A Wideband Linear FM Ramp Generator for the Long-Range Imaging Radar

DAN R. BROMAGHIM AND JOHN P. PERRY

***Abstract*—This paper describes the linear FM ramp generator that provides the wideband transmitted signal and correlation receiver reference for the long-term imaging radar (LRIR) developed and operated by the M.I.T. Lincoln Laboratory. The signal generated has a bandwidth of 1000 MHz and a duration of 250 μs. Because of its large time–bandwidth product, the signal is generated actively by sweeping a voltage-controlled oscillator. Special attention is given to the means for achieving linearity, reproducibility, and coherence of the generated ramps.**

I. Introduction

THE Haystack Observatory, located in Westford, MA, is a radar- and radio-astronomy facility designed and constructed by the M.I.T. Lincoln Laboratory and currently operated by the North East Radio Observatory Committee (NEROC) with the support of the National Science Foundation. The preeminent feature of the Haystack Observatory is its precision, radome-housed Cassegrainian antenna system. The primary reflector is a paraboloid of 36.6-m diameter, having a surface tolerance adequate to provide useful gain up to 40 GHz or more. A variety of operating configurations can be obtained through the use of interchangeable RF modules ("boxes") which are mounted on the antenna at its focus behind the Cassegrainian subreflector. Each RF box contains its unique antenna feed, transmitters or receivers, etc., as required by the individual user's experiments. The RF box is supplied with power, excitation, and the control from equipment on the ground, and supplies its received signals to ground equipment where the signal processing and data recording are done.

Recently Lincoln Laboratory has installed at Haystack a LRIR [1] operating at X band, which is designed to acquire and characterize satellites out to synchronous range and beyond. For this function the radar requires the sensitivity provided by the Haystack antenna coupled with a high average power (200-kW) transmitter and low-noise receivers. The transmitter and receivers are contained in the LRIR RF box together with the monopulse feed system. Some of the more challenging components utilized in the RF box are described in [2]–[4].

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The authors are with the Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, MA 02173.

A variety of waveforms are transmitted by the LRIR, namely long CW and narrowband linear FM pulses used for target acquisition and track initiation, and a wideband coherent pulse train used for target characterization. The waveform selected for this purpose is a 1-GHz bandwidth linear FM pulse with a fixed pulse duration of about 250 μs, transmitted at repetition frequencies up to 1600 Hz. The purpose of this paper is to describe the ramp generator that produces this wideband signal and show the performance that has been achieved. Before doing this, however, we shall briefly review the correlation processing technique used by the LRIR which permits the use of such a high (250 000) time–bandwidth-product signal.

II. Correlation Processing

Satellite characterization is conducted in a simple environment, generally consisting of a single tracked target which is spatially well confined but which can consist of multiple scattering centers that evolve and move relative to one another as the target rotates. In this environment we need be concerned only with the radar echoes within a small range window of extent greater than that of the target complex. This fact is exploited in the LRIR by mixing the target's echo with a replica of the transmitted waveform that is regenerated at the time corresponding to the target's known range. For linear FM ramps of swept bandwidth W and duration T, a scatterer at a relative range delay of $\delta\tau$ will be manifest at the mixer output by a frequency component at $\delta f=(W/T)\delta\tau$, which persists for the pulse duration T. Multiple scatterers are separable one from another by frequency analysis of the resulting complex waveform. This "correlation" technique for pulse compression [5], [6] possesses two important features for targets having range delays near that determined by the time of regeneration of the correlation ramp: first, slowly varying departures from linearity tend to cancel in the output of the correlation mixer, permitting much larger low-frequency errors in the ramp than would be usable with a wideband matched filter, and, second, the frequencies contained in the output of the correlation mixer span a narrowband. The range window over which this procedure is effective is determined by the bandwidth spanned by the frequency analysis filters. For the wideband LRIR waveform, $W/T \cong 4$ MHz/μs, and three filter bandwidths of 0.8, 1.6, and 3.2 MHz are provided, corresponding to range windows of 30, 60, and 120 m, respectively.

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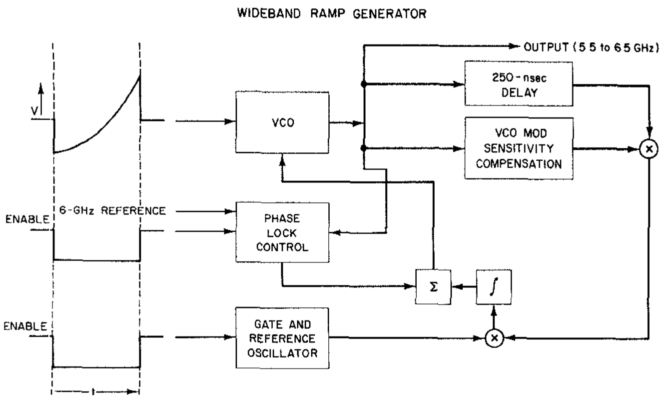

Fig. 1. Block diagram of the LRIR wideband ramp generator. Between ramps, the voltage controlled oscillator (VCO) is phase locked to the 6-GHz CW reference. The VCO is driven by a shaped video waveform. Its output is linearized by a slope detector referenced to a gated reference oscillator in a feedback loop.

The LRIR wideband ramp generator is used for generation of both the transmitted waveform and the range-dependent correlation ramp, so it must be capable of being regenerated with full fidelity at a staggered pulse repetition frequency of twice the transmitted PRF, or up to 3200 Hz. A 50-μs maximum recovery time was specified to make this possible.

III. Functional Description

Fig. 1 is a block diagram of the wideband ramp generator which shows its major functional elements. The ramp is generated by a voltage-controlled oscillator (VCO)[1] operating in C band. (The transmitted signal is obtained from this generated ramp by upconversion to X band.)

Before a ramp is generated, the VCO is phase-locked to a 6-GHz CW reference derived from the radar's frequency standard. The phase-lock loop is released at ramp initiation time, and a video drive waveform is applied to the VCO via one of its two input ports, which has a sensitivity of about 100 MHz/V and a modulation bandwidth of 500 kHz. If we denote the VCO tuning curve at this port by $f = g(v)$, then the video drive should approximate $v(t) = g^{-1}[f(t)]$, where $g^{-1}(\cdot)$ is the inverse function to $g(\cdot)$ and $f(t)$ is the desired linear frequency ramp. To accomplish this, the video drive is stepped negatively to a carefully controlled clamped voltage level corresponding to an output frequency of about 5.5 GHz. An adequate approximation to the shape of $g^{-1}(\cdot)$ is then obtained by doubly integrating a square pulse of duration somewhat greater than that desired for the output ramp. Thus the ramp output frequency sweeps positively from 5.5 GHz and passes through the 6-GHz center frequency, to which it was initially phase locked, near the center of the output pulse.

Despite the care taken to stabilize the starting voltage and shape of the video drive, the resulting linearity and stability of the VCO output are not good enough to satisfy the system requirements. Two further steps are taken to improve the ramp quality, the second of which will be discussed in the next section. The first of these involves the use of a linearizing feedback loop in which the generated ramp is mixed with itself delayed by 250 ns. The phase of the resulting signal is then compared with that of a gated CW reference signal which is started with identical phase at each ramp initiation time and rings at constant frequency for the duration of the pulse. After amplification and low-pass filtering the phase error signal is fed back to the VCO as a correction signal into the second VCO input port, which has a modulation bandwidth of 10 MHz and so can respond rapidly to any nonlinearities present in the generated ramp.

We may model the action of the linearizing loop as follows. Let the desired linear FM ramp be represented by

$$\text{rect}\,(t - t_0/T)\,\exp\,[2\pi j\phi_0(t)]$$

where

$$\phi_0(t) = f_0 t + \tfrac{1}{2}\mu(t - t_0)^2 + \phi_0$$

is the desired phase function with f_0 the center frequency, $\mu = W/T$ the ramp slope, ϕ_0 a constant phase, and t_0 the time at the center of the pulse, at which the instantaneous frequency is f_0 and is related to the time of ramp initiation. The phase of the ramp that is actually generated is $\phi(t) = \phi_0(t) + \phi_e(t)$, where $\phi_e(t)$ represents the phase error. The mixer that follows the 250-ns delay line in the linearizing loop produces a signal of phase $\phi_1(t) = \phi(t) - \phi(t - \tau)$, where τ represents the delay which expands to

$$\phi_0(t) = \mu\tau t + f_0\tau - \tfrac{1}{2}\mu\tau^2 - \mu t_0\tau + \phi_e(t) - \phi_e(t - \tau).$$

If $\phi_e(t)$ were a constant, this would represent a signal of constant frequency $\mu\tau$ with a phase that depends on t_0 and hence on the ramp initiation time. The gated reference oscillator is adjusted to have this same frequency and a starting phase such as to provide zero average output from the bipolar video detector, which is represented as a mixer in Fig. 1. Under these conditions, and for small phase errors varying slowly compared to the delay time τ, the signal fed back to the VCO will be nearly proportional to the phase error difference $\phi_e(t) - \phi_e(t - \tau)$, which is thereby reduced from its open-loop magnitude.

This method for linearizing and stabilizing active ramp generators has been used in previous systems [7], [8] and the loop response analyzed for various configurations [8], [9]. An alternative technique based on comparing the ramp phase at discrete sampling times with the phase of a frequency comb has also been described [10]. For the LRIR wideband ramp generator, the delay τ was chosen to be 250 ns, which is small enough to compensate for the relatively slowly varying errors due to the VCO and its video drive, while providing a tractable frequency out of the slope detector. For our desired slope of 4 MHz/μs, this output frequency $\mu\tau$ is 1 MHz. As shown in Fig. 2, this frequency is converted to 11 MHz through the use of a 10-MHz offset between the frequencies used for down conversion in the slope detector. This offset frequency is introduced so that the correction signal frequency will be outside the radar return signal band of interest and to ease the problems of shaping the frequency response of the feedback loop and

[1]The VCO is a Watkins–Johnson Company model WJ-2834-17 built to Lincoln Laboratory specifications.

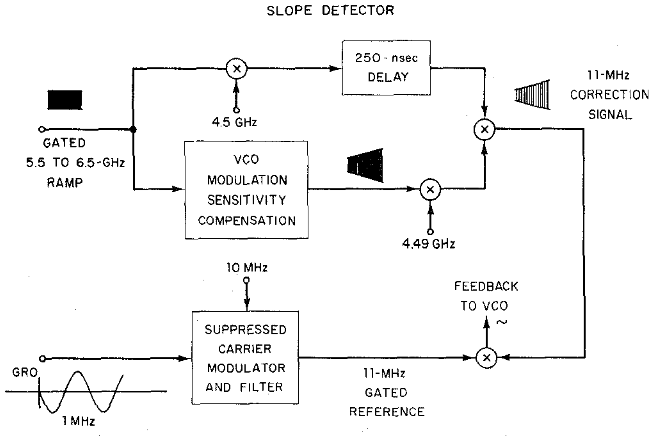

Fig. 2. Detail of the slope detector. The gated reference oscillator (GRO) is generated with the same phase at the start of each ramp.

the discharging of the simple *RC* integrator in preparation for reramping. Similarly, the 1-MHz gated reference oscillator output is suppressed-carrier modulated with a 10-MHz carrier before being applied as the reference signal to the bipolar video phase detector. The mixing and filtering operations in the slope detector and suppressed-carrier modulator are so configured that the phases of the local oscillators cancel out before being fed back to the VCO. Low-frequency phase disturbances on the 10- and 4500-MHz oscillators will then tend to cancel, as has been experimentally verified.

The VCO modulation sensitivity varies over the 1-GHz band of interest, decreasing by approximately 8 dB from 5.5 to 6.5 GHz. Additional loss at the high-frequency end of the band occurs in the down converter and in other components with a total additional loss of more than 3 dB. The compensating filter in the undelayed channel attenuates the low-frequency end of the band by an excess of approximately 12 dB over the high end of the band and maintains the linearity control loop gain constant within approximately 2 dB over the pulselength. The mixers that follow this filter are operated linearly, the amplitude compensated signal being introduced to the mixer through the small signal port. A gain margin of 12 dB was provided in the final design.

Fig. 3 is a photograph of the LRIR wideband ramp generator showing its construction. The 250-ns delay cable used in the slope detector is wound and potted within the vertical slide-out drawer on which the other components and chasses are mounted. Power supplies and digitally controlled timing and gate generation circuitry are housed in a separate rack. Two such units were constructed, the second serving as a wideband test target generator and spare.

IV. Performance

Fig. 4 is an oscilloscope photograph of the spectrum resulting from correlating the *C*-band output of the wideband ramp generator with itself after a delay of 250 ns. The test setup is indicated at the bottom of the figure. The spectrum is a close approximation to the sin x/x shape that would be expected for an ideal linear FM pulse. Although this test permits the inference that the generated ramp has a constant (or slowly varying) slope, it does not test the reproducibility required by the radar's correlation processor in which the echo resulting from the transmission of one ramp is correlated with a ramp generated later, near the time of the echo delay. Fig. 5 shows the compressed pulse shape as obtained by actual radar operation against a point target (a sphere) at a range of about 1000 km, following non-real-time processing of the recorded digital data. Transversal equalization was applied to the data to correct for amplitude and phase errors in the radar transmitter and other micro-

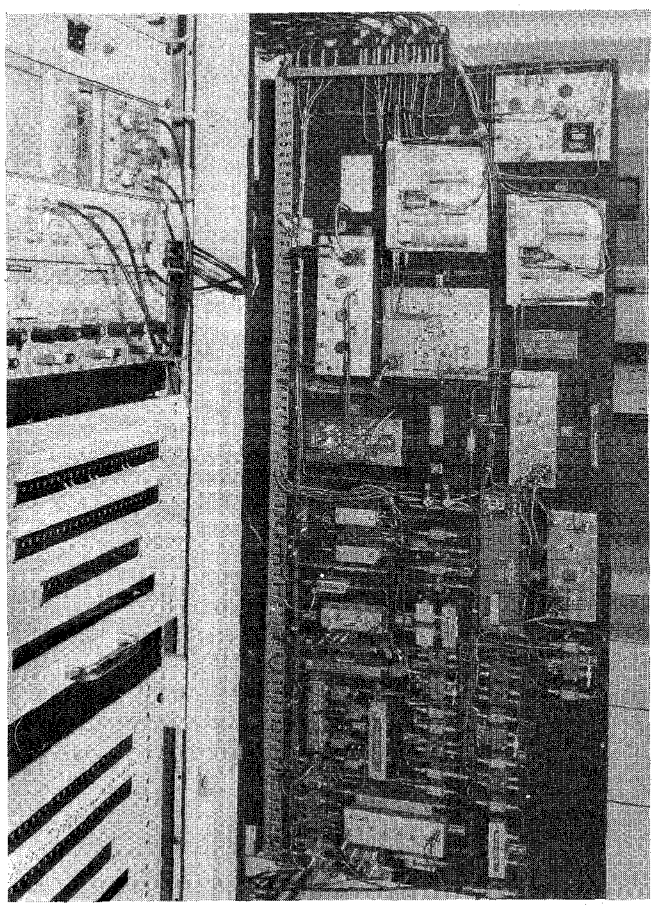

Fig. 3. Photograph of the LRIR wideband ramp generator showing its construction. The 250-ns delay cable used in the slope detector is wound and potted within the slide-out enclosure on which the components and chasses are mounted.

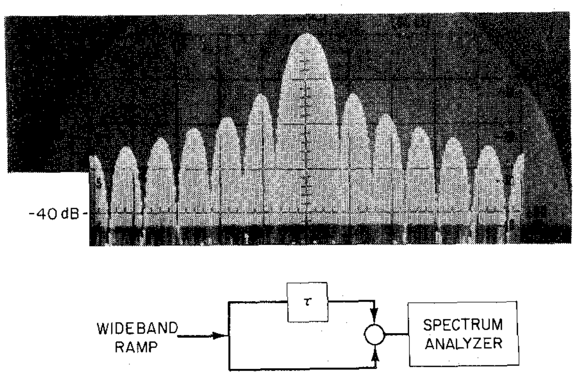

Fig. 4. Oscilloscope photograph of the output spectrum of the wideband ramp generator when mixed with itself after a delay of 250 ns, demonstrating a close approximation to the desired sin x/x spectrum shape.

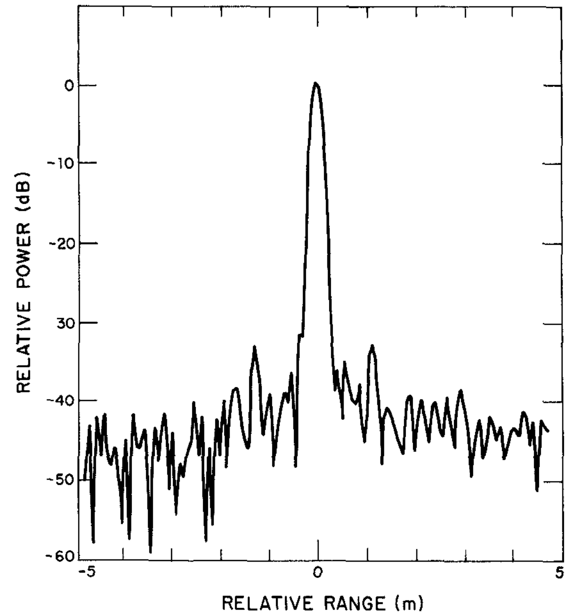

Fig. 5. Compressed pulse shape obtained after non-real-time processing of the echo from a sphere.

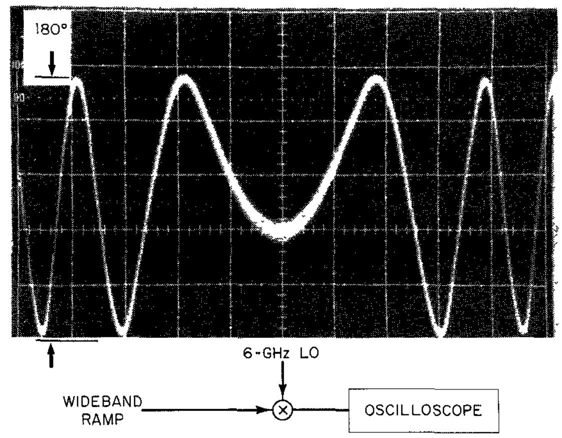

Fig. 6. Oscilloscope photograph of the output of the wideband ramp generator after mixing with the 6-GHz CW reference to which it was initially phaselocked. Repetitive traces are displayed, taken near the center of the pulse where the instantaneous frequency passes through 6 GHz. The width of the trace at zero-beat is an indication of the pulse-to-pulse phase stability.

wave components. For identical transmit and reference ramps, the ramp errors will depend on the position of the echo within the range window and cancel completely at the center. The typical results shown in Fig. 5 shows a worst sidelobe level of -32 dB with respect to the main lobe of the response.

Pulse-to-pulse phase coherence is required in the LRIR in order to be able to resolve the target's scattering centers in the cross-range direction and to improve the signal-to-noise ratio through coherent integration. Fig. 6 shows the beat between the ramp generator output and the 6-GHz CW reference to which the generator was initially phase-locked. The display encompasses only a few cycles of the mixer output near the center of the pulse. Multiple traces are displayed, so the width of the trace at the time of the zero beat is an indication of the pulse-to-pulse phase jitter. The peak-to-peak amplitude of the oscillatory signal before or after the time of zero beat corresponds to 180° of phase. It is inferred from the results shown that the pulse-to-pulse phase jitter is less than about 3° rms. However, without further correction the phase at the time of the zero beat tends to drift slowly due to thermal variations, which is manifested by a rolling of the display of Fig. 6. This phase drift normally is slow enough not to affect system performance except for very long integration times. However, it is undesirable and was corrected in the LRIR ramp generator by sampling the phase at the time of the zero beat, smoothing the samples with a long time constant, and feeding the result back to the phase locking circuitry. With this correction, which is not shown in Fig. 1, the display of Fig. 6 is stationary and one can be confident that the wideband ramp generator will not limit the long-term coherence that can be achieved with the LRIR.

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