DIGITAL GENERATION OF WIDEBAND LINEAR FM WAVEFORMS

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ABSTRACT

A technique for the direct digital generation of linear FM waveforms with up to 900 MHz bandwidth and T-B products to 450,000 is presented. The technique is applicable to high resolution Synthetic Aperture Radars, and to target identification and target count modes in multimode airborne radars. Origins of representative system requirements are outlined, mmechanization details are described, and testing methods and results showing waveforms of excellent coherence and fidelity are presented.

I. INTRODUCTION

The Synthetic Aperture Radar (SAR) mode in modern, multimode airborne radars requires broadband microwave signals to measure range profiles of targets of interest and opportunity. Regardless of waveform format, range resolution R_R requires transmitted bandwidth B of at least $B = aC/2R_R$, where C is the propagation velocity of light and a is a constant (usually 1 to 1.2) related to signal processing weighting.

Systems utilizing large signal bandwidths may utilize "stretch" waveforms as described by Caputi[1] to reduce IF and signal processing bandwidths by transmitting waveforms of duration longer than the range swath collection time. Stretch systems can require waveforms of 900 MHz bandwidth and 500 µsec duration.

The system time-bandwidth product TB is thus 450,000 and the waveform slope k is 1.8×10^{12} Hz/second.

Linear FM waveforms of very large time-bandwidth product (greater than 10,000) are difficult to generate using passive techniques. The survey by Godfrey, et al,[2] shows that surface wave devices are not now practical for such applications, although tremendous advances are being made in that area. In addition, passive techniques generally provide one waveform slope per device, requiring a line or line pair for each slope in a multi-slope system. These considerations, plus the fact that modern radars already use frequency synthesizers to generate a large number of microwave channels, make it practical to consider the use of active techniques to generate linear FM waveforms of very large time-bandwidth product selected from a large number of available slopes. We present here a technique wherein an ordinary phase-locked synthesizer can be adapted to the generation of such waveforms with exceptionally good fidelity and coherence. The methodology is particularly well suited to the introduction of high resolution capability into multi-mode airborne radars since it requires only moderate changes to hardware which often already exists in such systems.

II. WAVEFORM REQUIREMENTS

The "stretch" radar is a convenient means of realizing range resolution without carrying commensurately wideband signals through the receiver, A/D converters, and signal processor. Such signals are difficult to handle, at best. Stretch systems, however, utilize RF bandwidth commensurate with the required range resolution, but require signal processing bandwidths of perhaps a few tens of MHz. A linear FM waveform of bandwidth B and duration T is transmitted and a similar waveform delayed by nominal round trip time T_{RT} is used as a correlation waveform at the receiver first LO. We assume that $T_{RT} > T$, although this need not be true for certain classes of systems. Received signals from many ranges are down-converted by the swept LO to form an intermediate frequency which is proportional to range. Returns from the "nominal" range of interest fall at the center of the IF. The IF bandwidth is B_I, thus passing only signals from a limited range swath T_S. These quantities are related as:

$$B/T = B_I/T_S$$

Waveform Linearity Considerations

Low order (quadratic) frequency errors degrade range resolution by smearing the return over a number of range cells. The low order waveform nonlinearity can be expressed as:

$$F(t) = Bt/T + B_E t^2/T^2$$

The waveform from some point in the range swath is delayed from this by T_D. Its frequency is:

$$F(t - T_D) = B(t - T_D)/T + B_E(t - T_D)^2/T^2$$

Their difference is time dependent and can move across a number of range filters of width 1/T. To restrict this to 1/2 range cell requires that:

$$B_E < 1/4\ T_D$$

High order non-linearities in the FM waveform result in undesireable range sidelobes on strong radar returns. These appear on the imagery as faint reproductions of the strong returns at other ranges. The effect is quantized as follows:

The correlation (LO) waveform can be represented by:

$$F(t) = Bt/T + \sum_n F_E(n) \cos (2\pi nt/T + \phi_n)$$

where $F_E(n)$ is the n'th Fourier coefficient of frequency nonlinearity, and t is time from the initiation of the correlation waveform. If an exact replica of this waveform has been transmitted and is being received at time T_D relative to nominal round trip time, the IF signal is composed of a carrier offset from the nominal IF frequency by ($B \times T_D/T$ Hz), with phase sideband pairs each of which is below the carrier by 10 Log $D_R(n)$. $D_R(n)$ is the n'th order range sidelobe, and:

$$D_R(n) = \left[\frac{F_E(n)\ T}{n}\ \mathrm{SIN}\left[n\pi T_D/T\right]\right]^2$$

$$-T_S/2 \le T_D \le T_S/2$$

For low order ($n < T/\pi\, T_D$) nonlinearities and returns from the edge of the range swath, the waveform linearity requirement is found to be:

$$F_E = 2\, D_R^{1/2} / \pi\, T_{SW}$$

III. WAVEFORM SYNTHESIS

Westinghouse has expended considerable effort toward the development of direct digital generation of wideband linear FM waveforms, resulting in the simple but exceptionally versatile methodology shown in Figure 1. Described in U.S. Patent 4,160,958, the approach

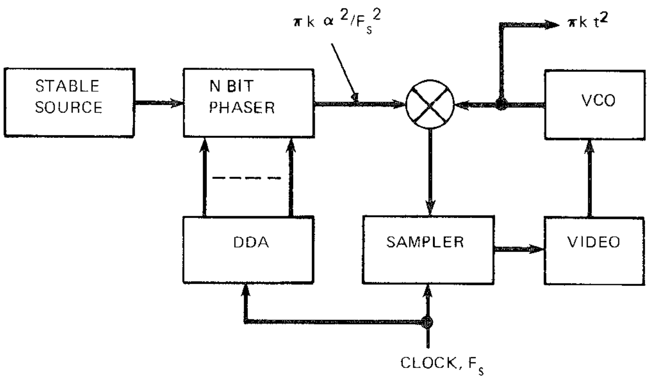

Figure 1

DIGITAL WAVEFORM GENERATOR

consists of a stable source whose phase is set by a binary phaser, and a tuned oscillator (VCO) which is locked to the phased source via a sampled phase-lock loop. The instantaneous phase of the desired linear FM waveform is computed by a Differential Data Analyzer (DDA), a common digital computer element, which drives the phaser through the desired progression. A balanced mixer compares the phase of the VCO to that digitally generated. The difference is sampled, forming the error signal for the wideband phase-lock loop. The VCO acts as a smoothing filter and reproduces the desired waveform. The computation is performed and the phaser updated at rate F_S, typically 30 MHz. Since we wish to generate waveforms of 900 MHz bandwidth, the sample aperture must be less than 200 picoseconds. The phaser spectrum of bandwidth F_S is impulse sampled at rate F_S, causing the phaser spectrum to be reproduced continuously over the large bandwidth determined by the narrow sample pulse. The 30 MHz phaser update rate serves the entire 900 MHz desired waveform bandwidth.

As described in Figure 2, the phase computation is performed by a cascade of DDA stages whose function is described by:

$$W_u(i+1) = W_u(i) + W_{u-1}(i)$$

where $W_u(i)$ is the output of the u'th stage after the i'th pulse of clock rate F_S. We use two stages of N parallel bits for linear FM of slope k, whose phase progression is:

$$\phi_{(i)} = 2\pi s i^2/2^N$$

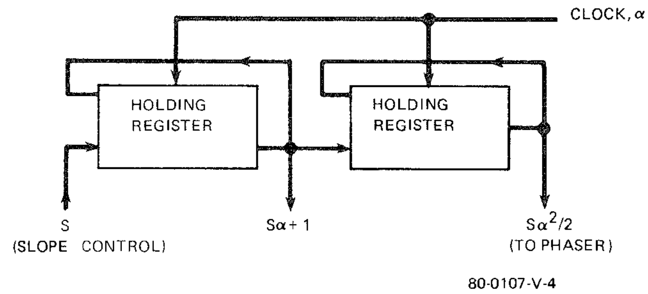

Figure 2

DDA PHASE COMPUTATION ALGORITHM

The DDA output to the phaser is $W_2(i)$, where

$$W_2(i) = si^{-2}$$

Then: $W_1(i) = W_2(i+1) - W_2(i) = 2Si + S$

and: $W_0(i) = W_1(i+1) - W_1(i) = 2S$

S is the slope designator. The resultant phase progression is $2\pi W_2(i)/2^N$ or:

$$\phi_{(i)} = 2\pi\, ki^2/F_S^{\,2}$$

Then: $k = SF_S^2/2^{N-1}$

The desired slopes k may be realized by the appropriate choice of F_S and N which can be fixed within a system, and by the selection of slope number S which can be under system software control and selectable from a large number of values. For example, with 16 bits, 30 MHz sampling rate and 1024 selections, one can choose any slope up to 28 MHz/μsec in 0.027 MHz/μsec steps. This should be an adequate selection for most radar system designers. The 16 bit DDA in this example represents a moderate amount of digital hardware. The accompanying 16 bit phaser is, however, more difficult. In practice, the 16 digital bits are truncated to seven phaser bits, which is consistent with -40 dB range sidelobes. The 16 digital bits are necessary to achieve the slope resolution. Only seven of these are actually connected to a phaser. The remaining nine are considered "fractional" bits and are necessary for computational purposes.

The seven bit phasor (Figure 3) is an array of quadrature hybrids with individual PIN diode reflection elements. Bit size is determined by coupled line transformers which also serve as DC blocks. Isolators between bits and on input and output reduce cross-talk to levels necessary for seven bit accuracy. RMS phase error is about 0.47 degrees and switching speed is about 1.8 nanoseconds. The diode drivers, Optimax DS07, were found to exhibit excellent switching speed when used in combination with high speed PIN diodes.

The VCO[3] (Figure 4) consists of a silicon bipolar transistor oscillator with GaAs hyperabrupt tuning diode, followed by a FET power amplifier. Including the power amplifier within the linearizing servo loop eliminates the need for low order amplifier phase linearity, although amplitude flatness remains important.

Typical low order VCO nonlinearity is about 5 MHz, while the system requirement is about 500 Hz. The gain required is then simply 5 MHz/500 Hz or 80 dB at video frequency 1/T. This calls for a Type III servo with

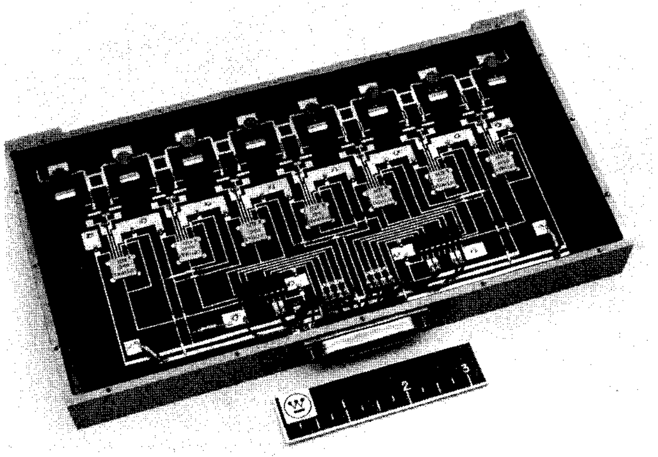

Figure 3
SEVEN BIT BINARY PHASER

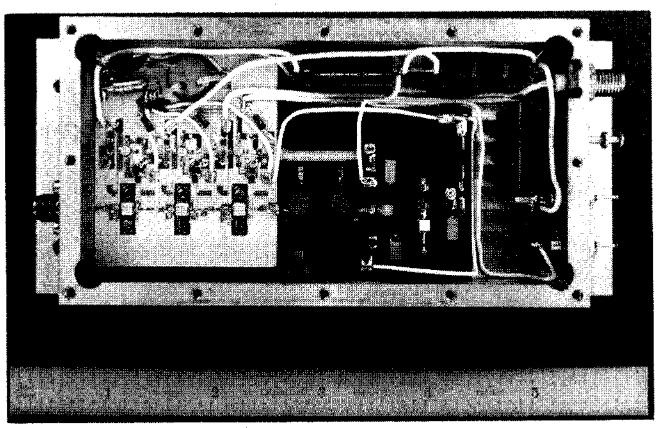

Figure 4
LINEAR VCO

several MHz bandwidth, which is the reason for choosing such a high (30 MHz) sampling rate.

Waveform linearity and coherence is measured by cross-correlating two similar units, with selectable time delay to detect any correlated nonlinearity. The resulting amplitude and phase error data is analyzed using a Discrete Fourier Transform. If A(J) and Ø(J) are the amplitude and phase error functions, the impulse response is calculated from:

$$F(k) = \sum A(J)\ W(J)\ e^{i(\phi(J) - 2\pi JK/N)}$$

W(J) is the Hamming weighting function. Figures 5 and 6 are representative phase errors and their resultant impulse response, which is adequate for most mapping systems.

CONCLUSIONS

Digital generation of linear FM waveforms of large bandwidth and T-B product has been successfully demonstrated, with performance and versatility for high resolution mapping radars and other applications. The technique uses readily reproduced microwave hardware whose requirements are not difficult to achieve.

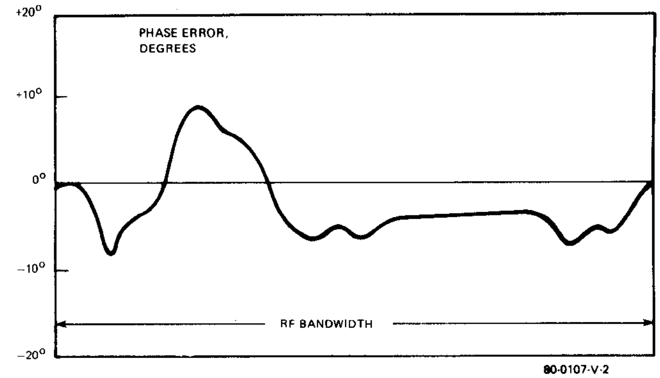

Figure 5
MEASURED PHASE NONLINEARITY

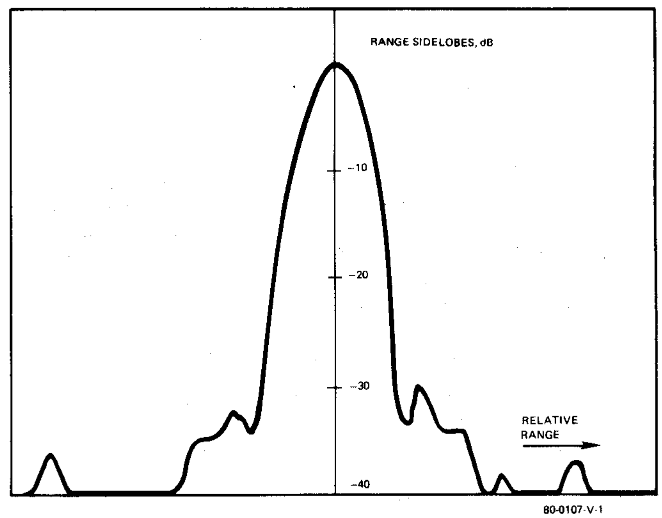

Figure 6
WEIGHTED IMPULSE RESPONSE

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