Microwave Systems Design for High-Performance Moving Target Indicators in Radars

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Abstract —**Clutter cancellation of 65 dB and better is directly proportional to good radar stability, and since many hardware areas produce instabilities at various levels, the architecture of a radar requires special design considerations to support this high stability. The noise character and generation methods of these instabilities in the various hardware areas are described and design solutions given to eliminate them. A reliable, accurate method of measuring radar stability in L- and S-band radars is described.**

I. Introduction

The objective of ground-based moving target indicator (MTI) radars is to cancel ground clutter, leaving a clear plan position indicator (PPI) screen to track moving targets. The demand for better clutter cancellation over the past two decades has increased the requirement for MTI radar stability to the 65 dB range and better. This requirement has placed new demands on the microwave system and its components. As Fig. 1 shows, progress in clutter cancellation capability has been improved from 23 dB to the 60 to 65 dB range in S-band and L-band radars over the last 20 years. This is based on actual measured data on ground-based radar systems at Westinghouse. This performance has resulted from state-of-the-art hardware improvements as well as architectural advances in radar design.

Any instabilities in the MTI radar signal transmission or receiver circuitry can contaminate the radar signal with a noncoherent noise which will appear as a moving target. Because of this contamination, the level of cancellation of the fixed target returns is directly related to the stability of the radar system [1].

Over the years as radar stability has been gradually improved, instabilities have been traced to a vast array of contributors in the hardware areas of the radar. With instabilities so prevalent and widely scattered throughout the system, a radar stability measuring technique is an essential tool in measuring the progress in achieving stability. When such a tool is not available, considerable effort may be expended in making stability measurements

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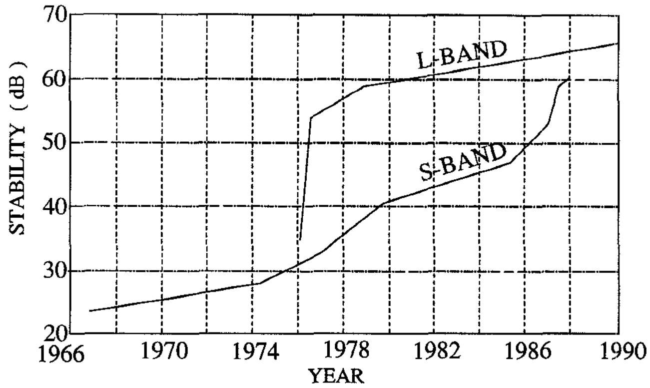

Fig. 1. MTI radar stability chronology.

using a permanent echo target, where the target returns may be contaminated by interference signals or unstable ground clutter, or the target may be more unstable than the radar being measured. This illustrates the need for a radar system stability measuring technique that does not depend on radiating to a target in the outside environment.

The transmitter, even if connected to a dummy load, has sufficient EMI leakage to jam the receiver during transmit time, thus making the receiver unusable. The frequency generator STALO (STAbilized Local Oscillator) noise (PM and FM) visibility to the radar is range dependent and is self-canceling at zero range (zero delay). These two facts demand that a radar system stability measuring technique provide a microwave delay. The most obvious way of obtaining large microwave delays is to use returns from stable permanent echo targets of sufficient size and distance from the radar. Finding such targets is not always convenient or even possible. Despite the difficulties, if a suitable fixed target is available, this method has two distinct advantages, i.e., long delays and the inclusion of the entire system in the measurement. However, such stable targets are not often available, and for most applications a more repeatable and convenient stability measuring technique is desired, such as the microwave delay line.

A microwave delay line circumvents all of the problems encountered with the permanent echo technique just described [2]. The longest microwave delay line available for

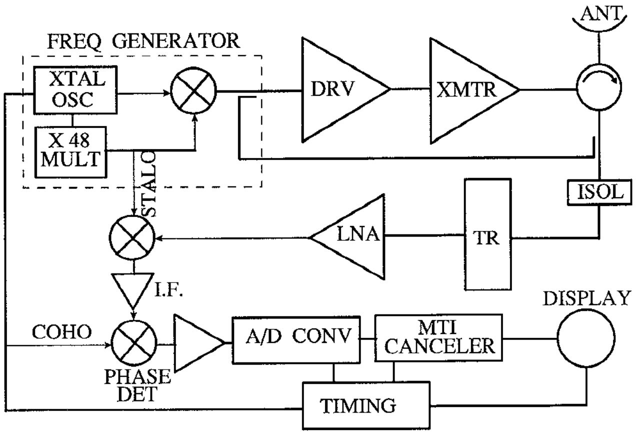

Fig. 2. MTI radar block diagram.

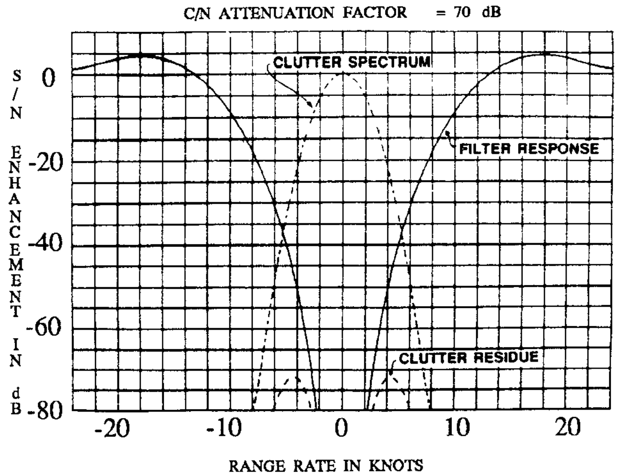

Fig. 3. Ground clutter filter response to mountain clutter.

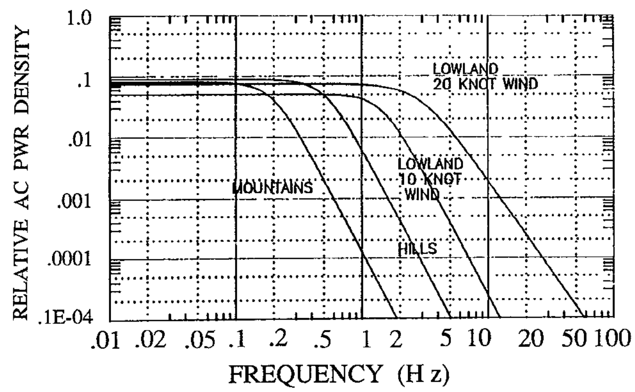

Fig. 4. Spectral density of land clutter ac power.

use at L-band and S-band frequencies is a 15 μs sapphire bulk acoustic wave (BAW) delay line. For higher frequency radars, smaller delays must be used to keep the insertion loss down to a usable level. The question is raised as to the adequacy of this delay time to provide sufficient visibility for stability measurements of the STALO noise. For transmitter measurements it is adequate for the more common pulse widths, which are less than 15 μs. For STALO measurements, analysis made in this paper will show that this delay does provide sufficient decorrelation for accurate STALO noise measurements.

II. How Stability Affects Clutter Cancellation

The uniqueness of an MTI radar that allows it to detect moving targets and cancel clutter is the coherent phase detection feature. Coherent detection is made possible by creating the transmit signal from the sum of the STALO and COHO signals, as shown in Fig. 2. This makes the IF frequency identical to the COHO frequency in the receiver, thus producing coherent detection at the phase detector. Coherent detection produces a phase and amplitude stable (clutter) signal from a fixed (nonmoving) target in a ground-based MTI radar; conversely, a moving target produces a signal varying at the Doppler frequency rate. This fact allows separation of the Doppler and clutter signals with a high-pass filter at the phase detector video output. The clutter filter is in the form of a notch filter centered on zero frequency which accommodates both positive and negative Doppler targets. The solid curve in Fig. 3 is the MTI clutter filter on a radar presently being designed to detect targets as slow as 20 knots while rejecting the HILLS clutter model in Fig. 4. The dashed curve in Fig. 3 represents the hills clutter return with the scanning modulation added to produce a realistic performance scenario. After the clutter is rejected by a seven-pulse ground clutter filter in the radar processor, the residue left after cancellation is below 70 dB.

With such an elegant radar design, what are the limitations to the system that might restrict the accomplishment of this 70 dB cancellation ratio? Assuming adequate dynamic range, the major restriction to cancellation is instabilities of the radar system.

An MTI radar is susceptible to noise at any frequency in its velocity response range. The high-pass ground clutter filter, in Fig. 3 for example, determines the low-frequency response of this particular MTI radar velocity response filter, which cuts off at approximately 50 Hz. The staggered pulse repetition frequency (PRF) mode is preferred over a fixed PRF because it reduces blind speeds to dim speeds and is considered the standard mode for MTI radars. Utilizing a stagger PRF extends the velocity response curve to 500 kHz (half the IF filter bandwidth). The penalty paid for using staggered PRF involves instabilities introduced by the analog switching circuits owing to inconsistent transients between long and short PRT's. Any phase, frequency, or amplitude modulation side bands that sneak into this system in the velocity response frequency range (50 Hz to 500 kHz) can cause degraded performance in MTI cancellation, provided that the total integrated noise in this velocity response bandwidth is more than the desired clutter cancellation. A single discrete noncoherent spurious at this integrated level can also cause similar degraded performance.

III. Instabilities in MTI Radar and Some Design Solutions

The following are examples of instabilities found in MTI radars and the design solutions to cure or work around these problems.

A. Transmitter Filament Modulation

The undesirable characteristic of transmitter tubes is the modulation of the beam current by the ac powered filaments. This creates noiselike side bands on the carrier frequency that limit MTI cancellation. Identical tube types have been seen to produce instabilities anywhere from 20 dB to 40 dB owing to filament power modulation. This problem can be eliminated either by synchronizing the filament ac power to the system timing or by gating off the filament power during the transmit time. Usually, dc filaments are impractical because of the high potential above ground.

B. STALO Noise

STALO noise is a natural phenomenon starting in the crystal oscillator and is increased 6 dB in every frequency doubling stage. It is not uncommon to find this noise increased by more than 30 dB for an L-band or an S-band radar STALO. The integrated STALO noise of an L-band radar designed 15 years ago by the author is -64 dBc. The integrated noise of an S-band STALO designed 13 years later, as shown in Fig. 5, is -74 dBc. Considering the 2:1 difference in frequency (6 dB), this translates to a 16 dB improvement in STALO noise quality. Significant design improvements were made in oscillator circuit noise, crystal noise, and multiplier noise to accomplish this improvement.

C. Receiver Ringing

The high powered transmitter burst of energy, although limited with a receiver protector, will invariably find its way to the receiver chain, causing saturation. Because of base-to-emitter rectification of this overdrive signal in the receiver amplifier, the transistor will be biased-on very hard, thus drawing excessive collector current. If the dc circuit is not designed properly to provide this excessive current without causing a drop in the supply voltage, the dc recovery at the end of the transmitter pulse will ring at the resonant frequency of the large decoupling capacitors and chokes. This ringing causes amplitude and phase modulation and can devastate good receiver performance. Small capacitors and small low-Q coils can diminish the resonant recovery time. The addition of dc regulators inside the receiver modules can provide the excess current to reduce receiver recovery to acceptable levels. These regulators are very effective in keeping unwanted noise modulation signals (50 Hz to 500 kHz) from riding in on the dc lines, thus replacing the filtering lost by reducing the capacitors and inductors to small values for improved recovery times.

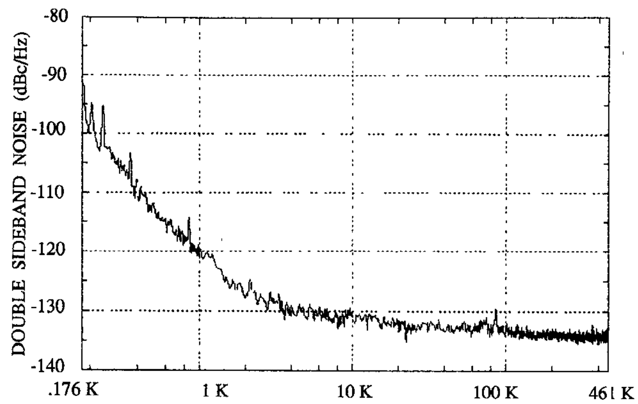

Fig. 5. S-band STALO noise.

D. Stagger PRF Instabilities

Blind speeds, which are caused by Doppler targets at the same frequency as the PRF rate and multiples thereof, are reduced to dim speeds in the radar velocity response curve by using a variable length pulse repetition time (PRT). The variable length dead time at the end of each PRT of different length is the variation that causes the settling time of the RF switches in the radar to produce instabilities. For example, if the STALO is switched during dead time to do ECM analysis, height calibration, or STC calibration, the STALO will have a longer time to settle after the final transmit frequency selection is made in a long PRT compared with a short PRT. This difference in settling time causes instabilities which can be significant even with fast switches when looking for 65 dB or better stability in a radar system.

The solution to eliminating this instability is to change the timing of the radar system so all dead time analog switching is synchronized to the next transmit pulse instead of the previous transmit pulse. This provides equal settling times in every PRT for RF switches preceding each transmission. This almost completely eliminates instabilities in the stagger PRT mode caused by RF switches.

E. Transmit/Receiver Protector (T/R)

Most high powered radars (1 MW peak) use gas discharge T/R tubes to protect the low-power receivers. The receiver is usually connected to the transmitter through a circulator (Fig. 2) with only about 25 dB of isolation; therefore, 3 kW of power can easily reach the receiver T/R tube. When the gas T/R tube fires, a short is created, thus reflecting a tremendous amount of this energy (600 W = 27.8 dBW measured on one radar) back to the circulator. Because of the T/R tube's inherent inability to accurately fire at the same precise voltage every PRT, the reflected power is totally noiselike in character when compared on a PRT to PRT basis. This noise energy travels through the reverse 25 dB isolation path in the circulator to add to and contaminate the clean transmit signal at the antenna port with +2.8 dBW of noise power. This limits stability to 60 dB − 2.8 dB = 57.2 dB. An additional isolator must be added, as shown in Fig. 2, to trap this noise energy if system stability greater than 57.2 dB is to be realized.

F. Flexible Waveguide

Flexible waveguide is sometimes used in ground-based radars. Vibrations produced by equipment cabinet cooling fans have been seen to energize mechanical resonances in flexible S-band waveguide sections which in turn produced phase modulation that limited radar system stability to 55 dB. The waveguide was then loaded with weights to reduce the resonance, which eliminated the problem.

G. Module Electromagnetic Interference (EMI)

Any module in the RF and IF chain starting at the frequency generation source through the transmitter and receiver chain is subject to introducing instabilities into the radar. If nonsynchronous spurious or noise is allowed to penetrate these modules and modulate the radar signal, it degrades stability accordingly. Since the radar's processor responds to target velocities usually in the 50 Hz to 500 kHz Doppler frequency range, power line ripple on dc power lines and logic spikes are the primary signals that inject noise at these frequencies into the RF modules. This noise modulation has shown up as a 40 dB limit in some cases. Using dc to dc regulators in conjunction with low-pass feedthrough filters inside these modules is an excellent technique for eliminating these modulation paths.

H. Coax Connectors

Coax connectors can be a source of noise in radar system instabilities. A good-quality threaded connector (no bayonet) is needed and must be kept tight for good low-noise performance.

Flange-mounted connectors on modules can be a tremendous source of noise if two or more modules are mated directly through coax connectors and then mounted to a common plate to create a stress on the flange-mounted connectors. With time, the screws and/or module threads are stressed beyond their elastic limit, causing elongation. This creates an intermittent loss of ground on one side of the flange-mounted connector. This can produce phase noise in the radar. This problem can of course be designed out by (1) choosing a large base flange connector using large screws and (2) designing module mounting so tolerances can be adjusted to eliminate most of the stress.

I. YIG Filters

YIG Filters are a convenient and economical approach to implementing an easily tunable radar. But the disadvantage is that voltage versus frequency phase sensitivity of the YIG filter tuning port is a perfect point for unwanted noise modulation to sneak into a system, as it has on many occasions. This can be filtered out but at the expense of drastically reducing the tuning speed. Not only is pickup noise on the tuning line a problem, but the operational amplifier noise driving the magnetic tuning coil translates directly into phase modulation at the filter. All this noise can be filtered out but at the expense of tuning time.

IV. Measuring Radar Stability

As seen from the above examples, instabilities can show up in many hardware areas. The transmitter and frequency generator stand out as the two hardware areas in which it has been the most difficult to achieve and maintain stability; therefore, a radar stability measuring technique must provide visibility for all components, especially these two.

A. Transmitter Difficulties

A typical transmitter providing a megawatt of peak power will render the receiver useless in making stability tests without delaying the microwave transmit signal.

B. Frequency Generator Difficulties

At first glance, one might think that frequency generator stability could be measured utilizing the RF test target (RFTT) along with the rest of the radar system, since this test target can be digitally delayed until live time when the transmitter is off. The STALO (first LO), transmit, and RFTT all have identical noise when generated at the frequency generator. The major source of noise on these three signals is phase and frequency modulation from the STALO crystal oscillator (multiplied to microwave). Assuming a perfect transmitter, this noise is still identical at the transmitter output. When either the RFTT signal or the transmit signal is down-converted with the STALO in the receiver, the identical phase and frequency noise on these two signals cancels, thus producing a clean IF signal completely void of frequency generator instabilities; therefore, the RFTT signal can be used only to evaluate stability of the IF circuitry through the phase detector, A/D converter, and MTI canceler. This leaves the two most probable noise sources yet untested, specifically, the frequency generator and the transmitter.

C. STALO/Decorrelation

STALO noise shows up in the radar output only when there is a delay in the transmitted signal before it is mixed back with the first LO at the receiver first down-converter, as in the case with a live target. This delay creates a decorrelation between the STALO noise on the returned live target from the transmitted signal in relation to the identical but undelayed STALO noise on the receiver first LO. Fig. 6 shows this range-dependent filter (decorrelation) characteristic, which is expressed mathe-

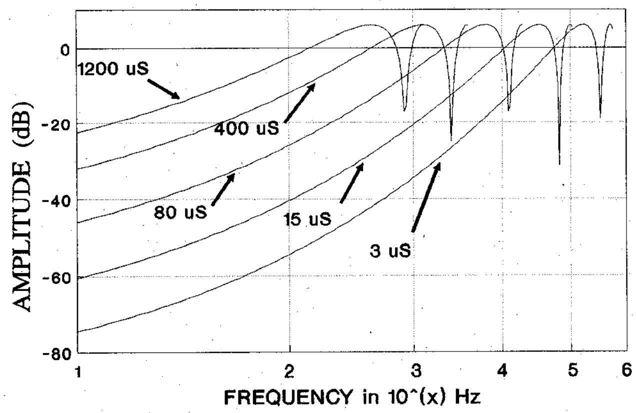

Fig. 6. Decorrelation versus delay.

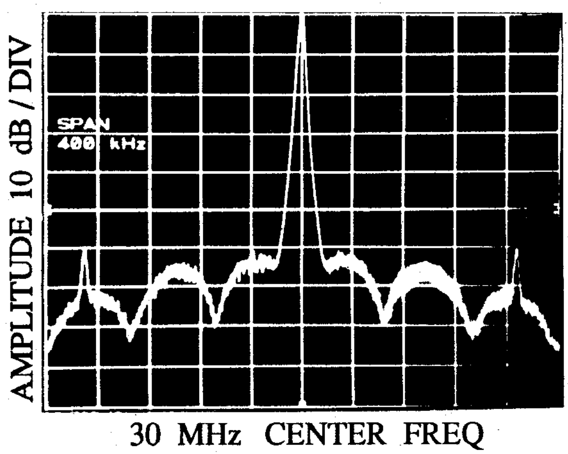

Fig. 7. Decorrelation on STALO noise in a CW lab radar.

matically by Taylor [1] as

$$\text{Decorrelation (dB)} = 10\log\left[4\sin^2(\pi f_m T_d)\right]$$

where

f_m = modulation frequency (Hz)
T_d = time delay = $2\ R/C$ (s)
R = range (m)
C = propagation velocity (3×10^8m/s).

As the curves show, the more delay between the two signals, the more decorrelation at the low frequency end of the noise spectrum (close to the carrier).

To demonstrate the decorrelation effects of delay on STALO FM and PM noise, Fig. 7 shows STALO noise as viewed at the IF on a laboratory CW radar model with a 15 μs delay line connected as shown in Fig. 8. The 15 μs delay produces nulls every $1/15\times10^{-6}$ or 66.6 kHz due to cyclic period (360°) difference in the two noise side bands, thus producing cancellation as if there were zero delay. The noise frequencies at one half this 66.6 kHz will be 180° out of phase, thus adding coherently (6 dB) to the total noise and creating peaks as shown in the noise spectrum.

This repeating of in-phase and out-of-phase noise addition creates the side band lobes in Fig. 7. If the delay is

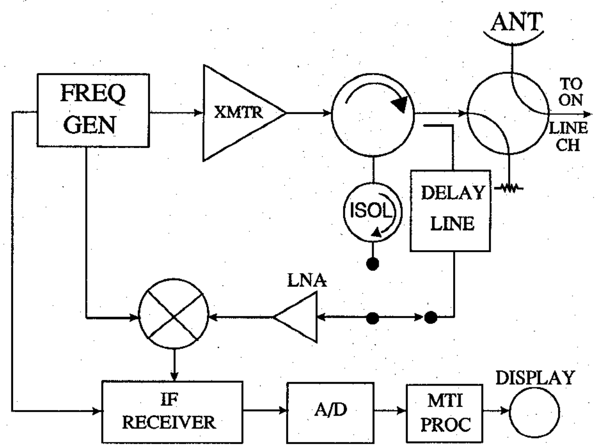

Fig. 8. MTI radar configuration for stability testing.

extended to infinity to create total decorrelation, then the noise side band powers in both signals add to give a 3 dB increase in average side band energy at the IF frequency of the radar.

Since STALO noise power is distributed such that it asymptotically increases at low frequencies close to the carrier, and delay decorrelation decreases at low frequencies, the question is, How much delay is necessary to adequately evaluate the STALO noise? To investigate this, a practical 15 μs delay will be evaluated using the sample STALO noise curve shown in Fig. 5.

D. The Delay Line Solution

The industry at present can make a single microwave delay line of 15 μs with a usable insertion loss at S band. If several smaller delay lines with interleaved amplifiers are used in series to produce a longer delay, the triple travel effect can cause unacceptable pulse distortion; therefore a single delay line is preferred. Also the noise floor can be a real limitation if the signal level is not kept high and the amplifier and delay line gain and losses are not carefully matched. This single 15 μs delay line provides a technique for measuring radar system stability that overcomes the two major problems of (1) transmitter jamming the receiver and (2) lack of STALO noise decorrelation, which is necessary to provide visibility of the STALO noise for stability measurements. The delay line is preferred over the technique of radiating into the outside environment and selecting a stationary permanent echo target of the proper size and distance away. The echo from an outside target is affected by

a) interference from flying aircraft in the detection path;
b) ground clutter near the fixed target area contaminating clean signal return (especially in long pulse radars);
c) the unknown quality of the chosen fixed target.

Therefore, a closed system such as the delay line, which does not expose the test signal to the outside environment, is much preferred.

E. Delay Line Implementation

To make delay line stability measurements on a radar, the radar system is configured as shown in Fig. 8. The 15 μs delay line is inserted between a coupled sample of the transmit signal and the low-noise amplifier in the receiver chain. The radar should be terminated with a dummy load or the stand-by (off-line) channel should be used to prevent noisy clutter from contaminating the stability measurement results. Once the properly delayed transmit signal has been established at the receiver, the technique for implementing the stability measurement of the radar can be made.

F. Stability Measurement Technique

With a properly delayed signal, from either a delay line or from a permanent echo (search-lighting), the stability measurement can be made by one of several different techniqiues. The most common techniques are:

1) Cancellation of Fixed Versus Moving Target: This is a manual method requiring adjustment of signal level with a calibrated attenuator to measure the cancellation of a fixed target relative to a simulated moving target. It requires implementing a phase modulation on every other PRT RF transmission to simulate a moving target as a reference.

2) Radar Processor Normal Versus Doppler Comparison: This method requires the radar processor to have a normal video output channel (no cancellation) as well as the Doppler video output channel (canceler). This is usually available since MTI radars usually do have a normal video output as well as the canceled output. This method requires some software but can be made into a very versatile troubleshooting tool.

3) External Computer Normal Versus Doppler Comparison: This is the same as technique 2 above except the signal is taken from the A/D output before processing, collected using a data buffer, and then fed to an external computer. This computer has software that duplicates the processing in the radar, thus providing one with a somewhat portable test station.

4) Fast Fourier Transform (FFT): This technique is independent of the radar processor. A digital signal from the A/D output is also needed, as above, and is collected using a data buffer. Since the FFT is a time- to frequency-domain converter, the dc magnitude represents the amplitude of the uncanceled signal, whereas the spectrum represents the instabilities.

5) Discrete Fourier Transform (DFT): This is a more general form of the time-to-frequency transform than the FFT. The DFT allows variations in sampling times while producing a true spectrum of the time-domain signal when sampling a stagger PRF sequence.

Any of these five techniques can be used as long as sufficient samples across the pulse width are taken to include edge jitter. Method 2 has the potential to provide a fairly comprehensive built-in test capability with ease of use by the operators, whereas method 5 might be the preferred method for engineering evaluation since the spectrum display could be of troubleshooting value.

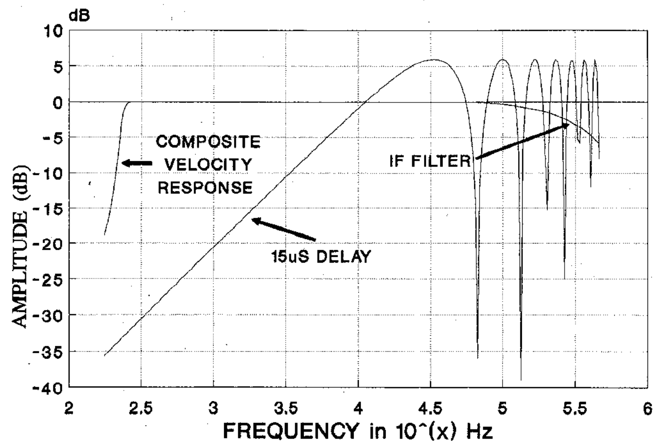

Fig. 9. Radar filters and 15 μs delay.

G. 15 μs Delay Stability Analysis

The objective is to determine how much of the range-dependent STALO noise in Fig. 5 is visible using a 15 μs delay line for radar system stability measurements. There are three steps necessary to arrive at this answer.

1) Determine the amount of double side band STALO noise the radar sees.
2) Determine how much double side band STALO noise is seen after 15 μs of decorrelation.
3) Compare the integrated results of the above two results for STALO noise visibility at 15 μs.

The radar filtering determines the amount of STALO noise the radar sees. The composite radar velocity response in Fig. 9 determines the low-frequency roll-off. Since blind speeds are virtually eliminated because of the PRF stagger, the velocity response is somewhat flat from the composite velocity response low-frequency cutoff point up to one half the IF frequency bandwidth. The high-frequency roll-off is limited by the IF filter response, which is also shown in Fig. 9. The STALO noise of Fig. 5 is restricted by these two filters and the remaining double side band integrated energy is -75 dBc. This is the STALO noise (modified by the radar filters) that the radar system sees, and it is shown as the top curve in Fig. 10. This is the standard way of measuring the STALO noise and calculating the STALO noise impact on system performance.

Now, if we modify this filtered STALO noise the radar sees by the 15 μs decorrelation curve in Fig. 9, we get the decorrelated STALO noise the radar sees at 15 μs in range. This is shown as the bottom curve in Fig. 10, and the integrated energy is -76.2 dBc. The introduction of the range-dependent filter introduces a total integrated energy difference of only 1.2 dB.

Thus, an accurate system stability test can be made with a 15 μs delay because the STALO noise contribution

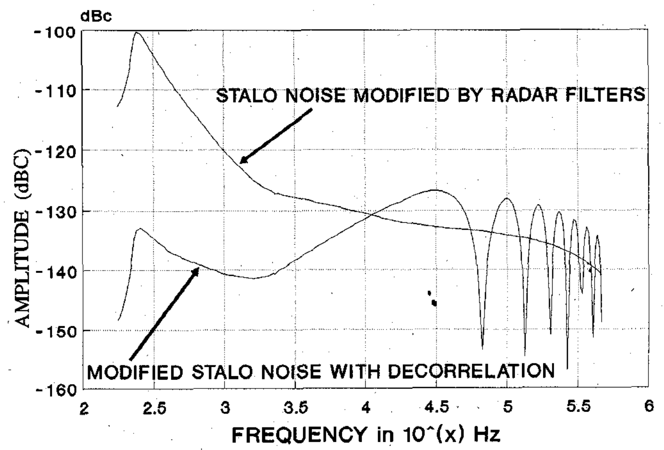

Fig. 10. STALO noise modified by radar.

is within 1.2 dB of the measurement made in the laboratory on the STALO noise alone using conventional laboratory noise test equipment. The laboratory measurements are, of course, made early in the design phase to predict the stability contribution of the STALO noise.

V. Conclusions

Radar instabilities are likely to appear in almost any area of the radar hardware. Stability has to be designed into the basic architecture of the radar system to overcome the many natural phenomena throughout the hardware that would otherwise erode and destroy system stability.

To design and build a highly stable MTI radar, one must develop the capability of measuring the radar system stability. The first major task in developing this capability is to generate a properly delayed microwave signal return.

The 15 μs BAW microwave delay line eliminates all the problems encountered in using a permanent echo for the test target. It has the additional advantage of being small enough to be incorporated into systems to provide a built-in stability test capability. Analysis showed that a 15 μs delay is adequate to make system stability measurements, since all of the previously measured double side band STALO noise is visible at this delay except 1.2 dB. Also the BAW delay line has proved capable of measuring 65 dB stability on S-band systems and yet is without the problems associated with radiating to the outside environment to a permanent echo test target.

The net result of the work reported here is that the techniques described have produced an MTI system capable of achieving 65 dB clutter cancellation, with a cancellation measurement capability to monitor the performance.

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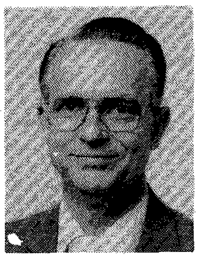

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Currently he is the system stability director on all programs in the Westinghouse Ground Based Radar Division, currently called the Design and Producibility Engineering Division. Since 1956, he has been with the Westinghouse Electric Baltimore Defense Center and has been involved in communication and radar design. He has led the development of several frequency generator designs and helped advance the STALO technology to support an MTI radar system cancellation of over 65 dB. He has worked at the radar system level in design check-out and has done consulting work both in this country and abroad. He has done extensive work at the MTI radar system level in stability design and evaluation. He recently completed a series of seminars that were structured to teach the design engineers how to design for stability in an MTI radar. He was recently awarded a patent on technology for measuring and analyzing radar stability at the system level.