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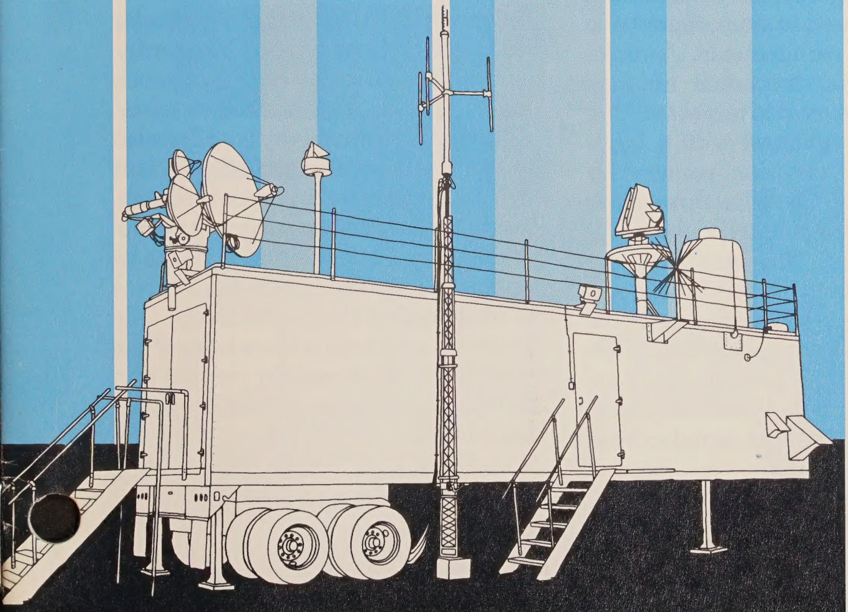
Integrated Techniques For Precision Waveform Measurement



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Tech-notes

Techniques for measuring microwave signal parameters are rapidly increasing in capability through the use of laboratory instrumentation technology. By intelligently integrating appropriate subsystems, signal acquisition and technical analysis that has traditionally consumed months can be done in days, or even in real time.

The primary hardware ingredients are a control computer to set up the instruments, and a digital storage medium which allows the raw data to be immediately available to analysis programs. De-emphasizing custom electronics in favor of commercial equipment exploits the advantages of relatively inexpensive hardware and allows modular, low-cost upgrades as instrumentation evolves. At the same time, there are performance areas where custom design (such as low-noise front ends, broadband tuner/demodulators or surveillance/DF receivers) is a necessary augmentation.

As shown in Figure 1, integrated mobile equipment is used to support precision measurement requirements. A multiband high-gain directional antenna system can be slaved to target-tracking inputs and is equipped with a large-magnification television camera for optical tracking. The taller three-dipole array is an intercept and DF system for hf through uhf. The spinning antenna at the far end has its radome removed to display the antenna for the surveillance and direction-finding receiving system. Other mast-mounted antennas include omnidirectional antennas and radiated self-test signal sources.

Strategic Reconnaissance

Strategic reconnaissance has typically used non-engineering personnel at the receiver controls, with the task of recording signal activity on analog tape for later analysis. By the time the decision is made to analyze the tape, the knowledge of what was recorded, and the signal path configuration of the receiving system may long since have evaporated. In contrast, an engineer with a digital storage and analysis capability could record much the same data, automatically annotate the recording conditions, and perform the analysis immediately. From the hardware point of view, the major challenge is developing a receiver with sufficient sensitivity to obtain a useful signal-to-noise condition for a distant signal. In addition, interesting classes of emitters exhibit frequency agility and broad signal bandwidths as well as exotic modulations. This is a dual requirement, calling for a sensitive system, yet with broadband capability.

Electronic Combat Equipment Evaluation

Electronic combat equipment evaluation presents a similar receiving challenge: to illustrate the interactions between a victim radar and a particular electronic countermeasure. Frequently, one of the two emitters is at a much higher power level at the receiver. Although high sensitivity is still needed to process the weaker signal, sufficient dynamic range must be provided to accommodate both. Often, in equipment evaluation, there are detailed questions to be answered as to the quantitative values of modulations and signal levels. This demands an accurate knowledge of the receiving system transfer curve(s) and its response to frequency and amplitude modulations.

ECM Training and Mission Evaluation

In ECM training and mission evaluation, emphasis shifts to how well the air or ground crew reacted to the electronic threat, who won and what real time feedback is available to the aircrew.

Since many ECM and ECCM equipments are hands-off boxes, there is little information to be had beyond "did the lights come on?" The capability to quantify the signals and their interactions is the basis for an accurate decision, and there is an ascending scale of difficulty. One ECM versus one victim is the least difficult, since two signals can conveniently be processed simultaneously, or gated to display the features of only one signal or the other. More difficult is the question of many emitters or techniques against multiple threats, but this data can be acquired sequentially if the timescales are long enough. Much more difficult is the possibility of many ECM-equipped platforms against multiple ground threats, since the receiver must attempt to record an extremely volatile environment where critical parameters can change over microsecond timescales. Finally, and extremely difficult, is the requirement to quantify many ECM platforms in "free play" against both air and ground threats. Low signal levels, platform mobility, and high degrees of freedom in tactics all outdistance a general-purpose receiver.

Frequency Management and Emitter Control

In all of the above applications, frequency management and emitter control are often overlooked and underfunded. This is an activity that must take into account the verification of expected emitter characteristics, the susceptibility of all receivers to all known emitters, the possibility of unknown emitters, and the expected signal levels implied by the emitter locations. A receiving system is required to support this activity by identifying signals, determining their location (bearing) if unknown, and reporting interfering emitters in real time. In the context of electronic warfare evaluation, there is an exceedingly high cost to ignorance: missions

Figure 1. Integrated mobile equipment.

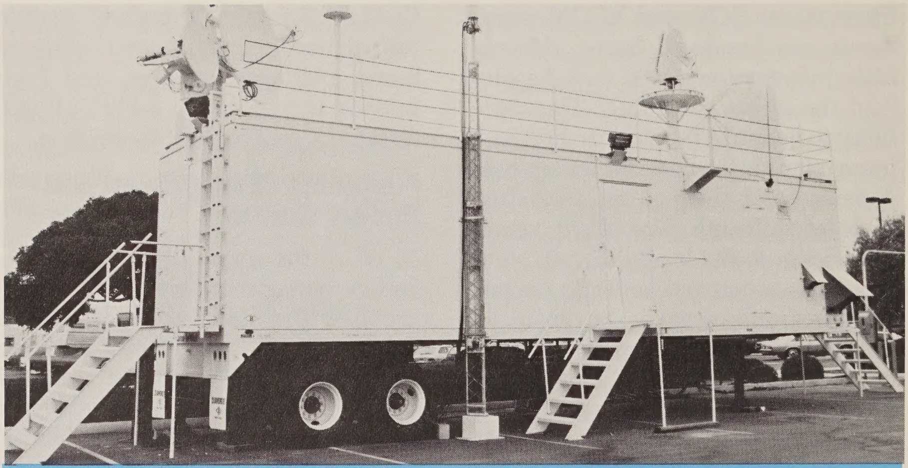


Figure 2. System installation in equipment van.

are run with nothing gained, misleading interpretations are made of corrupted data, and very high-cost decisions to deploy equipment may be based on invalid or insufficient data.

Modus Operandi

Computing power and instrumentation have come to the point where a different modus operandi is feasible. For example, consider an approach where one engineer is assigned to the project (be it equipment evaluation, or ELINT collection). By virtue of training, the engineer understands the important features of the signals and what data must be collected and analyzed. This depth of understanding allows the engineer to coordinate a collection plan with the information user, considering the technical capabilities of the receiving system versus the signal behavior and mission objectives. When the mission is run, the engineer, perhaps with an equally skilled associate, gathers the relevant data and ascertains in real time that the data is adequate. The data is stored digitally on a large-volume disk.

Figure 2 shows the installation of the systems into the equipment van during the final phases of integration. The HP9000 control code is user-modifiable to allow customizing in the field. In this case, HP BASIC was selected in order to provide the best mix of structure, rapid flexibility, and instrument control.

Immediately following the mission, the control computer transforms into an analysis station, using standard computer tools such as histograms, scattergrams, FFTs, and other transforms to convert raw data into useable information. Proper annotation of graphs, with titles and classification markings is all straightforward for the computer to generate, when guided by the engineering intellect. The product is a timely, quantitative report in which each result has supporting evidence presented, and which has an identifiable author who is personally responsible for the validity of the results.

The computer assists with two important appendices: A data log showing the contents of every record taken, and an automatic equipment performance verification which shows that every signal path had been tested and was performing within tolerance at or near the time when the data was recorded. The problem with this scenario is that the required personnel assets are typically unavailable. Data is taken and muddled through a diffuse process of analysis, or is taken without equipment verification, thereby losing its credibility and worth.

Given the scenario above, where talent and technical continuity are the key elements of the information quality, it is possible for one engineer to plan, collect, analyze and report on the events selected. The entire process from planning (mission minus 5 days) to report (mission plus 5 days) consumes 10 days. Compare *that* to current reporting timescales.

There are corollaries. EW technology is not standing still. State-of-the-art emitter diversity is increasing rapidly. This means that the receiving system of a few years ago is now probably unable to capture newer modulations. Keeping up requires a continuous thrust to upgrade collection and recording technology. The only way to achieve a low-cost upgrade is to rely as heavily as possible on non-custom instrumentation, which can be replaced on a unit-by-unit basis to take advantage of performance developments.

In addition, users continue to ask for more processing, and more analysis of previously unconsidered or unavailable aspects of the data. In response, there must be a continuous process to upgrade the analysis capability as emitters, modulations, and users' queries diversify. This means that the software for system control, as well as for data acquisition and analysis, must be suitable for on-site maintenance and development which, in turn, means high-level user-modifiable code.

Measurement Requirements

The most obvious requirement is to cover the frequencies of interest with high sensitivity and high processing bandwidth. For radar intercept receivers, that usually translates to a receiving system covering frequencies from 100 MHz to 18 (or 40) GHz, with sensitivities in a 1-MHz bandwidth of roughly –105 dBm (–135 dBm including the antenna gain). Processing bandwidths need to be of two types: narrow (2 to 20 MHz), for best sensitivity and selectivity, and wide (500 MHz or greater), for coverage of frequency-agile emitters. A more subtle point is that a collection system can use directional antennas to achieve remarkably low system noise floors, although the antenna must be pointed at the signal.

One attractive possibility to direct the high-gain system is to combine a general purpose high-probability-of-intercept surveillance receiver with automatic direction-finding capability. This serves as the environmental monitor while precision measurements are made using other equipment. Sensitive receiving systems with automatic signal processing and automatic DOA determination are available, and may be controlled remotely by the same computer that serves to control the precision measurement and recording system.

To address the need to make measurements on simultaneous signals (not necessarily at the same rf), several independently tunable channels are required, along with the appropriate demodulators, reporting instrumentation (such as a multichannel digital oscilloscope), and storage medium (such as a large-capacity hard disk). One area where special attention pays off is in the design of the rf front end to support the multiple-receiver processing. The special flexibility of a distribution system, possibly with tracking preselector filters, is an area where custom design is inevitable. The payoff is enormous, however, in that front ends can be made which have noise figures of 6 to 10 dB that will support dynamic ranges on the order of 70 dB. A low-noise front end transforms a relatively insensitive spectrum analyzer into a highly sensitive receiver.

Signal measurements can be categorized into data types:

- Amplitude versus Frequency
- Amplitude versus Time
- Frequency versus Time
- Predetected Amplitude versus Time
- Special Purpose Demodulator Output versus Time

Amplitude Versus Frequency

Spectral occupancy (amplitude versus frequency) can be provided by a spectrum analyzer in its sweeping mode, from which emitter frequency and power spectral distribution is observed. In the case of ECM, the bandwidth characteristics of noise are illustrated. By taking this data in rapid succession, the time evolution of broadband frequency excursions can be shown. Also, by using a display feature (for example, MAX HOLD on a Hewlett Packard 8566 spectrum analyzer), one can allow the sweeping receiver to display the results of many sweeps, thus mapping out the total frequency envelope of successive intercepts.

Figure 3 shows an amplitude versus frequency plot. Several radars as well as cw signals in the San Jose, California area are illustrated using the MAX HOLD feature of an HP8566 spectrum analyzer. Annotation of the rf path configuration as well as the recording-device parameters are stored and posted on the plot. The time corresponding to this record is read from a satellite receiver.

An alternative way to present related data is to use the output from a scanning intercept receiver, and present the results on a "pan display" covering the

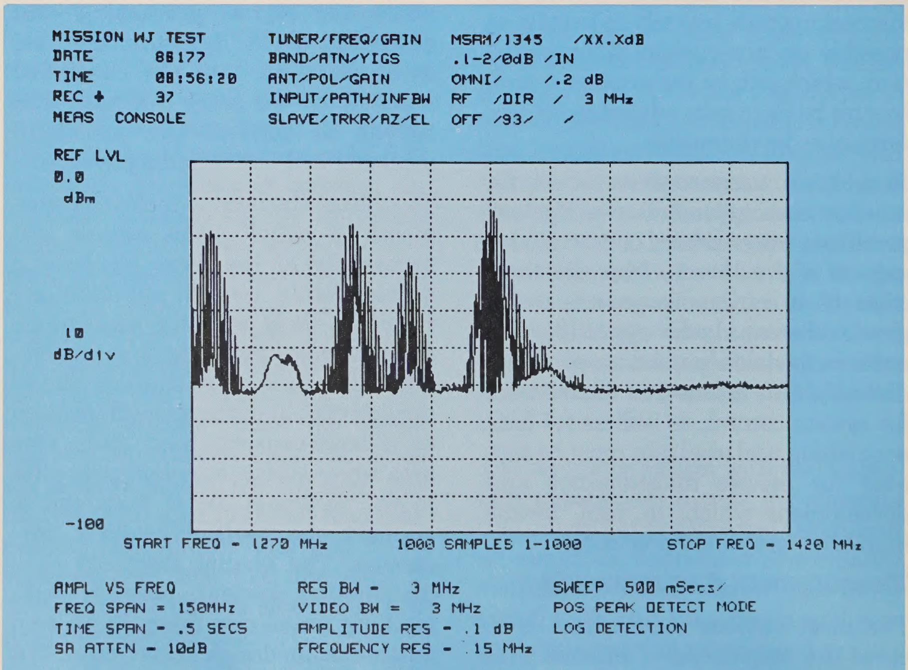


Figure 3. Plot of amplitude versus Frequency.

frequency range under surveillance. This data can be updated rapidly, thus giving a dynamic picture of the active signals. Under certain conditions, the same data can be presented in a three-dimensional "waterfall" display, which can show a consecutive time sequence of the pan display. This receiver can be the same ESM equipment which is providing emitter angle-of-arrival information to the precision measurement system.

Amplitude Versus Time

When a receiver is tuned to a signal (or a spectrum analyzer in SPAN ZERO mode), one may demodulate the signal to recover the AM waveform. Normally, a spectrum analyzer is considered a narrow-band device. For example, the maximum displayed bandwidth of an HP8566 is 3 MHz. However, the HP8566 makes available an IF having 25 to 50 MHz bandwidth when the tuned frequency is above 2.5 GHz. By processing a sample of this IF in an amplitude detector, it is possible to gain a wideband function without disturbing the narrow-band functionality. Returning the other split signal to the spectrum analyzer at 0-dB gain preserves normal operation. When the demodulated signal is recorded by a digital oscilloscope, the signal-to-noise ratio, rise time and other on-pulse parameters are determined by using the calibrated response (counts out versus input power) to find the appropriate levels on the pulse.

Using the spectrum analyzer in the fixed-tune mode allows measurements of antenna scan parameters: scan type and rate, beamwidths, sidelobe levels and a variety of longer term measurements such as modulation depth and rate. To quantify ECM techniques frequently demands that many seconds of modulation be recorded to illustrate

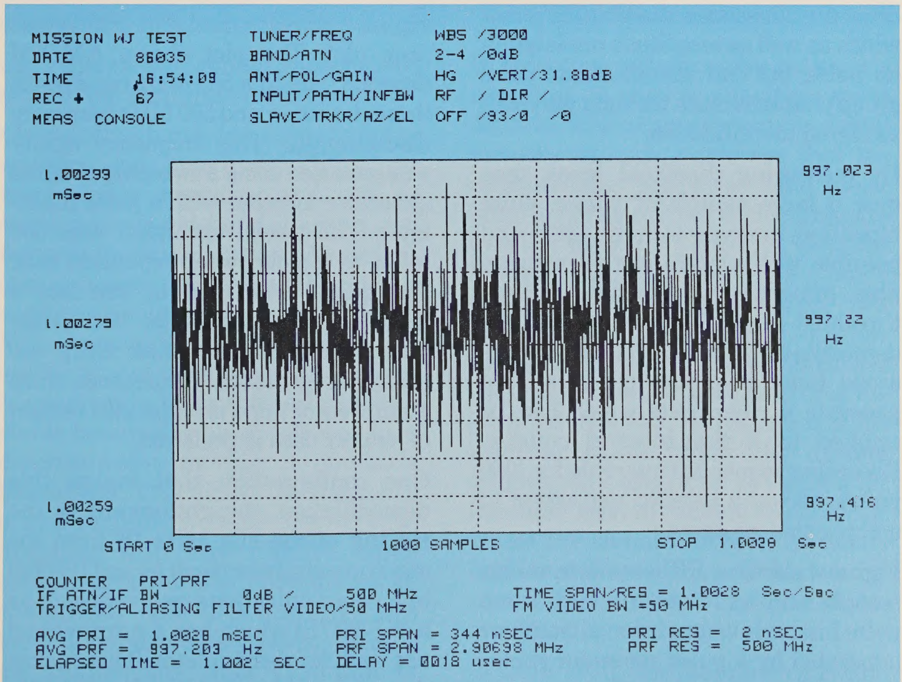


Figure 4. PRI sequence versus sample number.

the interaction between the victim radar and the ECM signal. This is done by reading out the spectrum analyzer display continuously, possibly several times per second. In the ECM versus radar scenario, a useful technique to isolate one or the other signal is to apply a gate to the wideband IF path (described above), so that the displayed signal is that which is passed through the gate. Two signal paths, one gating the other, is not hard to arrange, and provides either a spectral or time-domain display of only the selected signal.

Measurements in the time domain have traditionally been regarded as more difficult than those in the frequency domain; however, multichannel digital oscilloscopes have made it possible to record not only pulse shapes, but also simultaneous am and fm on pulse by using a log detector in conjunction with a frequency discriminator.

Amplitude-versus-time information certainly illustrates the emitter pulse-width as well as amplitude modulation on pulse, but can also illustrate pulse group characteristics for such purposes as signal identification.

By measuring threshold break time over a large sample of pulses, pulse repetition interval, stagger, jitter, and possible wobbulation are all measurable, provided that the time of each threshold break is stored. Using the demodulated amplitude as an oscilloscope input is a convenient way to generate a clean gate which can be applied to a time-interval counter. Recording sequential intervals for 1000 pulses allows a detailed exposition of complicated staggers.

Figure 4 shows a PRI sequence versus sample number. Data for 1,000 inter-pulse intervals versus interval numbers generated by a pulse generator shows that a clean signal produces an extremely accurate estimate of emitter PRI. In the case of an emitter using stagger or jitter, a straightforward calculation can illustrate the intervals in use, their sequence and their variance.

Frequency Versus Time

The use of frequency discriminators to obtain frequency information in the time domain applies to two widely divergent bandwidth regimes: narrow band and wideband. Narrow band (tens of kHz) quantifies fine-grained frequency-modulation-on-pulse such as Doppler shift, low-level chirps, or ECM velocity walkoff, and wideband (500 MHz or greater) covers wide frequency excursions such as hopping, broadband chirp, or noise-like ECM. As in the case of amplitude, fine frequency measurements may allow emitter identification to be based on the spectral coefficients of the frequency modulation on pulse. Also, there is the possibility of quantifying ECM velocity-deception programs.

Figure 5 shows a dual AM/FM versus time plot. The plot shows AM/FM detected data in a 500 MHz bandwidth through a tuner and 500 MHz frequency discriminator. This frequency agility was produced using a sweeping rf signal generator together with a pulse modulator. The sweep excursion was 500 MHz, at a slow sweep repetition rate. The pulser was used to simulate a frequency-hopping emitter. Both pulse-pulse agility and on-pulse chirp are easily recognizable. To measure chirp excursions or slope, an expanded version of similar data is preferred.

One configuration that makes this demodulation straightforward is the routing of the 21.4 MHz IF from the spectrum analyzer (such as an HP8566) to a communications receiver (such as a WJ-8617B) which has a narrowband am and fm demodulator. This makes demodulated bandwidths from 10 kHz to 4 MHz available to a digitizer, which

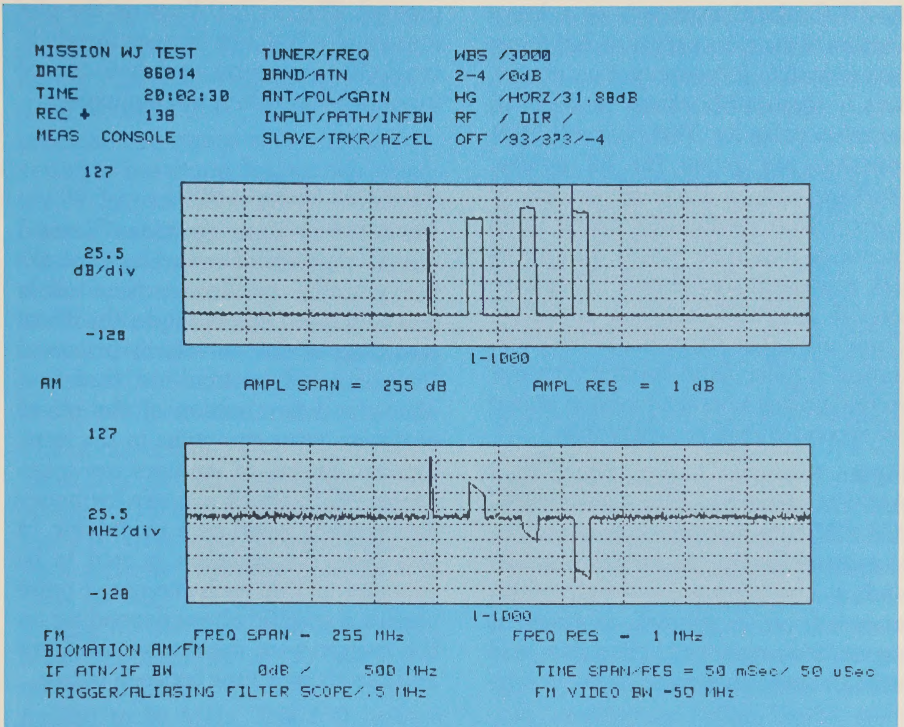


Figure 5. Dual AM/FM versus time.

can generate the familiar dual-channel plots of am (and fm) versus time.

On the other hand, frequency-hopping emitters and broadband chirps are increasingly common, and can be studied using wideband receivers and frequency discriminators. As before, one can use the "high IF" of the spectrum analyzer to provide a 25 to 50 MHz bandwidth output. This bandwidth is not adequate for modern hoppers, and a better solution is to use a stable broadband tuner, followed by a discriminator having a 500-MHz bandwidth. This allows the frequency of every successive pulse to be recorded (together with any FMOP). Additionally, a broad filter often allows an entire ECM "spot" to be quantified as a band of noise, possibly swept. Using a cw trigger, the time evolution of various sorts of swept noise can be recorded.

In order to record successive pulses, it is necessary to employ a multiple event digitizer, which can segment the digital memory in such a manner that the uninteresting interpulse time (noise only) is not stored, but each successive event is stored. In order to view the leading edge of the pulse, such digitizers also allow control of the "pre-trigger" ratio (the fraction of time preceding the threshold break that caused the trigger, relative to the length of the recorded interval). The duration of the interval stored when the system triggers can easily be set by reading the timebase from an analog oscilloscope, where the signal has been manually optimized. Obviously, prior knowledge can similarly be used in predictable situations.

Control over the sample rate and sample size allows either few samplings per pulse and a long sequence of pulses (to fill the local memory), or a large number of samples per pulse, but fewer pulses to fill. Experience has shown that a reasonable range is from 16 samples/pulse for 2000 pulses to 1024 samples per pulse for 32 pulses. Digitizer rate is evolving extremely quickly with reasonably priced units currently available which digitize at 100 megasamples/second, (10-nanosecond intervals between samples). There are other limitations, but illustrating a pulse train having 30-nanosecond pulses at several million pulses per second is readily achievable.

Figure 6 shows a multi-event dual AM/FM versus time plot. Dual-channel AM/FM data is shown corresponding to a signal having one-millisecond PRI and a one-microsecond pulsewidth recorded on a custom multi-event segmented memory digitization and storage unit. Interpulse time is suppressed. The vertical lines on the plot are actually TOA bits for each threshold break (10-nanosecond resolution). Signal input is from built-in test equipment.

Analysis of I/Q Data

Pre-detected data provides several unique features of recording that are not possible to recover from other demodulators. For example, the direct recording of the waveform preserves the phase information and, therefore, allows a determination of the phase evolution from one pulse to the next. Certain classes of emitters are interrupted cw, in which a single-frequency sine wave is gated by a modulator. In this case, the emission is said to be coherent, in that each successive pulse carries a specific phase depending on the frequency of the master oscillator and the elapsed time between pulses.

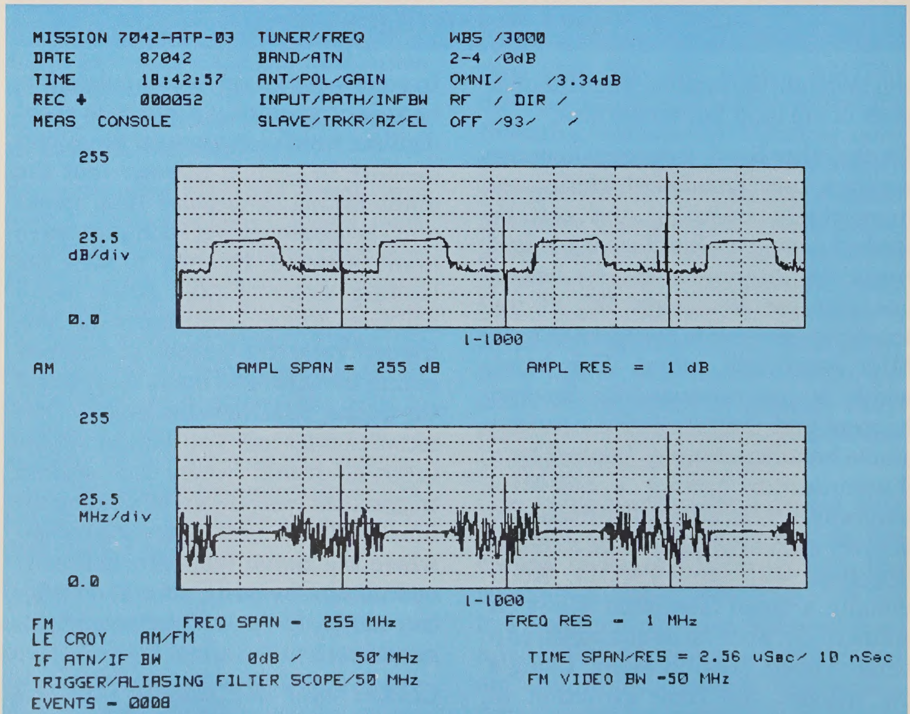


Figure 6. Multi-event dual AM/FM versus time.

One of the important techniques for recording pre-detected waveforms is the use of "in-phase/quadrature-phase" (I/Q) demodulation. This technique produces two copies of the signal, converted to baseband frequencies which are 90 degrees out of phase with each other. The signals are then bandpass filtered, and both are digitized. The use of both signals allows both positive and negative frequency components to be recorded, and extends the information bandwidth beyond the Nyquist limitation of digitizing a single channel.

The utility of using I/Q demodulation for ELINT (as distinguished from radar processing) is that the technique can be made to cover broad bandwidths, and yet is accurate for narrow-band applications as well. For example, a system having 50 MHz of video bandwidth, when digitized by a 100 Msample/second digitizer would be Nyquist-limited to 50 MHz. The I/Q process maps the rf spectrum into frequency components from -50 MHz to +50 MHz, and the entire information bandwidth of 100 MHz is preserved.

I/Q demodulation is done either in a linear mode (having perhaps 25-dB dynamic range) or in a limited mode in which the amplitude information is destroyed, but the phase information is preserved. Thus, the strengths and weaknesses of this technique are complementary to those of log AM detection. Possibly, the most interesting application is the demodulation of simultaneous phase and amplitude-modulated signals.

Recovery of signal amplitude information is done by adding the square of the I and Q components in quadrature. Recovery of the instantaneous phase is done by taking the arctangent of the Q/I ratio. Each digitization produces a record of amplitude and phase from which successive values of phase can be differentiated to calculate the instantaneous frequency. The power of the approach is that amplitude, phase and frequency are all recovered, with double the available Nyquist bandwidth.

Figure 7 shows a reconstructed AM/FM plot of a local radar using linear I/Q data. This data has an information bandwidth of roughly 100 MHz, even though the video bandwidth and digitizing bandwidth is 50 MHz. Reconstructed amplitude is formed by adding the I and Q channels in quadrature, and the reconstructed phase is calculated using the inverse tangent of the Q/I ratio. Frequency is determined by differentiating the instantaneous phase. Since this is a linear detection process, the dynamic range is limited to slightly more than 20 dB, which is adequate for modulated-carrier signals, but minimal for pulse signals. For improved dynamic range performance, one may use Limited I/Q processing, which looks quite similar, except that amplitude information is largely destroyed by the limiting process. Phase information is preserved, so that this becomes the preferred technique for illustrating phase and frequency modulations on pulsed signals.

Any ELINT system has custom requirements, such as spread spectrum demodulation and PSK. Typically, the outputs of such special-purpose demodulators can be made into a baseband waveform that is conveniently recorded in the same time-domain digitizer as above.

Data Products

Much emphasis has been placed on the inexpensive near-real time capability to gather and present raw data, such as:

- Spectrum analyzer data — both scanning and fixed tuned
- AM/FM to time-domain digitizer
- AM(1)/AM(2) to time-domain digitizer
- I/Q to time-domain digitizer
- PRI interval counter/storage

These are primarily used only to verify that the appropriate data has been recorded, but detailed analysis is not usually possible during the frenetic collection of a typical mission.

ANALYZED DATA

The primary distinction of off-line data analysis is that the time pressure to acquire raw data is no longer present. Therefore, the analyst can move back and forth throughout the collected data, sorting and selecting those records that are pertinent. One of the first steps is to remove known instrumentation effects by calibration corrections. The next step is to apply the analysis tools that turn the data into information: markers, windows, histograms, scattergrams, and various forms of digital filtering and transforms. Also important is the ability to select events meeting certain criteria, in order to perform statistical analysis on an ensemble of data. Much of this is done to support individual requirements, and tends, therefore, to be custom-coded to support the information requirements of the end user.

CALIBRATION DATA

The remaining necessity is to take data to establish that the receiving system was, in fact, operational, and that the conversion from rf energy level to digitizer counts is understood to the required level of precision. There is no other way to achieve this than to supply an rf signal source at a calibrated power level into the upstream end of the receiver. The response can be evaluated at a set of constant frequencies, where the input power level is varied in order to describe the system noise floor and compression dynamic range. The dynamic range of the system depends not only on the properties of the front end, but also on how the video outputs are presented to the digitizer. It is possible to misalign a system, such that the digitizer saturates well before the front end; thus, the usable dynamic range could be far less than is supported by the rf section. It is also possible to mismatch a receiver such that the actual dynamic range is high, but the output response is mapped into only a portion of the digitizer counting range. This degrades the available amplitude resolution.

To characterize the system response, an expression for the gain is needed to relate the power out (counts) to the input power (dBm). The problem is that the gain is frequency-dependent, and will be different for each signal path leading to the digitizer. In order to determine gain, using the same signal source at constant power while stepping in frequency generates a "cross-band gain curve" from which a fit determines parameters to approximate the cross-band gain (both in and out of band). The equation for output counts then can be inverted to find the input power.

The use of a frequency discriminator also requires that information be gathered on the response across the passband. The voltage output of the discriminator is transformed into frequency by inverting an expression relating the digitized response (counts) to the discriminator slope (counts/MHz) plus possible correction terms for non-linearity or offset. Data to illustrate the response may be acquired by sweeping a signal source across the discriminator, marking the nominal band edges, and recording the output of both AM and FM detectors. This has the advantage of mapping the AM passband response as well as characterizing the FM. Differences are to be expected both as a function of rf and input power level, thus a complete characterization will step both these parameters as well. The process generates a great deal of data; however, all can be done under computer control,

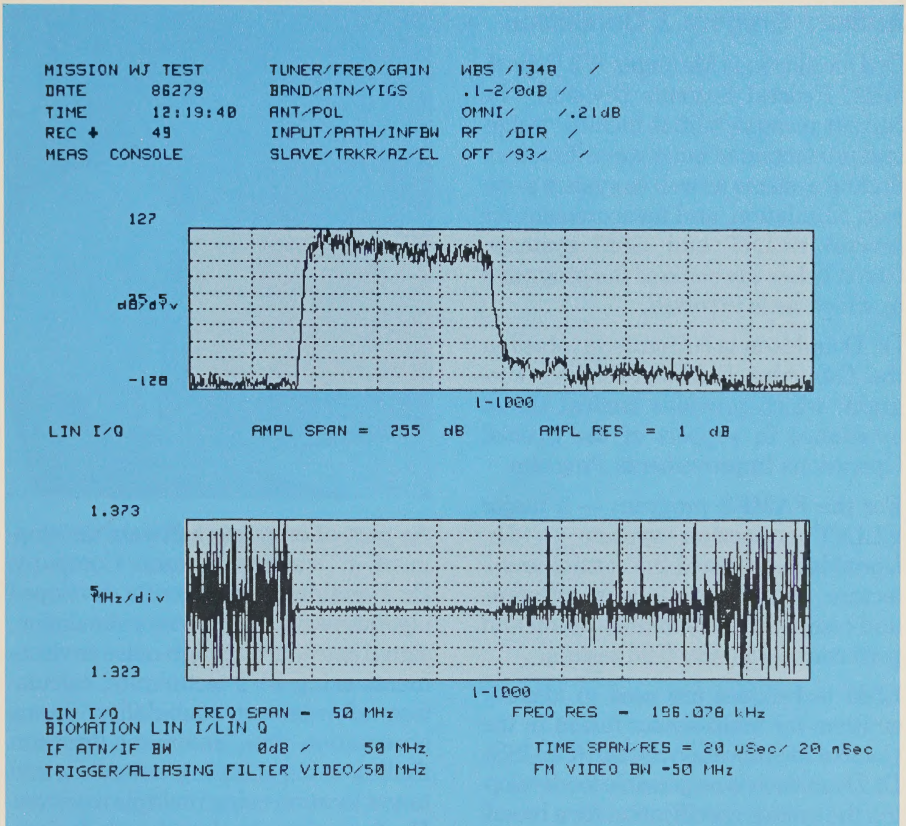


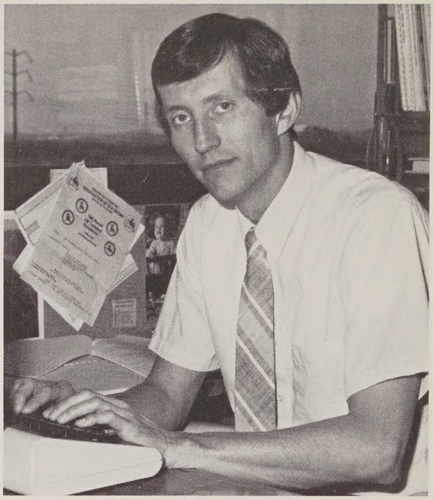
Figure 7. Linear I/Q versus time.

using machine-calculable criteria for linearity, offset, etc., to reduce the volume of output data.

Conclusions

The application of precision waveform measurements to support strategic reconnaissance, countermeasures equipment evaluation, training missions scorekeeping, and range-emitter management share certain technical requirements, among them the ability to quantify modulations and signal levels. Much of this activity can be achieved using standard laboratory instrumentation such as spectrum analyzers and digital oscilloscopes. An important addition is required by modern emitters: low-noise front ends followed by precision broadband demodulation. A second addition is the addition of a sensitive automatic direction-finding receiver which can steer the directional antennas to signals of interest. Bringing the ensemble under the control of a single computer has the advantage of making the data available digitally and subject to immediate manipulation. A trained engineer, working with software analysis tools can convert the raw data to information suitable for the end user in a matter of hours or days, depending on the complexity. Such an approach appears to make maximum use of inexpensive instrumentation, with minimal reliance on high-cost custom electronics and can have the effect that highly sophisticated measurements can be acquired, analyzed, and reported quickly.

Author: Gregory J. Donaldson



Dr. Donaldson is Manager, W2 Department, Federal Systems Division. His current responsibilities include design and production of microwave direction-finding systems as well as system analysis, simulation, and measurement for several ELINT and ESM systems. Given below are some of the programs in which he is involved.

Dr. Donaldson is currently involved in the Gunships Direction-Finding Program, which provides tactical threat avoidance in support of the Special Operations Improvements Program.

For the FAMES program — a major ELINT collection system — Dr. Donaldson designed the control architecture and data analysis software, and completed system integration and performed extensive field testing.

ESM techniques are used to identify emitters for multi-sensor fusion in the Combat Identification System (CIS-ISS). Dr. Donaldson is responsible for developing the system specification for a broadband monopulse antenna system, obtaining the data base, and for developing the algorithms to identify the emitters of interest. He is also responsible for implementing the test program objectives, acquiring data, and performing system analysis on the results.

As part of on-going software development at Watkins-Johnson Company, Dr. Donaldson has recently developed algorithms for I/Q processor simulation, signal extraction in high-noise environments using FFT techniques, calculation of intercept probability versus observation time, automatic direction finding using spinning antennas, and target location using multiple receivers. He has also developed a technique whereby the range of an airborne emitter can be passively estimated from an airborne receiver.

Dr. Donaldson received a B.S. (Magna Cum Laude) and PhD. in physics, Stanford University.

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