A HIGH STABILITY TWTA FOR GROUND SURVEILLANCE APPLICATIONS*

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ABSTRACT

A high stability, C-band transmitter capable of supporting -68 dBc subclutter visibility over a wide range of pulse widths and duty factors was developed for use in a multimode, battlefield surveillance radar. The transmitter was mode-switched between groups of 1/4, 20 and 65 microsecond radar pulses and long duration (100 ms) FSK bursts. A key feature was the use of a high speed, intrapulse regulator to maintain proper TWT voltage and to limit ripple independent of waveform without the need for excessively large energy storage. Actual measured performance met the 100 mV cathode ripple specification without the use of PRF synchronization, independent of PRI, duty cycle and pulse width and was confirmed via direct evaluation of electrode voltages, serrodyne phase jitter and the radar pulsed-Doppler spectrum.

INTRODUCTION

A key parameter for any high sensitivity ground surveillance radar is its subclutter visibility--the ability to detect small moving targets in the presence of large stationary clutter. Such performance requires extremely stable phase and amplitude coherence of successive radar pulses. In addition this radar had to support extremely long duration FSK communication bursts, which further stressed the design in a manner orthogonal to the subclutter visibility requirements.

This paper will first discuss the pertinent radar system parameters and their translation into required transmitter performance and choice of the power output device. A discussion follows of the design topology employed to minimize the risk in attaining the desired transmitter specifications. Lastly, measured performance data from three independent techniques will be presented. It was imperative that transmitter performance be substantiated to the most exacting level possible prior to integration within the radar. The remainder of this paper will address the measurement techniques and the data obtained on electrode voltage and phase stability performance made at the plant, and provide corroborative data obtained from an examination of the instability residue on the pulsed-Doppler spectrum following field installation within the radar.

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RADAR SYSTEM DESCRIPTION[1]

The transmitter operates at a nominal 5 GHz center frequency with 500 W peak output power. By use of an electronically scanned, cylindrical array antenna, the radar can scan from one azimuth angle to another virtually instanteously, without the processing dead time associated with a mechanically-scanned antenna servo system. This feature allows the radar to interleave MTI processing among several separated areas-of-interest and report (or net) the information to a Target Integration Center on a second by second basis using the radar itself as the integral data link instead of a separate data link system than any separate netting system.

Although highly attractive from a system viewpoint an integral radar and data link concept places stringent demands on subsytem performance. The salient radar parameters that govern transmitter specifications are:

TABLE 1

GENERAL
- 5 to 5.5 GHz center frequency
- 300 W peak output power
- 3 phase 400 Hz prime power

RADAR MODE--MTI pulsed output
- 0.25 to 65 us pulse width
- Non-linear FM SAW phase coding
- 350 to 450 us PRI
- -68 db post-processor clutter instability residue

DATA MODE--FSK modulation
- 100 ms pulse width
- 1 s repetion rate
- -40 db post-processor signal instability residue

The 10 percent bandwidth, high peak power and low spurious modulation characteristics demand the

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use of a travelling-wave tube as the output device which can operate quasi-CW to accomodate the extremely long 100 ms data link pulses.

TRANSMITTER SPECIFICATIONS

The impact of these specifications in determining transmitter power supply design can be divided into four categories that deal with regulator and modulator characteristics.

Pulse-Width and Duty Cycle

The 100 ms pulse width requirement makes it virtually impossible to perform intrapulse regulation solely with energy storage. The regulator and power supply must be capable of delivering the peak load, continuously during the pulse. Response time should be short compared to the pulse width with well-defined transient characterisitics governed by the following constraints.

Regulation from Pulse to Pulse

Any variation in amplitude or phase of the complex radar return from pulse to pulse is interpreted by the processor as a moving target. Thus if a target were moving in close proximity to a large, stationary object, any instability in the transmitter would generate modulation sidebands of the stationary clutter that would in turn mask the small mover. The worst case exists when all instability energy is concentrated at a single frequency. The relative amplitude of each sideband can be calculated from FM theory and Bessel Functions[2], and, assuming low level modulation, is given by:

$$dBc = 20 \log |A/2|. \qquad (1)$$

where A is the peak phase deviation in radians.

Thus to achieve the desired subclutter visibility of -68 dBc the peak value of any sinusoidal spurious phase disturbance must be less than 0.06 degrees. Since a TWT is used as the output device, the phase stability specifications can be translated directly into voltage variation limits on the various electrodes via the tube pushing factors. Performance is set by the ripple on the cathode which with a typical phase pushing factor of 0.5 degrees/Volt is then limited to 100 mV peak. There exists analogous calculations that bound the allowable voltage ripple due to AM-induced spurious on the instability residue. However, a careful choice of quiescent voltages and operation of the tube in the saturated mode will reduce the amplitude pushing factors to the level where their effect on instability limitations is inconsequential in comparison to that of phase modulation (typically by 10 to 15 dB) and need not be calculated.

Regulation During a Pulse

It is important to note that the above constraint on ripple applies pulse to pulse for a given point within the transmitted waveform. The variation of voltage within a pulse has no effect on subclutter visibility and is bounded primarily by the limit on the acceptable range/time sidelobes generated by the Surface Acoustic Wave IF filters. Since the SAW expansion and compression units are assumed to be matched then any modulation imparted by the transmitter will decorrelate the return.

Because the regulator will respond during the pulse, the effect of linear voltage droop will be neglible.

Of much greater concern are the effects of cyclic voltage changes during a pulse. It can be shown,[3] that the amplitude and temporal location of unexpected sidelobes in the matched-filter impulse response are directly related to the amplitude and periodicity of the phase disturbance during the pulse, and may be calculated with an equation of the same form as Eq. (1). For the particular SAW devices in question, a -30 dB sidelobe level sets a 1 degree, and hence 2 V, bound on cyclic disturbances and thus define the limits of regulator transient reponse.

It is worth pointing out that no mention has been made of the FSK data mode during discussion of regulation requirements because the spectral stability demands for FSK operation are not as restrictive as those imposed by the MTI radar mode. In particular, the 1 degree cyclic ripple bound set by the SAW device performance results in -35 dBc frequency sidebands which is more than adequate signal-to-spurious ratio for detection in an FSK scheme.

Modulator Switching Speed

The modulator design must accomodate both very long (100 ms) and very short pulses (0.25 us), with less than 1 us switching speed. Because of the critical pulse to pulse repeatibility requirement, the beam must be activated prior to the application of RF, so that output spectral stability will not be affected by modulator transient characterisitics.

SYSTEM IMPLEMENTATION

Based on the preceeding performance requirements a travelling-wave tube and circuit topology were chosen. This section will describe the hardware implementation, including tube, power supply and modulator, needed to meet those requirements.

Travelling-Wave Tube

The tube is a Teledyne-MEC MTC-6002 depressed-collector helix-TWT with focus electrode for beam control and is capable of supporting the 500 W peak RF output power requirement for the duty-cycles and pulse widths described in Table 1. The salient operating parameters are given in Table 2.

A depressed-collector TWT was chosen partly to improve power conversion efficiency. More importantly, a depressed collector configuration can take full advantage of the large difference in phase pushing factors to allow regulation of the critical cathode voltage and its associated current load (25 mA) to be isolated from the high current, but low regulation demands of the collector supply (600 mA).

TABLE 2

Cathode voltage:	-10 KV w.r.t. ground
Collector voltage:	5 KV w.r.t. cathode
Focus voltage	
beam off:	-3 KV w.r.t. cathode
beam on:	-50 V w.r.t. cathode
Collector current:	600 mA peak
Helix current:	25 mA peak
Phase sensitivity.	
Cathode:	0.5 degrees/Volt
Focus:	1 degree/Volt
Collector:	0.01 degrees/Volt
Amplitude sensitivity:	
Cathode:	0.01 dB/Volt
Focus:	0.02 dB/Volt
Collector:	0.0004 dB/Volt

Two major design decisions were made that shaped the actual system implementation. First, thermionic (vacuum-tube) rather than semiconductor devices were employed for all interfaces to the TWT itself to reduce the potential risks to the tube during arc conditions. Second, a cathode modulation scheme was developed to simplify system design and reduce power supply count. The basic circuit topology used to meet all of the aforementioned design objectives is shown in Figure 1.

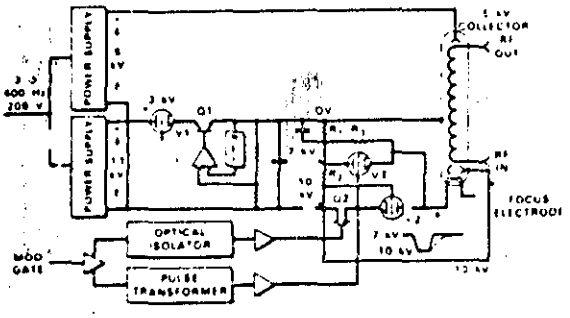

Fig. 1. Power Suppiy and Modulator Topology.

Voltage Generation

Separate, non-stacked power supplies were used to independently generate the cathode and collector voltages, to isolate helix from collector current loading, as described in the above paragraph. The primary high-voltage outputs needed for both cathode and collector supplies were generated by basic, polyphase rectification of the 3-phase, 208 V input, using a choke-coupled, wye-delta winding pair for each output with a motor-driven Varia controlling the transformer input level. This approach has a number of advantages. Transformer upconversion eliminates the need for DC-DC switching converters. Since subclutter visibility depends directly on the ripple, it is inherently lower risk to employ a design that reduces ripple at each conversion stage rather than generating the large amplitude, high frequency square waves needed for switch-mode conversion. This polyphase transformer configuration results in an extremely high ripple frequency and thus an inherently low ripple voltage. The motor-controlled input transformer level allows compensation of long term line variations and provides a "soft-start" mechanism to reduce inrush currents during power on.

Voltage Regulation

Because of the low modulation sensitivity of the collector voltage no further regulation was required on the 5 KV floating supply beyond that supplied by the rectifier-filter assembly. For the critical cathode voltage a series- bucking regulator was used, consisting of pentode V1, and transistor Q1. The 10 KV cathode voltage was generated by summing the 13 KV floating rectifier-filter output with the nominal 3 KV pentode voltage drop. The extremely accurate regulation was maintained by sensing any change in the cathode output and varying the drop in pentode pass regulator accordingly. It is interesting to note that the polyphase rectification technique of the previous section produced only 1 V ripple, which with no loop gain in the feedback loop would be passed through to the cathode. As loop gain was increased, the pentode developed a ripple voltage of equal magnitude but opposing polarity so as to maintain constant cathode output. Response time had to be short, on the order of 20 us, with minimal overshoot or ringing as required by the SAW sidelobe response. Loop gain was adjusted to balance the conflict in requirements of steady state error, response time and loop stability. From a practical viewpoint, even infinite loop gain would not have produced zero ripple. Non ideal error sources such as ground ripple and pick up in the feedback path required extremely careful construction and shielding techniques.

Beam Current Modulation

As mentioned earlier, beam current control is by cathode voltage switching. This of course implies that the just described "cathode regulator" is only indirectly connected to the cathode through the series switch, comprised of power pentode V2 and power FET Q2. Operation of the modulator is as follows. The focus electrode is maintained at the cathode regulator output voltage. In the absence of a gating signal, the cathode is held at -7 KV established by the resistive divider comprised of R1 and R2. Switch tubes V2 and V3 are nonconducting. Under these conditions the focus electrode is -3 KV with respect to the cathode and the TWT is biased off.

When the modulator signal is coupled up through the optical isolator, V2 is activated, and the cathode-to-focus electrode difference reduces to the V2/Q2 on-state drop (nominally 250 V), enabling TWT conduction. Actual beam current level is set by critical adjustment of the focus electrode voltage, using a portion of the V2 screen voltage as the offset source.

With the modulator signal removed, the TWT turnoff transient would be slow, despite the rapid turnoff of V2, because of the the high resistance discharge path through R3 for the cathode voltage. Modulator response time is maintained by the inclusion of switch tube V3, which is pulsed on after V2 is off to actively force the cathode through a low impedance path to return to the -7 KV, off state.

MEASURED PERFORMANCE

One of the key issues in this program was the development of a set of test measurements to verify the stability performance of the transmitter prior to evaluation in the radar itself.

Voltage Measurements

A necessary but not sufficient performance check is electrode voltage measurement. Figure 2 is

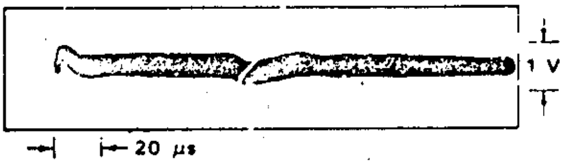

Fig. 2. Cathode Regulator Response.

the cathode regulator response during a radar pulse. Overshoot is less than 0.5 V with a 10 us response time. The vertical width of the trace bounds the voltage instability to approximately 200 mV peak. The nominal 1 us switching characteristics of the cathode modulator are shown in Figure 3. The two

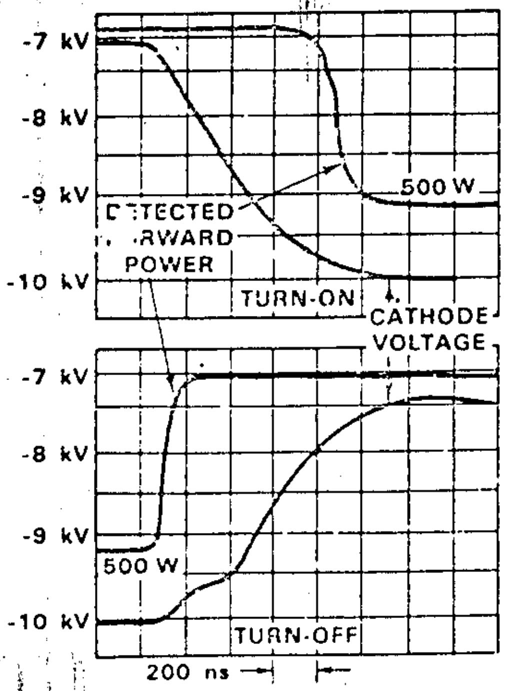

Fig. 3. Modulator Switching Speed.

distinct cathode voltage discharge rates associated with switch-tube V3 are quite evident during TWT turn-off.

The key measurement of cathode voltage repeatability--100 mv variations on a 7 KV quiescent level with 3 KV pulsed fluctuations--is virtually impossible to make with a high degree of confidence.

Phase Measurements

Voltage regulation is not the final arbiter in any case. Because of the above difficulty a serrodyne phase measurement was devised to properly evaluate instability performance (see Figure 4). A

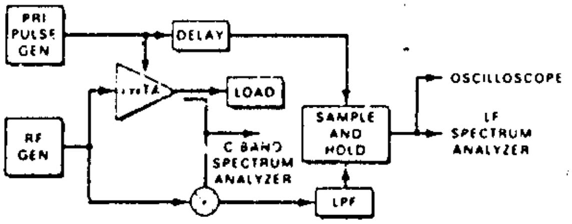

Fig. 4. Preliminary Transmitter Phase Stability.

sample of the TWT output was mixed with the stable RF input producing a voltage proportional to the relative phase between the two signals. The sample-and hold was synchronized to the PRI with variable delay to allow sampling of any point within the phase waveform.

The system was calibrated by first injecting a sufficiently large signal into the cathode regulator error amplifier to increase output ripple. The magnitude and frequency were chosen so that resultant sidebands could be easily measured and distinguished from the PRI lines on a C-Band spectrum analyzer. See Figure 5a. A 4 V peak,

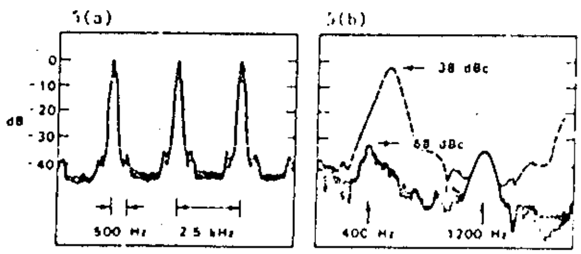

Fig. 5(a). C-band Spectrum.
5(b). Sampled Phase Noise Spectrum.

500 Hz induced cathode ripple produced a 1.5 degree peak phase modulation and a -38 dBc sideband level, which is within 0.5 dB of that predicted by equation (1). This procedure provides a calibration point on the dashed sampled phase noise spectrum of Figure 5b. The residual phase noise spectrum after

removal of the external modulation represents true transmitter instability, as shown by the solid curve. Performance is limited to −68 dBc by a single spectral line at the power frequency.

In Situ Radar Performance

Performance within the radar is measured by an examination of the instability residue in a pulsed-Doppler spectrum of a large stationary clutter discrete. Figure 6 is the discrete Fourier

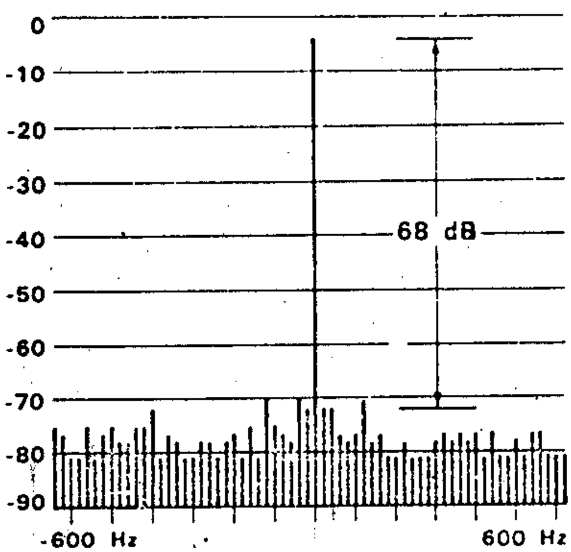

Fig. 6. Overall Radar Signal Stability Spectrum.

transform of a 64-point time series consisting of the returns from such a target, situated 3 km from the radar. For a perfectly stable radar system, the spectrum would be described by a single central line representing the target at zero Doppler, with all other filter bin magnitudes at a level commensurate with the receiver front-end noise. Any other lines result from the spectral decomposition of all contributors within the radar to the instability residue, primarily the transmitter and frequency synthesizer, and indicate a minimum of −65 dBc suppression. Since the effects of oscillator instability are directly proportional to the range of the target, it was possible to isolate the synthesizer effects and substantiate the −68 dBc measurement obtained for the transmitter alone.

SUMMARY

The −68 dBc instability residue obtained was acceptible for the radar application, but should not be considered a limit to the state of the art. There is no doubt that with additional time and more refined shielding and construction techniques further reduction could have been attained.

In summary, subclutter visibility is a performance parameter that must guide a transmitter development from the very outset, as it affects all aspects of the design. In addition, because of the very nature of the phenomena that tend to limit system stability, it is imperative that equal care must be given to development of a real time stability test to monitor and fine tune performance during system integration.

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BIOGRAPHY

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