An Ultra-Wideband Exciter for Ground-Penetration Radar Systems

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ABSTRACT

Waveform requirements for a ground penetration ultra-wideband exciter (UWBE) include generating a frequency spectrum over a wide bandwidth, with a low-start frequency. A scripted linear-frequency-modulated waveform is used for the frequency coverage, with the added ability of arbitrarily notching-out portions of the transmitting spectrum in which radio frequency interference (RFI) exists. This exciter uses an arbitrary waveform generator (AWG), which scripts waveform packets with notches in the spectrum. The AWG is coupled to a frequency synthesizing architecture (FSA) device for waveform packet placement to create a phase-continuous broad-band response.

INTRODUCTION

A critical requirement for ultra-wideband (UWB) imaging techniques for ground-penetration radars is to identify near-surface or sub-surface targets in sufficient detail to allow unambiguous identification. A waveform meeting this requirement must have wide bandwidth for high down-range resolution, and low frequency for efficient propagation of the radar waveform into the soil. The Army Research Laboratory (ARL) has developed an impulse radar to meet UWB ground-penetration requirements. One disadvantage of an impulse radar is that the spectrum of the radiated emissions is not readily controlled, which may limit its applicability in dense environments commonly used by commercial communications equipment (e.g., FM, TV, and cellular radio).

Introduction of a linear-frequency-modulation (LFM) ultra-wideband exciter (UWBE) would meet the requirements for ground-penetration radars, and alleviate the problem of radio frequency interference (RFI). The UWBE uses a linear-frequency-modulated waveform with a low start frequency (~10 MHz), a wide bandwidth (~3 GHz), and an ability to script notches adaptively at appropriate places in the spectrum.

UWBE CONFIGURATION

Our approach in this research was to generate an LFM waveform from approximately 10 to 2800 MHz. We used an arbitrary waveform generator (AWG) Tektronix AWG2040 to generate multiple, smaller-bandwidth scripted packets and a frequency synthesizing architecture (FSA) device with the AWG to create an extended-bandwidth waveform with notches.

The AWG 2040 is a high-speed, programmable waveform generator with a 1-GHz clock, which waveforms can be generated through equation expressions or through point-to-point programming, theoretically makes a 500 MHz output possible.

The presence of images about the sampling frequency causes practical bandwidth limitations for each packet. In a tradeoff analysis of the output AWG frequency vs. out-of-band spurious products, we determined that a maximally flat (Butterworth) low pass response was possible for frequencies less than 415-MHz. Using a lowpass filter with a 440-MHz cutoff frequency suppresses the 500-MHz-and-above components by 60 dB; therefore, we selected 400 MHz as the chirp-stop frequency for each packet, in order to ease the image filtering.

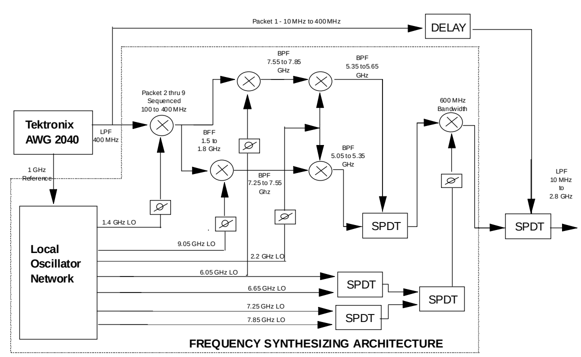

Figure 1. UWBE functional block diagram

0-7803-4603-6/97/$5.00 (c) IEEE

Figure 1 depicts a functional block diagram for the UWBE. The AWG generates nine waveform packets. The FSA then offsets and concatenates each packet to the desired frequency band, while maintaining phase continuity. The first packet produced by the AWG is from 10 to 400 MHz, with a duration of 1024 ns. This packet is delayed and bypasses the FSA to the exciter output. The subsequent eight packets are generated with an LFM from 100 to 400 MHz, with a duration of 800 ns for each packet.

Filters in the exciter chain produce transients or ringing in the time domain when steady-state conditions are disrupted. If the packets out of the AWG are all produced with an up-chirp direction from 100-MHz to 400 MHz, the first filter (as well as all other filters) will see an impulse-like transition between packets when the 400-MHz component at the end of one packet transitions to a 100-MHz component in the next packet. In order to avoid this occurrence, the packets out of the AWG alternate between a 100-to-400-MHz up-chirp and a 400-to-100-MHz down-chirp. To keep all the exciter filters in their steady-state conditions and to ensure proper concatenation of each the AWG packets in the final stage of the exciter, the remaining analog filters are constantly loaded with this up-down-chirp sequence. For this reason, the FSA has two parallel channels to convert the AWG output.

With consideration to filter ringing, the FSA's function is to translate and concatenate the remaining eight packets to create the extended LFM exciter output. In the following frequency plan, each of these AWG up-or-down chirp packets are first mixed with a 1.4-GHz local oscillator (LO). The resulting upper sideband (USB) of 1.5 to 1.8 GHz up-or-down chirp, respectively, is sought, and then split into two channels: the down chirp to the upper channel and the up chirp to the lower channel (see Fig. 1). The upper channel is modulated with a 6.05-GHz LO for which the resulted USB down-chirp from 7.55 to 7.85 GHz is used, while the lower channel uses a 9.05 GHz LO to obtain the lower sideband (LSB) down-chirp from 7.25 to 7.55 GHz. Both channels are then downconverted by a 2.2-GHz LO. The switch at the output of the two channels is timed to provide a 600-MHz, continuous down-chirp from 5.05 to 5.65 GHz, which has the effect of doubling the bandwidth. In the last stage, we switch sequentially in four different LOs that are 600 MHz apart and seek the resulted LSB up-chirp, effectively quadrupling the 600-MHz bandwidth. Relative to the initial 300- MHz bandwidth, we octupled the bandwidth, without multiplication. We now have 2400 MHz of bandwidth, covering 400 MHz to 2.8 GHz, which is combined with the first packet that bypassed the FSA to achieve the desired 10 MHz to 2.8 GHz of bandwidth.

Alignment in time of each LO is critical to minimizing the transients in the frequency domain at the transition points between packets. In order to preserve the phase-continuity at these transition points between consecutive waveform packets, alignment of the stop- and start-points are controlled by the AWG. In addition, minimizing the transient effects is achieved through the use of GaAs switches for high-speed switching between LOs, and phase is tuned to match delays between each LO line.

AWG WAVEFORM GENERATION

The following steps are taken to create each waveform packet. The UWB LFM waveform is generated; desired in-band notches are placed; the waveform is then downshifted by using the complex conjugate of the UWBE LOs, which will be used to up-convert it, and down-sampled to the AWG 1-GHz clock; and the effects of the AWG digital-to-analog converter (DAC) and errors introduced by non-ideal low-pass filters are compensated for.

The following equation is used to generate a complex chirp waveform with start frequency *f1*, stop frequency *f2=f1+B*, and pulse duration *T*: $C(t) = e^{j\left(2\pi f_1 t + \frac{\pi B t^2}{T}\right)}$, where *B* is positive for an up-chirp and negative for a down-chirp.

The challenges here are to position multiple notches where interferers exist and to create notches with sufficient rejection capability and minimal distortion to the passband. For this problem, we designed zero-phase finite impulse response (FIR) notch filters, and then convolved them with the LFM waveform for spectral in-band notch placement. Notches will be defined by center frequency f_n, bandwidth b_n, and filter impulse response time T_n . Basically, the sharpness of the transition between the passband and stopband is inversely related to the filter impulse response time—the sharper the transition, the longer the filter impulse response time. The tradeoff is in the order of the filter vs. the width of the transition region between passband and stopband for a given stopband attenuation. With this method, the passband, stopband, and transition bands are adjustable. Figure 2(a) is a spectrum analyzer plot of a 1024-ns LFM from 10 to 400 MHz, where several notches have been placed in the packets. All of the notches have the same stopband features, as shown in Figure 2(b). The notch passbands are ~3.75 MHz, with notch depths > 30 dB.

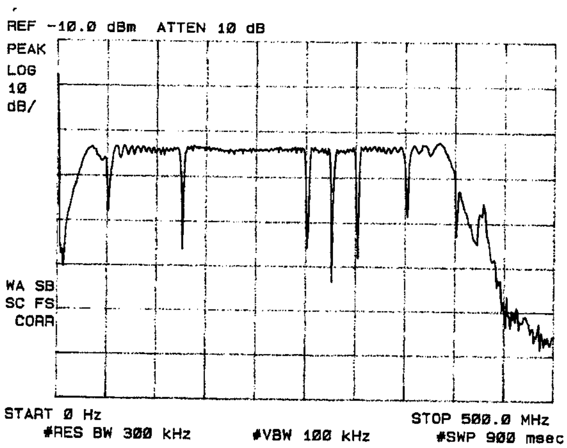

Figure 2 a. AWG packet with several notches

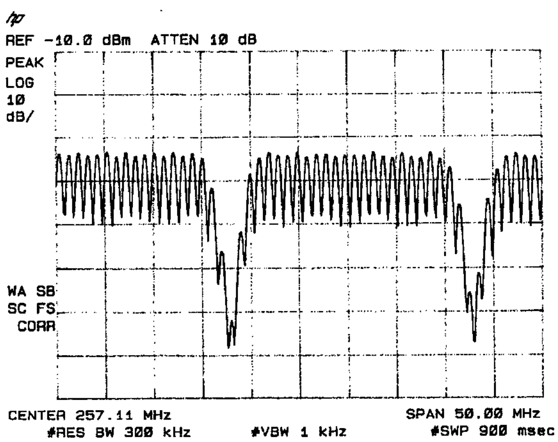

Figure 2 b. Notched AWG packet with stopband feature

The total filtered chirp is then down-converted by multiplying with the complex conjugate of the UWBE LOs, which are used to up-convert the waveform segments, as shown in Figure 1. Each LO is defined to start at the beginning of the transmission, and the exact phase of the hardware LO must be known in order to generate proper phase waveform segments for the AWG.

The AWG stored waveform is a sampled signal that contains repetitions about the AWG sampling frequency f_s. These signal repetitions can be eliminated by a low-pass filter with a cutoff frequency of $f_s/2$. However, this process results in waveform distortions, due to the non-ideal response of the low-pass filter. In addition, the AWG waveform samples must take into account the effects of finite rise and fall times of the AWG digital-to-analog converter (DAC). These effects manifest themselves in an amplitude roll-off as a function of frequency. In our application, we corrected the system errors due to these effects by measuring the system-transfer function and predistorting the signal with a compensation filter. The compensation filter was computed as the inverse of the transfer function over the frequency region of interest. Figure 3 illustrates a 100-to-400-MHz chirp before and after predistortion compensation. Figure 4 illustrates the magnitude and phase of the compensation correction filter implemented in the AWG 2040. Amplitude flatness is achieved at the expense of peak power.

Figure 5 illustrates the filtered chirp and spectrum. This waveform output was derived from a suggested list of notch frequencies and bandwidths, which are illustrated in Table 1. The waveform is a 10-2800 MHz complex chirp, with a pulse time of 7.424 μs. As a result, the notches were well-behaved at all frequencies and bandwidths.

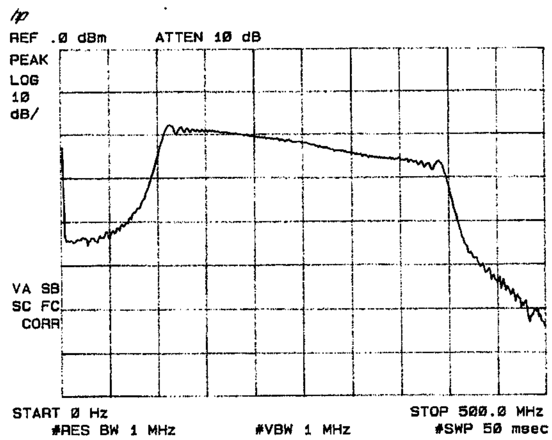

Figure 3 a. Uncompensated AWG packet

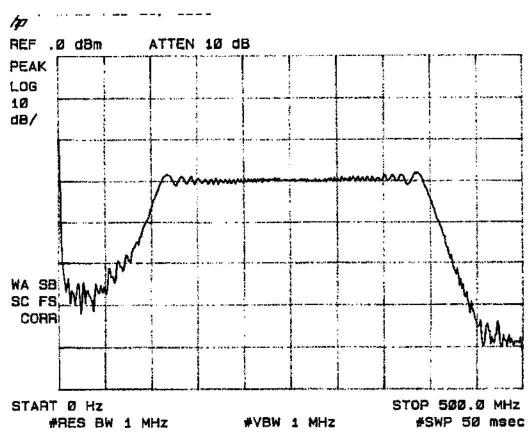

Figure 3 b. Compensated AWG packet

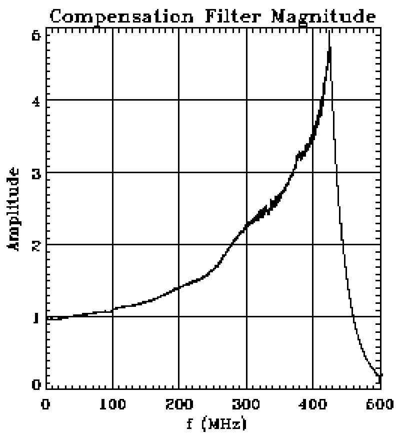

Figure 4 a. Compensation filter magnitude response

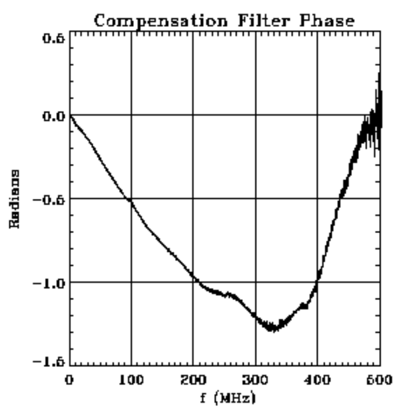

Figure 4 b. Compensation filter phase response

CONCLUSION

The UWBE can transmit a LFM waveform with large bandwidth for high-resolution imaging and a low-start frequency for efficient propagation into the soil. These waveform requirements are essential for ground-penetration radars. Furthermore, the LFM waveforms can be generated with notches in the radiated emissions at selected frequencies, which prevent exciter interference with other emitters on-site.

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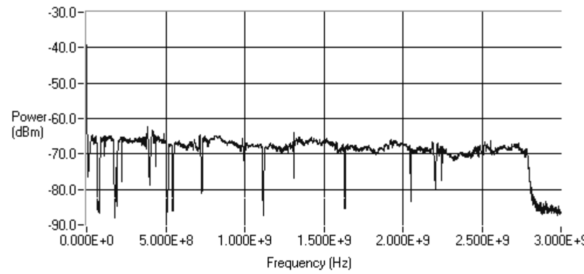

Figure 5. Output frequency spectrum of LFM from 10 MHz to 2.8 GHz

Table 1. Frequency notches

Frequency range (MHz)	Center frequency (MHz)	Required bandwidth (MHz)	Filter bandwidth (MHz)	Equipment nomenclature
66-72	69	6	6	TV Channel 4
76-82	79	6	6	TV Channel 5
112.48-112.52	112.5	.04	.4	ILS/Localizer
174-180	177	6	6	TV Channel 7
186-192	189	6	6	TV Channel 9
220-221	220.5	1	1	MIdas BCN
434.5-435.5	435	1	1	V Wind Profiler
506-512	509	6	6	TV Channel 20
542-548	545	6	6	TV Channel 26
722-728	725	6	6	TV Channel 56
1112-1118	1115	6	6	ACTRBS IFF/Trans.
1306.8-1308.1	1307.5	1.26	1.26	AN/PPS-117
1628-1632	1630	4	4	AN/APN-133
2048.9-2051.1	2050	2.2	2.2	FDM/FM P-P
2249.9-2245.1	2245	.02	.02	RSDR

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