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TRADE OFF ANALYSIS OF PULSE COMPRESSION FOR A SATELLITE RADAR ALTIMETER

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ABSTRACT

The Trade off Analyses of Pulse Compression for satellite radar altimeters conclude that when 10 cm accuracy in altitude measurement is sought, pulse compression results in increased instrument life and greater power efficiency. When accuracy requirements exceed two meters, it is no longer required.

INTRODUCTION

This study(1) was made to establish the contribution that pulse compression could make to implementing a radar altimeter for a geodesy satellite. We are presenting this study to you because there is a substantial advantage to the use of pulse compression when high accuracy altimetry is sought from satellite altitudes.

Before we enter into the technical analysis, let me address a few words to the question of why satellite altimetry is useful in geodesy. The aim of geodesy is to measure the shape of the geoid. The surface of the ocean would represent the shape of geoid if it was not disturbed by meteoroceanographic effects. Measurements of the shape of the geoid will lead to a knowledge of the crustal structure of the earth and possible mineralogical wealth that it may possess,(2) as well as monitoring changes in shape of the ocean surface which may provide warning of potential natural disasters. Kaula(3) has already prepared maps of the geoid such as are shown in Figure 1 based upon observing how perturbing forces alter the simple elliptical orbits predicted by Keppler. These maps are probably no better than 20 meters in estimating the departure of the geoid from the spheroid. It is currently anticipated that GEOS C, the first satellite that will carry a radar altimeter into space, will result in the reduction of this uncertainty to 5 meters and future satellite altimeters will reduce that error even further to 1 meter and perhaps even 10 cm. The radar altimeter measures the altitude of the satellite by measuring the transit time of a pulse that is reflected from the ocean surface at the subsatellite point. Pulse compression is a technique whereby the radar pulse signal returns that are extended in time can be processed to give a shorter duration pulse. This pulse has the ranging accuracy and resolution of the shorter pulse, but reduces peak power required to overcome interference from thermal noise by a factor proportional to the compression ratio.

TRADE OFF ANALYSIS

The purpose of the study is a trade off which is based upon the accuracy, power and life objectives of the system. However, this trade off must be performed in the light of hardware that is available and sound fundamental physics. The physics is presented in detail in the report upon which this study is based.

The organization of thought in this study is shown in Figure 2. It may be helpful to the reader to use this figure as a tour guide as he progresses through the study.

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ACCURACY

Pulse length and signal strength are the prime factors in determining the system accuracy. How the accuracy of the altimeter depends upon pulse length is shown in Figure 3 and the factors that contribute to this accuracy estimate are called out in Table 1.

The black bar graphs represent two specific designs, one with a 10 ns pulse length which will provide a 10 cm accuracy and the second with a 50 ns pulse length which will provide a 30 cm accuracy.

The errors that according to our analysis limit the ultimate performance of the system to 10 cm are independent of pulse length. They are:

1. Tropospheric Refractivity
2. Timing Reference Base
3. RF Power Source Jitter

The errors that depend upon pulse length are: bias and wave form errors which increase linearity with pulse length; sea clutter which increases as $\hat{t}^{3/4}$; and receiver noise which increases as $\hat{t}^{1/2}$.

$\hat{t}$ = compressed pulse length

Errors specifically related to pulse compression have also been considered such as side lobe, altitude rate ambiguity and hardware implementation.

Power Requirements for Providing Improved Accuracy. Accuracy demands larger peak power unless pulse compression is used to spread the transmitted pulse in time. We will show the specific relationships between peak power requirement and accuracy. The key to more accuracy is shortening the pulse width. This is clear from the error analysis. There are fixed errors such as: atmospherics, timing reference and sea state, which, in our current thinking, would limit us from trying immediately for better than 0. 1 meters. The other errors, as seen from Figure 3, are pulse length dependent and decrease at least as fast as $\hat{t}^{1/2}$.

For this decrease in pulse length, a price must be paid in terms of increasing peak power. This price is inversely proportional to the square of pulse length if S/N ratio is maintained constant.

Figure 4 can be used as a focus for thinking about this problem. It shows the requirements for power and the alternatives that pulse compression offers for providing it. The shaded area to the left represents a lower limit of peak power in a single pulse that must be available for efficient integration incoherently. This line is determined from the single pulse signal to noise ratio $(S/N)_{d\ell}$

$$\frac{S}{N}_{d\ell} = \frac{P_{PK}}{BW}(\hat{t}) \underbrace{\frac{c G^2 \lambda^2 \sigma_o}{64 \pi^2 h^3 KTFL}}_{K_o}$$

or for a matched filter system

$$\frac{S}{N}_{d\ell} = P_{PK} \hat{t}^2 K_o$$

$$\frac{S}{N}_{d\ell} = P_{AV} \hat{t} K_o / f_r$$

Where:

P_{PK} = Peak Power Transmitted Pulse

P_{AV} = Average Power Transmitted

G = Antenna Gain

h = Satellite Altitude

K = Boltzman Constant

T = Absolute Temperature

σ_o = Cross Section of Ocean Surface

c = Velocity of Light

λ = Wave Length of Transmitted Signal

L = Losses in Radar

The solid parametric lines represent contours of constant energy per pulse. The specific conditions for which this particular minimum power curve was derived is given in Table B-1 of the Space Geodesy Altimetry Study

Pulse compression added to a system would cause the point describing the system to be moved by a distance proportional to the compression ratio D along one of these iso energy lines, E = const. The system that was configured for GEOS-D in SGAS study is represented by a point ⊡ on the lower limit line. If the designer wished to shorten the pulse, say by a factor of 5 on this system, it would be necessary to increase the average power by a like amount in order that the system would not fall below the single pulse lower limit boundary. Hence, the peak power supplied to this system would be increased by a factor of 25 from 1 kw recommended in the SGAS report to 25 kw when the system has its pulse length shortened by 5. Now, if this system were to have pulse compression added to it, the transmitted pulse would be expanded in time along an isopower contour (② on Figure 5). The peak power could then be reduced by the compression ratio, a factor of 100 to 250 watts. This time expansion of the pulse length would not result in an improved signal to noise ratio nor a decrease in the accuracy of the system. The pulse could have been expanded before it was shortened (① on Figure 5). In this case, the final power could have been 10 watts. The signal to noise ratio would not have changed and the system accuracy would not have been improved beyond its initial value. The latter case suggests that under the constraint of maintaining SGAS accuracy, size and weight might possibly be reduced by going to a solid state transmitter. In summary, we can say for radar altimeters:

1. Peak power increase is required to improve accuracy.

2. The more accurate system must incorporate broader bandwidth.

3. Pulse compression at a fixed signal to noise ratio and energy can only be used to reduce the peak power requirements.

Comparison of Pulse Compression with High Power RF Sources What price must be paid if we attempt to use peak power alone to improve accuracy? There are three types of broadband microwave power tubes, magnetrons, Crossed Field Amplifiers, and Traveling Wave Tubes. The magnetron operated at the required power level has a short life expectancy, 500 hrs, and is subject to problems of both jitter and pulse stability. This uncertainty alone could amount to more than 2 ns (40 cm). The CFA is not subject to the short life problem but does have the jitter problem associated with magnetrons. However, it is a heavy device, approximately 50 pounds, and has a low power gain, 10 dB. As a consequence, it would have to be driven by a TWT that had a larger peak power rating than the TWT that could be used as a power output stage if pulse compression were to be incorporated into the system.

Let us turn to the use of a TWT as a power output stage. The problem here is that, at low duty factors, high power TWT's have low DC to RF conversion efficiency because of the large filament power requirements. This question of power efficiency is illustrated in Figure 5. The average power requirements of the radar altimeter will be under 10 watts.

If one examines the parametric curve of 10 watts, one sees that for TWT's with peak powers greater than 1 KW, the efficiency of the tube is low. For peak powers below 1 KW, the efficiency increases dramatically. Equally important as efficiency is the question of reliability. From Figure 5, it is also apparent that a decrease in peak power by a factor of 100 increases the MTBF by a factor of 8.

We can conclude therefore, that if we are seeking 10 cm accuracy, a TWT operated at a lower peak power with pulse compression appears to be a better alternative than any of the other RF sources, that are currently available, operated at higher peak power without pulse compression.

Comparison of Pulse Compression with Integration Techniques. Pulse compression provides a larger signal-to-noise ratio for a given expenditure of energy than any other type of system that spreads the energy in time. Two other systems are the coherent integration system used in the SGAS study and straightforward integration of incoherent pulses. The coherent integration of pulses is limited to less than the compression ratio of 100 by the doppler from satellite motion.

The number of pulses N_a that can be integrated coherently is determined by two factors: decorrelation time (t_d) and prf (f_r). The decorrelation time is the time that must pass for vehicle to travel a sufficient distance to provide independent radar samples of the surface. The maximum allowable prf is determined by the fact that successive pulses must be sufficiently spaced in time that they are not simultaneously illuminating the ground.

$$N_a = t_d f_{r(max)}$$

$$= \frac{1}{650} \times 20,000$$

$$= 33$$

If the same $N_a = 33$ pulses were incoherently integrated by an ideal post detection device, the resultant improvement of the signal to noise ratio would be less than 33. This loss in integration efficiency is caused by the non linear action of the second detector which converts some of the signal energy to noise.(5)

Influence of Other Operational Parameters

Do the other operational parameters that have not been considered affect the trade off conclusions? The answer is "no". We have considered accuracy, power and life in reaching our conclusions. The weight and volume of the pulse compression components are 200 gm and 100 cc respectively. The weight and volume saved in the modulator and the receiver would be about 2 kg and 1000 cc respectively.

The availability is dependent upon the time required to package and space-qualify components that are already available. This should be about one year.

Selection of a Method for Pulse Compression

Pulse compression can be accomplished in a number of different ways; the task that has been addressed here is the selection of a technique for pulse compression that is compatible with the stringent restraints on size, weight, reliability and freedom from adjustment that are imposed by satellite operation. The FM chirp surface-wave dispersive delay-line matched filter offers the most promise as a result of these studies. Further design studies have been made on this system to develop it to a point that it can be compared with the short pulse system that was developed in the parent study(4).

Six specific pulse compression implementations have been selected for comparison from the point of view of the practical applicability of the hardware involved and performance expectations. The consideration has been limited to those parts of systems that are directly concerned with pulse compression, the components for the initial expansion of the signal, the receiver, and the pulse compression components. The transmitter and processor will not be differentially affected by the various systems under consideration and hence have not been reviewed in the initial selection of approach.

The six systems that have been studied are:

1. FM* - Perpendicular-Diffraction Dispersive Delay-Line Matched Filter

2. FM* - Surface-Wave Dispersive Delay-Line Matched Filter

3. FM* - Correlation Receiver (Serrodyne Mixing)

4. Discrete Coded - Binary Phase Coding (Barker Sequences)

5. Discrete Coded - Staggered Spacing Pulse Groups

6. Discrete Coded - Stepped Frequency Sequences

The advantages that could accrue from pulse compression are increasing the bandwidth of the system so that an improved altitude resolution capability can be achieved; and increasing the possible time-bandwidth product so that lower peak powers can be realized. This decrease in peak power in turn would reflect in less weight and power consumption as well as improved reliability in the modulator transmitter parts of the satellite altimeter.

*Continuously Swept

Increasing the bandwidth, or in effect shortening the pulse to improve resolution, could undoubtedly improve accuracy materially at lower sea state levels; however, it has yet to be demonstrated that at higher sea states (e.g., 5 on Beaufort scale), where the effective pulse width is shorter than the wave height, a specific improvement would result. This latter question can only be answered when sufficient impulse response data is available from the aircraft flight test.

Turning next to the possible reduction in peak power by increasing the time-bandwidth product, the increased duration of the transmitted signal means that the average power required for detecting the signal return may be maintained while the peak power is reduced. If this peak power can be reduced from the present 1 kw to 5 watts, a solid state transmitter now would become a possibility. This would result in less transmitter weight and longer life expectancy of the transmitter and modulator. There are currently available TWT's and magnetrons that could be used for pulsed application, that have life guarantees on the order of 500 hours, while solid state devices could be expected to provide a life in excess of 2000 hours. However, it should be pointed out that it is well within the state of the art to develop a TWT of comparable life expectancy, although no such qualified tube is currently available. It will become apparent in the ensuing parts of the report that these improvements are paid for by increasing the basic complexity of the system.

The six systems that were specifically considered in the part of the study are compared in Table 2.

The accuracy goals of the parent study have been used to define the resolution requirements and, in turn, the minimum bandwidth requirement of 20 MHz. If an improvement in resolution can be shown to improve the accuracy performance of the system, the selected pulse compression system should afford the possibility of increasing the bandwidth to 100 MHz. The time-bandwidth product or dispersion ratio of 100 is readily achievable by all of the systems that we have chosen to consider.

FM Chirp Matched Filter Techniques

Of the two approaches noted above, the one in the most advanced state of development employs matched filter chirp techniques. The transmitted waveform for a chirp system can be generated actively, by sweeping a voltage-controlled oscillator (VCO), or passively, by impulsing a dispersive network. The systems shown in Figure 7 use a dispersive network to expand and to compress the pulse.

There are various methods for achieving dispersive delay devices; only two, however, have sufficient bandwidth (at least 20 MHz) and time-bandwidth product (at least 100) to be of value in the application at hand. They are perpendicular diffraction delay lines and lithium niobate surface dispersive delay lines. Perpendicular-diffraction delay lines utilizing a quartz medium are readily capable of 20 MHz bandwidths and dispersion ratios of at least 100. Experimental models have been built having bandwidths approaching 100 MHz.

Range sidelobes would most probably have to be suppressed by the addition of a weighting function in the receiver or by transmitting a nonlinear FM chirp. Sidelobe suppression by weighting the received signal would decrease the resolution of the radar by a factor of one and a half to two and also increase the power requirements for signal detection. Therefore, to achieve the same resolution as the present short pulse system, a bandwidth of considerably more than 20 MHz would be necessary. The requirement of increased bandwidth would also apply to a nonlinear chirp case.

Even though perpendicular-diffraction delay lines show promise of sufficient bandwidth, their bulkiness (see Figure 6) and high loss (typically 50 to 60 dB) would make them unattractive for satellite applications.

A recent development at Raytheon's Research Division shows a great deal of potential for producing small, lightweight dispersive delay lines in the very near future(6). These devices have interdigital arrays printed on lithium niobate and use surface-wave rather than bulk-wave techniques. Besides being small and lightweight, these delay lines would be relatively inexpensive and highly reproducible and would have much less loss than bulk wave type devices.

Typically, the surface wave lines have usable dispersive bandwidths of thirty to forty percent of their center frequency. The upper limitation on center frequency is dictated by present photolithographic techniques; however, a line with a 300 MHz center frequency and 100 MHz bandwidth seems quite feasible. These new lines offer good possibilities for chirp systems much smaller (see Figure 6) than many which have been built to date.

Phase-Coded Systems A conceptual diagram of a phase-coded pulse compression system is shown in Figure 7. There exists a veritable infinity of optimum and suboptimum discrete coded sequences of which phase coded sequences are one group(7). Most discrete coded waveforms can be disregarded either from the standpoint of poor sidelobe performance or from the standpoint of rather complex implementation. Another disadvantage that can be inferred from Figure 8 is that the tapped delay lines will constitute a size and weight problem.

The use of longer suboptimum codes to achieve higher compression ratios or the use of polyphase rather than binary phase codes to achieve better sidelobe performance does not alleviate the system problem, in that they would make the system prohibitively large and/or complex. In summary, the only sequences which show promise for the present application are the Barker sequences.

The maximum length, Barker sequence (N=13), has a theoretical sidelobe level of approximately -23 dB; and therefore, a modest amount of weighting may still be necessary, since it would be difficult to space the taps any closer than 50 nsec. The binary phase-coded system would not provide any increased resolution over the short pulse system, but would only serve to reduce the transmitter peak power (by a factor of 13:1 with the maximum length sequence). In comparison with the other coding systems discussed here, the binary phase-coded system would seem to be the least attractive approach because of the difficulties involved in operating the transmitter in a phase discontinuous mode.

As a result of the investigation of different forms of pulse compression, it is concluded that the lithium nobate surface dispersive line best meets the requirements of a satellite altimetry.

CONCLUSIONS

The analyses of this study have led to the following conclusions:

1. Altimetry power requirements differ from those of normal radar in that peak power must be increased as the inverse square of pulse length, because of the variation of target cross section with pulse width.

2. The accuracy of an altimeter operating at a pre-established signal to noise ratio is

10 cm	for	10 ns pulses
1 meter	for	50 ns pulses

3. Pulse compression (increases the duty factor and reduces peak power) for 10 cm accuracy sufficiently that tubes with greater efficiency and longer life expectancy can be specified and EMI is reduced.

4. The reduction in power requirements for accuracy design goals of 2 meters does not justify the added complexity of pulse compression.

5. The Rayleigh clutter of the return signal does not destroy the compression characteristics of the signal.

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Table 1

Error Summary

Error Item		SGAS Radar Errors	
		Estimated with Data Corrections	Estimated Error with Either Short or Compressed Pulse System
1.	Receiver Noise	.009 m	.01 m
2.	Sea Clutter	.04 m	.01 m
3.	Sea State	.01 m	.01 m
4.	Refractivity	.1 m	.05 m
5.	Integration	0	0
6.	Bias	.2 m	.05 m
7.	Waveform Variations	.1 m	.05 m
8.	Amplitude Variation	.05 m	.01 m
9.	Digital Counting	.1 m	.05 m
10.	Multipath	0	0
11.	Range SL	NA	.02 m
12.	Altitude Rate	0	.015 m
13.	Attitude	0	.02 m
Total (rss)		.26 m	.11 m

Systems Comparison

Table 2

System	Max. BW	Time Bandwidth or Disp. Prod.	Relative Size	Relative Weight	Remarks
Surface Wave Disp. Delay Line	100 MHz	200	1	1	Good resolution; high disp. prod., small, lightweight
Serrodyne Technique	200 MHz	400	1.3	1.3	Good resolution, high disp. prod., small, lightweight
Perpendicular Diff. Dis. Delay Line	100 MHz	200	3.5	5	Good resolution, high disp. prod., delay lines are large, and heavy
Discrete Frequency Sequences	20 MHz	N^2	0.5N+1	0.5N + 1	Requires N matched filters, marginal resolutions
Barker Code (N = 13)	20 MHz	13	2.3	2.3	Requires tapped delay lines, marginal resolution, low disp. prod.
Staggered Spacing Pulse Groups	20 MHz	M^{*}	$\propto T^{**}$	$\propto T^{**}$	Requires tapped delay lines, marginal resolution, low disp. prod. unless M is large.

* M = Number of pulses in ensemble

** T = Duration of ensemble

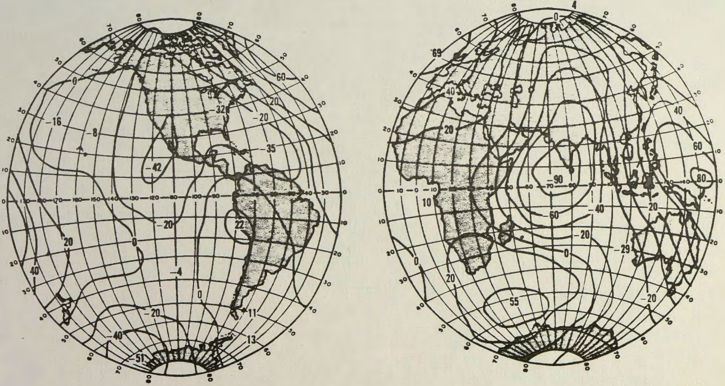

Figure 1 Geoid heights, in meters,based on the spherical harmonic coefficients through the sixth degree of Anderle (1966).

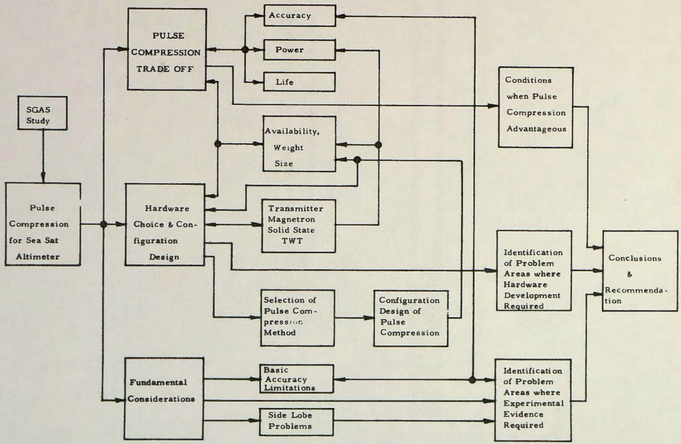

Figure 2 Study Flow Diagram

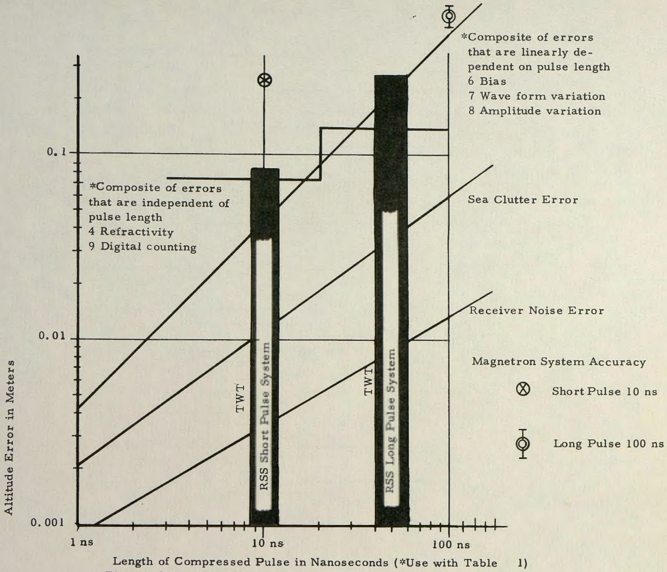

Figure 3 Accuracy Improvement Resulting from Shortening Pulse at Constant P_{av}

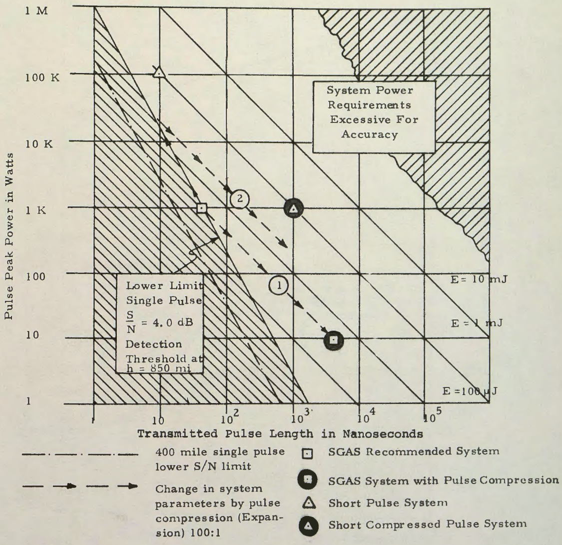

Figure 4 Time Bandwidth Power Allocations For Geodesy Altimeter Systems

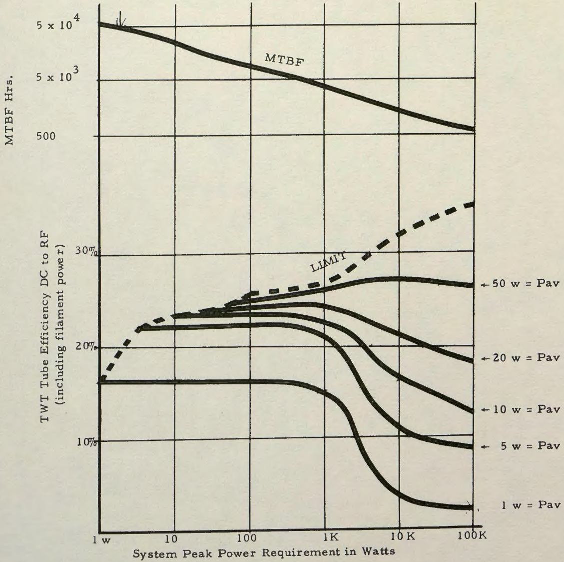

Figure 5 TWT Efficiency & Tube Life for Different Power Levels
(Generated from data provided by Dr. D. Winsor of Raytheon Power Tube Division)

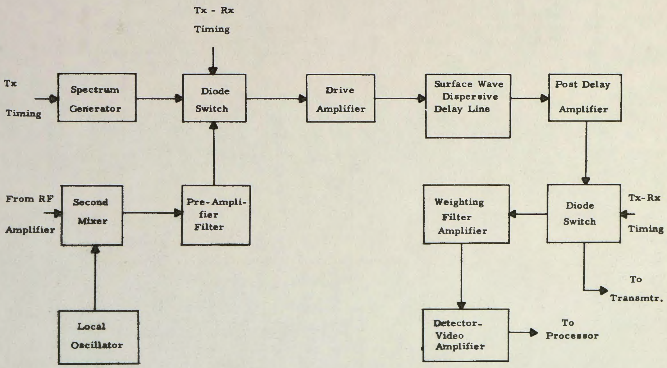

Figure 6 FM Chirp System with Surface Wave Dispersive Delay Line

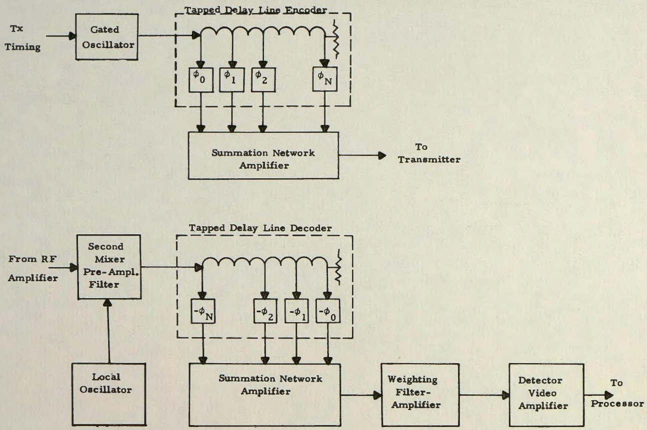

Figure 7 Phase Coded Pulse Compression