# AM/FM Noise in the Target Illumination Signal for Semi-Active Missiles

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In semi-active missile guidance, a high-power transmitter not collocated with the missile generates continuous wave or interrupted continuous wave illumination that is reflected from the target to the homing missile. Noise introduced into this illumination, which is reflected from rain, chaff, land, or sea clutter or is carried on spillover, can compete with the target return. The Navy has tasked APL to specify allowable illuminator AM/FM noise and to work with its contractors to design stable oscillators and noise test equipment to meet these noise requirements. This article focuses on the effects of noise on system performance, the specification of noise requirements, low-noise X-band sources, and test equipment used to measure noise.

## INTRODUCTION

The Navy's Standard Missile (SM), in its area antiair warfare role, employs semi-active missile guidance in its terminal phase of flight. This type of guidance is called semi-active because the transmitter and receiver, although linked, are not collocated. The continuous wave (CW) or interrupted CW illumination guidance signal, provided by a high-power shipboard X-band transmitter, is reflected from the target to the homing missile's front receiver, which detects and tracks the target of interest using Doppler processing. A portion of the illuminator's signal is received directly by the missile's rear receiver for use as a Doppler frequency reference.[1] Consider CW illumination without loss in generality. Equation 1 describes an ideal illumination signal in the time domain,

$$V(t) = A_0 \sin 2\pi f_0 t \,, \qquad (1)$$

where $A_0$ = voltage amplitude and $f_0$ = X-band illumination frequency.

This illumination signal is also reflected from rain, land, and sea. Such unwanted signal returns, called clutter, are typically at much higher power and smaller Doppler frequency than the target's power and Doppler frequency. Spillover, another unwanted signal, results from energy entering both the missile front and reference rear receivers via a direct path from the illuminator to the missile. Missile-received spillover power is much larger than missile target-received power and has zero Doppler frequency. This signal environment is shown in Fig. 1.

Since the missile primarily employs frequency domain target detection and tracking, the frequency domain representation of these signals "as seen" by the missile is of interest (Fig. 2a). For this ideal illumination signal case, thermal noise limits the missile's ability to detect and

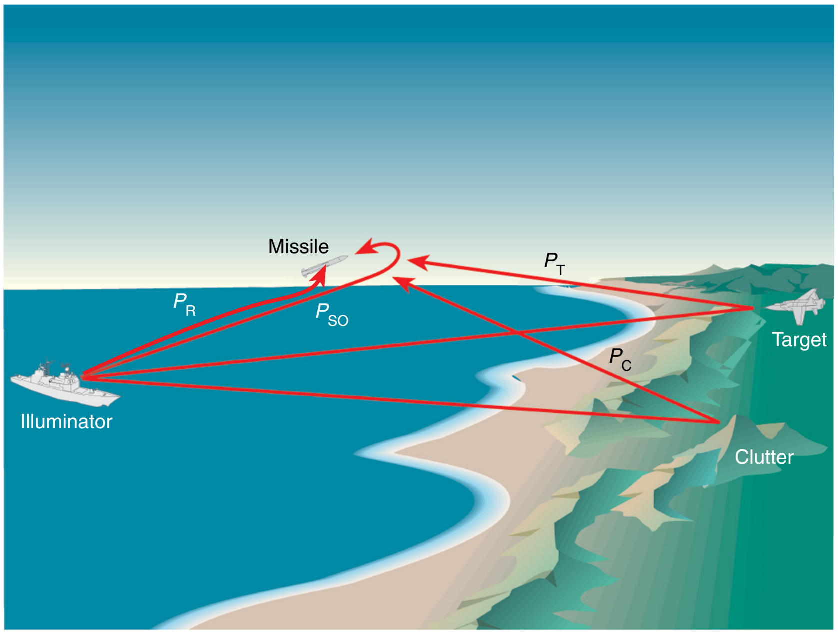

**Figure 1.** Signals pertinent to system performance. Spillover ($P_{SO}$) of the missile rear receiver reference power ($P_R$) into the front missile receiver is at a high power level and zero Doppler. Clutter ($P_C$) is at a high power level and is Doppler shifted. The target return ($P_T$) is low in power and usually has the largest Doppler.

track the target because of its presence at all Doppler frequencies in the missile receiver's bandwidth, whereas spillover and clutter occur at frequencies removed from the target Doppler frequency. The missile receiver requires a signal-to-noise power ratio somewhat greater than unity in order to declare a target detection.

Only real signals exist, however, and they exhibit random amplitude and phase fluctuations, resulting in a real illuminator signal that is random. And because it is random, it cannot be described mathematically in the time domain. This signal has a frequency domain representation that is no longer a discrete spectral line, as in the ideal case, but rather spreads out over frequencies that are both above and below the nominal signal frequency in the form of noise modulation sidebands due to random fluctuations. The real frequency spectrum "as seen" by the missile receiver is shown in Fig. 2b.

Clutter and spillover noise sidebands may also contain spurious coherent spectral lines (spurs). The source of these spurs may be components of the illumination or parasitic oscillations in the missile receiver. If a spur is sufficiently large and appears in the Doppler search band, it may be semi-actively acquired by the missile as a false target and cause missile flight failure.

APL has a long, distinguished history both in specifying allowable illuminator amplitude-modulation/frequency-modulation (AM/FM) noise and in working with industry to design state-of-the-art stable oscillators and noise test equipment to meet stringent requirements. The illuminator upgrade discussed here, concurrent with new missile variant upgrades, results in a system that realizes a subclutter visibility improvement over the legacy system. The primary subjects of this article are the specification of illuminator noise, illuminator hardware used to meet the specification, and the test equipment used to measure this noise. Future efforts are also discussed.

## NOISE SPECIFICATION

There are two sets of CW illuminator close-to-carrier or narrowband noise specifications, one consisting

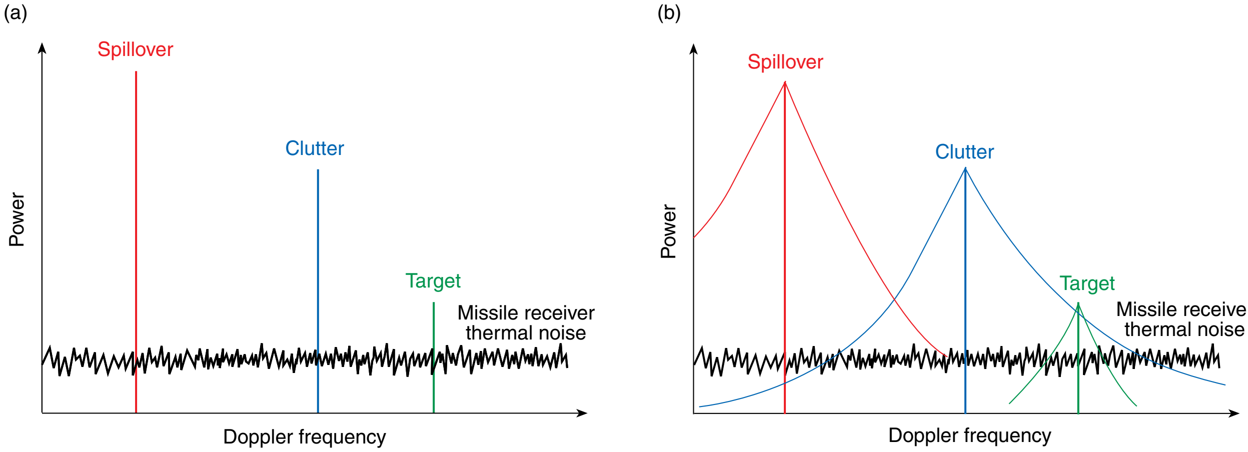

**Figure 2.** Missile Doppler spectra: (a) ideal (no FM noise on signal) and (b) real (FM noise on signal). (Receiver thermal noise has a constant power spectral density.)

of separate AM and FM noise specifications and the other having a combined AM and FM specification. The separate specifications address missiles that use the illumination signal directly for their rear reference receiver signal and the illumination target-reflected signal for their front receiver signal. In this case the missile processes AM and FM noise differently when the front and rear signals mix, resulting in a reduction of FM noise due to the correlation effect. AM noise does not correlate and therefore does not benefit from the correlation effect.

Noise specifications are typically given as curves showing the allowable noise versus frequency offset from the CW carrier. For all specifications, the abscissa represents offset or Doppler frequency. AM noise and combined AM/FM noise are expressed in decibels below the carrier (dBc) and consider noise in both sidebands. FM noise can be expressed as $\Delta f$ in either hertz root-mean-square (rms) or equivalently in dBc, and considers noise in a single sideband (SSB). The relationship between $\Delta f_{\rm rms}$ and dBc is given by

$$\text{dBc} = -20 \log(\sqrt{2} f_{\rm m}/\Delta f_{\rm rms}) \ , \qquad (2)$$

where dBc = decibels below the carrier, SSB; $f_{\rm m}$ = modulation rate or offset from the carrier in hertz, and $\Delta f_{\rm rms}$ = frequency deviation in hertz in a specified bandwidth.

This relationship can be derived from FM theory. The carrier has a peak amplitude of $J_0(\Delta f_{\rm p}/f_{\rm m})$, and each of the nearest sidebands a peak amplitude of $J_1(\Delta f_{\rm p}/f_{\rm m})$, where $J_0$ and $J_1$ are the Bessel functions of the first kind with orders zero and one, respectively. Higher-order sidebands are negligibly small. Assuming the arguments $\Delta f_{\rm p}/f_{\rm m}$ are small, as they must be for phase noise (used interchangeably with FM noise in this article), the Bessel functions may be approximated by

$$J_0(\Delta f_{\rm p}/f_{\rm m}) \approx 1$$

and

$$J_1(\Delta f_{\rm p}/f_{\rm m}) \approx \Delta f_{\rm p}(2 f_{\rm m}) \ ,$$

where $\Delta f_{\rm p}$ = the peak frequency deviation in hertz in a specified bandwidth. Taking the ratio of $J_0$ to $J_1$, then squaring to get power, and finally taking the log yields Eq. 2.

Low-frequency (approximately 10 to 400 Hz) noise limits are established such that target energy spreading out of the fast Fourier transform (FFT) bin occupied by the target does not adversely affect the missile's target coherency test. Mid-frequency (approximately ≥400 Hz to ≤5 kHz) noise should not allow clutter to mask a crossing or slow target. High-frequency (>5 kHz) noise should not permit maximum clutter or spillover from degrading target sensitivity.

When specifying noise, a specification bandwidth is also required. An industry-standard term for quantifying phase noise, denoted by $L(f)$, is defined as decibels relative to the carrier per hertz of bandwidth. (The terms phase noise and FM noise are used interchangeably in this article.) The noise specifications discussed in this article are given in various bandwidths as a function of frequency offset from the carrier. At the lower frequencies, a bandwidth that is 10 times smaller than the mid- and high-frequency ranges is typically used. We have some specifications where the high-frequency bandwidth is 100 times larger than the low-frequency bandwidth. The use of different bandwidths for different areas of the Doppler spectrum is a trade-off between two factors: (1) the need to detect narrowband signals in white Gaussian noise, which requires narrowband filters, and (2) the need to complete the measurement in a timely fashion, which requires a filter with a bandwidth that is at least 10 times wider than the low-frequency bandwidth.

## CW ILLUMINATOR HARDWARE

Early CW illuminator transmitters employed cavity-stabilized klystrons as low-noise X-band sources. The main disadvantages with these sources were their excessive low-frequency noise and the relatively long time required to manually change frequency channels. In 1971, the Universal CW Illuminator Modulator Program was initiated to provide a common low-noise source and modulator for Terrier, Tartar, and Aegis weapons systems which could be rapidly switched from channel to channel. Only Aegis ships remain in the Fleet.

This early CW illuminator's X-band source for Aegis was called a stable master oscillator (STAMO) since it did not include a modulator. With the planned introduction of the SM-2 Block IV missile into the Fleet and the Navy's desire to operate in the littoral regions of the world, APL recommended the development of a new STAMO to meet noise requirements that are more stringent than those required for SM-2 Block II in open ocean operations. Raytheon Company was awarded a contract to design and manufacture new STAMOs for Aegis destroyers DDG 79 and later.

The new STAMO employs a multiresonator low-noise crystal oscillator in a direct-synthesis design. The unit employs stress-compensated (SC) cut crystal resonators that are individually enabled via PIN diodes. Sustaining stage circuitry uses modular 50-Ω radio-frequency (RF) amplifiers. External heaters and appropriate resonator turnover temperature provide stability to meet SM-2 frequency accuracy requirements. The STAMO also generates the FM tone code modulation

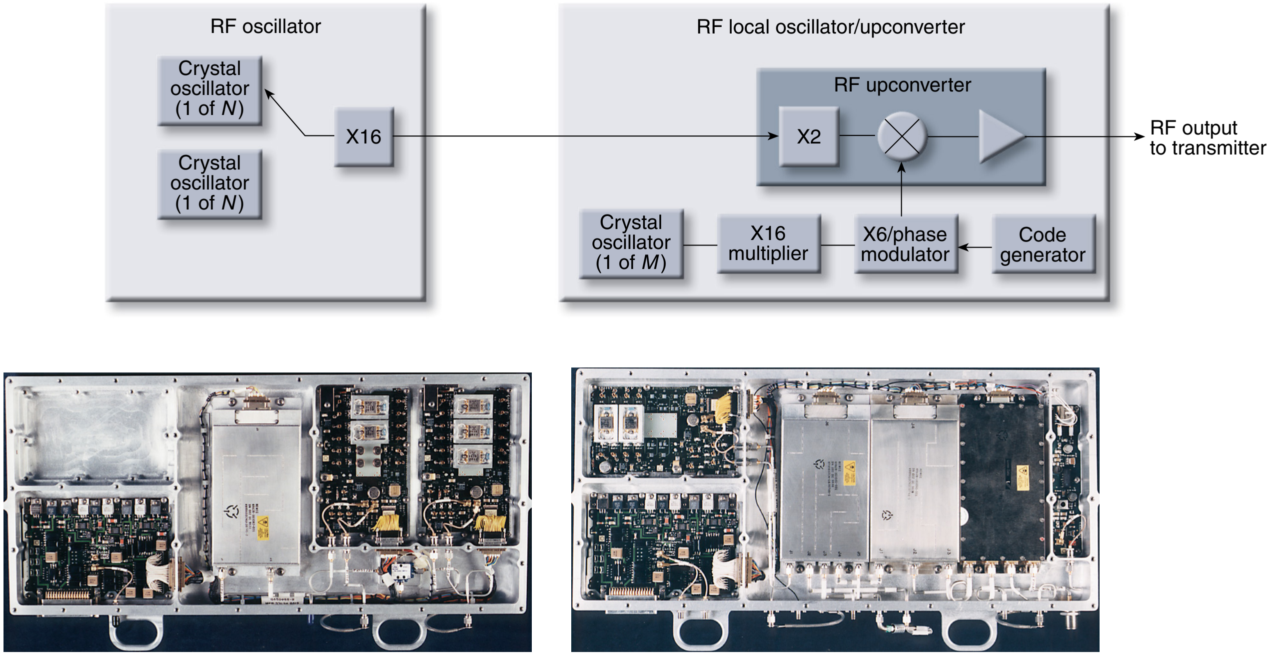

**Figure 3.** STAMO block diagram and photos.

required by the Evolved Sea Sparrow Missile (ESSM). Figure 3 shows a block diagram of the STAMO. It comprises an RF oscillator module and RF local oscillator/upconverter module, both with a multichannel-capacity multiresonator SC-cut crystal oscillator, low-noise voltage regulator, and low residual noise X16 multiplier. In addition, the low-noise, low spurious RF local oscillator/upconverter module contains a X6 multiplier/phase modulator, FM code generator, and RF upconverter. Measured STAMO phase noise has shown a decrease in $\Delta f$ by a factor of 5.6, which is needed to meet the new, more stringent missile requirements.

In addition to STAMO noise, CW illuminator performance is also degraded by noise from the illuminator's traveling wave tube (TWT) and power supplies. The TWT takes the nominal 20-dBm output of the STAMO and generates 10 kW of power. As part of the STAMO upgrade, a noise canceler (Fig. 4) is used to reduce TWT and high-voltage power supply noise. The noise canceler uses three independent feedback loops to provide AM and FM residual noise cancellation as well as TWT input power leveling.

The phase noise cancellation loop (Fig. 4) provides reduction of detected residual phase noise. The amplitude cancellation loop provides reduction of detected residual amplitude noise. The automatic level control (ALC) provides input power leveling to the TWT as the means to accurately control the input drive to the TWT to determine TWT gain characteristics. This function is required in the AM loop algorithm to determine an optimum, consistent operating point on the TWT gain-transfer curve.

Phase noise cancellation is achieved by detecting residual TWT noise using a phase detector and then correcting for short-term perturbations via a phase modulator. This approach provides residual phase noise reduction of all components configured in the feedback loop by an amount equal to the closed loop gain. The loop is capable of passing the FM coding modulation required by ESSM through sufficient time delay matching. Figure 5a shows an example of the FM noise reduction provided by the noise canceler. The spurious signals in the open loop (no cancellation) configuration are due to phase modulation of the TWT via the ripple on the high-voltage power supply. When engaged, the noise canceler provides >20 dB of FM noise reduction in this Doppler region.

Amplitude perturbations are detected using a crystal detector driven by a sample of the TWT. Cancellation is realized by amplifying the detected signal and applying it to an amplitude modulator 180° out of phase. The amount of noise reduction is equal to the closed loop gain under linear TWT operation. An embedded microcontroller is used to determine a constant operating point in the TWT gain characteristic to ensure that the overall loop transfer function is constant across the operating bandwidth. This is achieved by stepping the drive to the TWT via the ALC loop. The microcontroller samples the input drive ($P_{in}$) and output power ($P_{out}$) and calculates the gain for that drive level as ($P_{out}/P_{in}$). This process is repeated, incrementally increasing $P_{in}$ and collecting sufficient data to map out the TWT gain up to saturation. A second-order curve fitting algorithm is executed, and

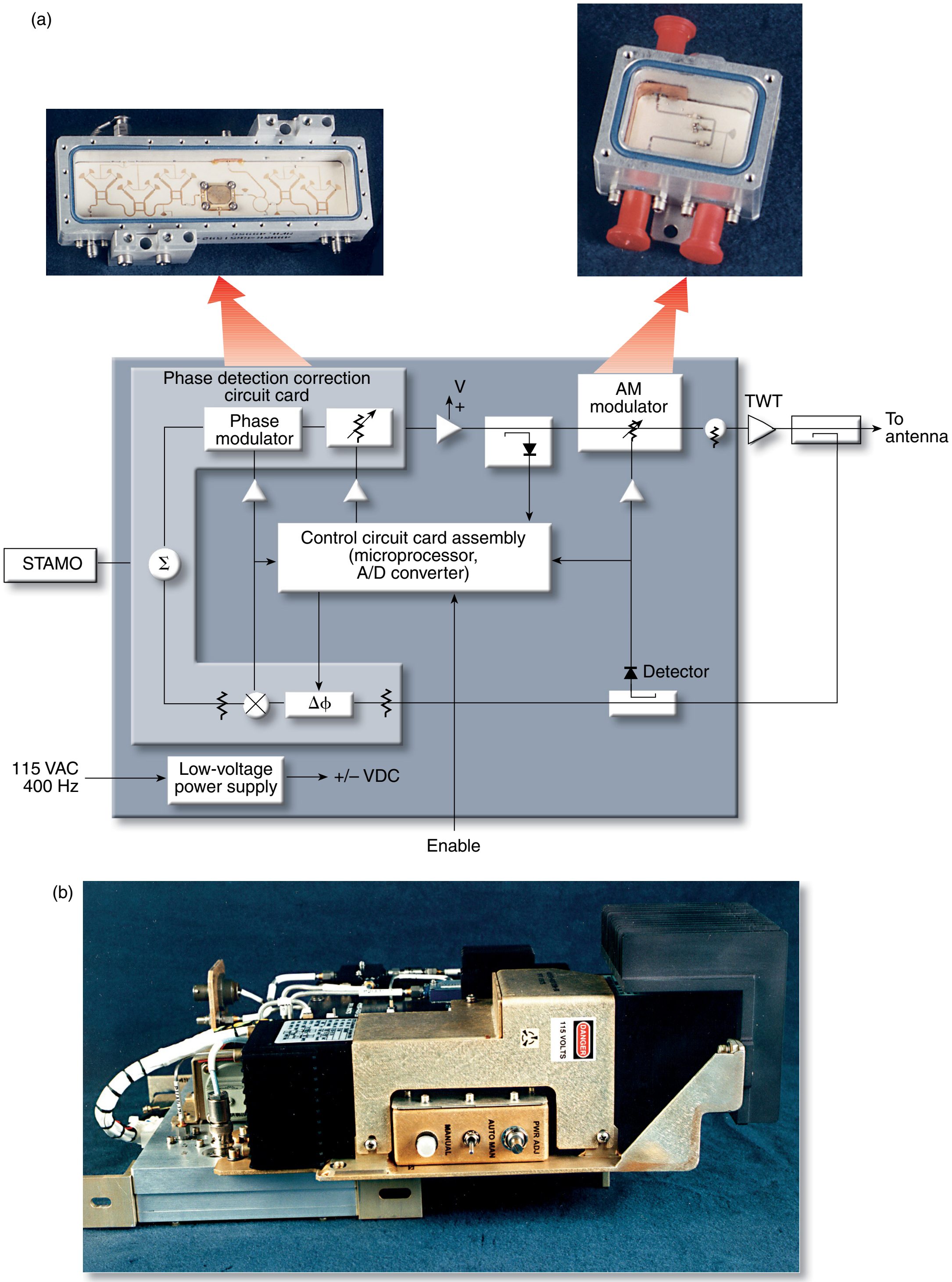

**Figure 4.** Noise canceler: (a) block diagram and (b) assembly.

the microcontroller derives the necessary $P_{in}$ to place the TWT at a predefined operating point on the curve. This feature not only ensures a constant cancellation across the band but, unlike previous operation at one fixed nameplate voltage setting, drives the TWT to virtually its maximum output power at each frequency across the band. Figure 5b shows an example of the AM noise reduction provided by the noise canceler. When engaged, the noise canceler yields >30 dB of AM noise reduction in the close-to-carrier Doppler region. The actual noise reduction realized is a function of the particular TWT performance. For the example shown in Fig. 5b, the TWT ripple components were a maximum of 25 dB above the canceler noise floor, so only that

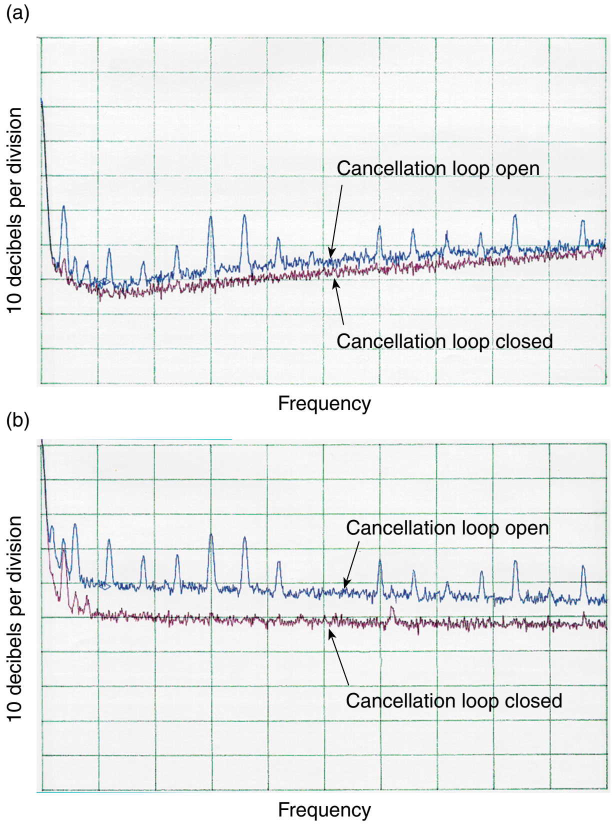

**Figure 5.** Noise reduction ($f_m$ < 20 kHz) from the TWT noise canceler: (a) FM and (b) AM. Here, center frequency = 10 kHz, span = 20 kHz, and resolution bandwidth = 100 Hz.

amount of cancellation was achieved. For noisier TWTs, the full 30 dB of cancellation would be observed.

The ALC is implemented using a coupler/detector and a voltage-controlled attenuator. However, instead of a constant reference voltage as in a conventional ALC architecture, the reference voltage is derived to achieve the operating point required to satisfy the AM loop gain as described previously. This reference voltage is supplied by a digital-to-analog converter via the microcontroller. Two filter time constants are implemented in this circuit, the first (faster) one to allow this voltage to be stepped quickly enough to support system timing requirements. Once this is achieved, the second (narrower) filter is enabled to maintain the required low-noise operation. APL suggested the use of a noise cancellation scheme in this application, and Raytheon has secured Patent #5,940,025 for the noise canceler assembly.

## NOISE TEST EQUIPMENT

To ensure that CW illuminators are meeting their noise specifications, noise is measured periodically onboard ship and just prior to missile firings. An early noise tester developed by APL and used for shipboard testing, while accurate, required the skill-level equivalent of a microwave engineer to obtain the measurements. The unit was also extremely bulky, making it difficult to move to the various illuminators on Navy ships. This led to the development of the first generation of portable noise test sets that could be operated by ships' crew. These test sets, developed by California Microwave Inc. (CMI), were designated as Mk 39 and tested illuminators to the SM-1 Block V AM and FM noise specifications.

With the introduction of the SM-2 Block II missiles to the Fleet, a test set with a noise floor lower than that of the Mk 39 was required. In 1984, APL developed a specification for a new universal narrowband portable noise test set and the Navy released a Request for Proposal (RFP). On the basis of APL's technical evaluation of the RFP responses, Aeroflex RDL Corp. (formerly RDL Inc.) was awarded the contract to design and manufacture the new test set, which was designated the Mk 666 Mod 0. The Mk 666, now in its third generation (Mod 2), measures noise to the requirements of SM-2 Block II, SM-2 Block IV/IVA, and ESSM. The Laboratory proposed many of the key features in the Mk 666 (Fig. 6).

As shown in Fig. 6a, an X-band input (e.g., the STAMO output or a sample of the TWT output) is applied to the MK 666 input port. After adjustment to the desired power level using a low-noise automatic gain control loop (not shown), this signal is switched to either the AM or FM detection path. For AM noise measurements, the X-band signal is routed through a precision AM modulator and then to an AM detector. The AM modulator is calibrated to produce precisely known AM sideband levels on the X-band signal. To calibrate the AM detector, the modulator is activated and the detected AM baseband spectrum is measured by the digital signal processor. The absolute voltage level at the calibration sideband frequency is measured and correlated to the known sideband level. The calibration sidebands are then removed, and the AM spectrum of the X-band signal is measured.

For FM noise measurements, the Mk 666 functions as a superheterodyne receiver to convert the RF signal to a constant 10-GHz intermediate frequency (IF). The IF is obtained by mixing the illuminator signal with one of several low-noise crystal oscillators. The Mk 666 IF is filtered using a narrowband waveguide bandpass filter to reject all undesired mixing products. This filtered IF undergoes a second conversion using an ultra-low phase noise X-band voltage-controlled oscillator as the local oscillator.

The nominal output frequency after this second conversion stage is 100 MHz. This signal becomes the input of the phase detector of an analog phase-locked loop (PLL) noise detection circuit. The reference input to the PLL is a switched crystal oscillator with phase

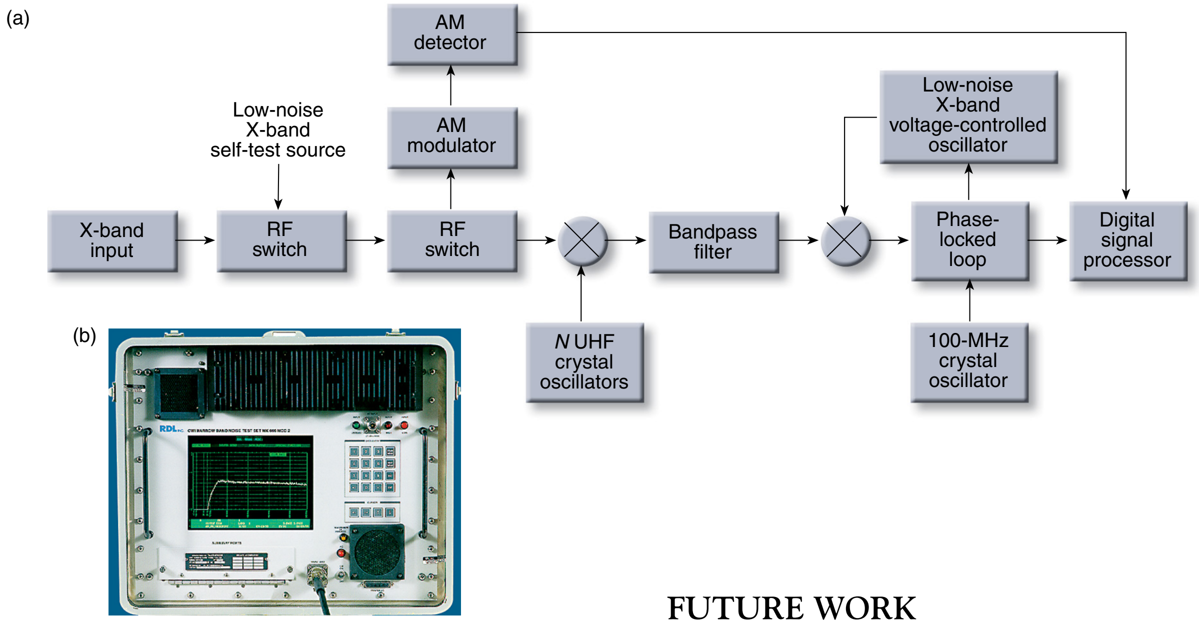

**Figure 6.** Mk 666 (a) block diagram and (b) Mod 2 test set.

noise well below the noise level of the downconverted illuminator signal. The FM noise spectrum is obtained by a PLL FM demodulation scheme.

One of the unique features of the second- and third-generation Mk 666s is their ability to measure phase noise in terms of both relative noise power (dBc) and frequency deviation ($\Delta f_{\text{rms}}$). Normally, either parameter may be measured and converted to the other using Eq. 1. If, however, the deviation is comparable to or larger than the modulation rate, wideband modulation results, and Eq. 1 cannot be used to convert a measured power spectrum into the corresponding frequency deviation. To allow the $\Delta f_{\text{rms}}$ spectrum to be measured directly, the Mk 666 uses unique filters that allow the simultaneous extraction of dBc and $\Delta f_{\text{rms}}$ spectra from the loop. Following AM or FM sideband demodulation, the resulting baseband signal is analyzed using an FFT to compute averaged modified periodograms (Welch's method of power spectral density estimation).[2]

The Mk 666 accepts an X-band input power variation range of 7 to 23 dBm. The test set incorporates a self-test mode utilizing an internal low-noise X-band source applied to its RF input. Thus, every component that contributes to the overall phase noise floor of the analyzer is exercised in this mode. The Mk 666 also performs its own calibration prior to each measurement, ensuring better than ±2-dB measurement accuracy. Additional Mk 666 Mod 2 specifications are as follows: noise floor, well below the most stringent composite missile specs; analysis range, 10 Hz to >200 kHz offset from carrier; resolution bandwidth, two (narrow and wide); measurement time, 35 s.

## FUTURE WORK

As noise requirements become more stringent, surface acoustic wave (SAW) oscillators (SAWOs) will more than likely replace the crystal oscillators in both the STAMO and the Mk 666. Raytheon is a world leader in SAW technology and has developed ultra high frequency SAWOs for an all-solid-state upgrade to the NATO Sea Sparrow Mk 73 transmitter.

Also, as the noise requirements for the missile and illuminator become more stringent, the need increases for a lower noise source to verify missile subclutter visibility and the noise floor of the Mk 666 test set. The latter must be much lower than the unit under test so as not to add unacceptable uncertainty to the measurement. For example, if the Mk 666 noise floor is 10 dB below the illuminator noise, the Mk 666 would add about 0.4 dB to the measurement. New technologies such as the Sapphire Resonator Oscillator (SRO) are now becoming state-of-the-art to achieve exceptional phase noise at X-band. SRO technology will be used in APL's new Guidance System Evaluation Laboratory (see the article by Marcotte et al., this issue) to verify missile subclutter visibility and by Aeroflex RDL, the test set contractor, to ensure that the Mk 666 meets newer, more stringent specifications.

Illuminators are now being developed that produce interrupted CW illumination with excellent phase noise. The Dutch-produced Active Phased Array Radar (APAR) for the Trilateral Frigate Cooperative Program is one such example. Aeroflex, using internal R&D funding, has developed a prototype test set to measure AM and FM noise on X-band interrupted CW illumination sources. This unit has been used by RDL and APL to characterize APAR noise from the antenna and exciter. The challenges here are to provide a measurement from the entire ensemble of active elements and to ensure adequate sensitivity with the pulsed (interrupted) waveform.

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