PRF). In actual practice, though, some altitudes would be lost because of the necessity of blanking the receiver during actual pulse transmission and because of receiver saturation by ground clutter. GONZALES and WOODMAN (1981) used such a scheme for HF partial-reflection studies of the mesosphere at Arecibo.

QUASI-COMPLEMENTARY CODE SETS

The results presented so far have all been based on the assumption that the transmitted pulses were perfectly coded. In practice of course this won't be true; the phase shifts will require a finite amount of time and will not be exactly 180 degrees, etc. As a result, the range sidelobes for the complementary code pairs will not cancel exactly; the location of the sidelobes will depend on what sort of error is made by the transmitter. SULZER and WOODMAN (unpublished manuscript, 1982) have developed a technique to minimize this problem. Rather than transmit just a pair of complementary 32-baud codes, they transmit a sequence of 48 different 32-baud pulses. Each is decoded individually and the results are combined coherently, so in a sense the whole sequence can be considered to be a single code. But from another point of view we can think of the sequence as 24 quasi-complementary pairs, each with a different set of small range sidelobes, due partly to errors in transmission and partly to the fact that the pairs are not perfectly complementary. Because the sidelobes produced by the individual pairs have a more or less random distribution, the resultant sidelobes of the entire sequence are lower and more uniform than those of a single (imperfect) complementary pair. This is no accident of course; the codes were chosen by an extensive computer search requiring about 350 hours (!) using a Harris computer and an FPS AP120B array processor. The major disadvantage of this technique is that no coherent integration before decoding is possible; at present only the Arecibo Observatory has the digital preprocessing equipment required for the extensive high-speed decoding.

A similar idea has been developed by the same authors for mesospheric observations at Arecibo. To achieve the desired resolution of 600 m (4 μs) and fully utilize the transmitter, one would ideally use a 52-baud Barker code, which unfortunately does not exist. A good approximation to this can be achieved by a pseudo-random sequence of pseudo-random 52-baud codes found by a 10 hour computer/array processor search.

CYCLIC CODES

These codes (also called maximal length sequences) are a well-known class of periodic code which repeats at intervals of $N=2^n-1$ bauds and can be generated by an n-bit shift register. The ACFs of such sequences have periodic peaks of amplitude N at intervals of N times the baud length but are unity everywhere else. Hence if the periodic major range sidelobes cause no range ambiguity problems, very high compression ratios can be achieved. These codes are used widely in radar astronomy, since the interval between sidelobes can be made larger than the target size and ground clutter is unimportant. In MST work, however, such codes are useful only for bistatic radar systems.

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