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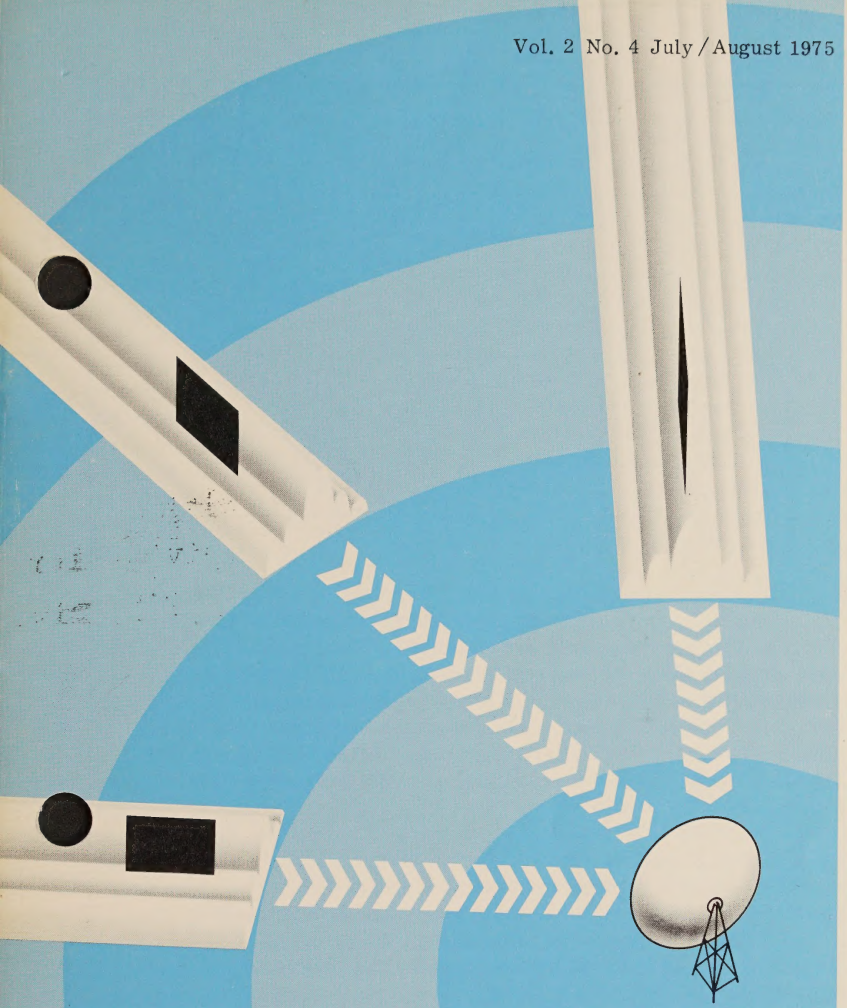


High Probability of Intercept Receivers

In EW Environments

Future Electronic Warfare (EW) Systems require the development of new technology within the next 5 to 10 years in order to cope with the increased density and complexity of emitters, and to process and react to the resulting emissions on a timely basis. Peak rf pulse densities in the order of one million pulses per second can be easily and realistically projected. Techniques must be developed to handle these pulse densities on a real-time or near real-time basis without the use of buffer storage, queuing or other techniques which limit the amount of data processed and cause a loss in useful data. EW systems must also be developed to maintain a high sensitivity and wide geographic field of view. In addition, receivers must be open to a wide instantaneous frequency field of view in order to maintain high probability of detection on exotic emitters such as multi-beam radars, dual rf, wide-band chirp and frequency hopping signals.

Conventional signal processors are not capable of operating under the anticipated rf density increases. High-speed preprocessing and/or sorting must occur in order to compact the data into a digestible digital data stream for association, identification and timely response. Even sophisticated technical intelligence collection requirements demand that the data be digested and associated. There is no time for recording and playback on a nonreal-time basis; there are just too many data inputs to process.

All of these conditions brings the focus of attention to that portion of the system which converts rf signals into a digital data stream for preprocessor association—the receiver. This device must transform incoming pulses into digital word descriptions on a pulse-by-pulse basis, very rapidly and with extremely high quality data. A throughput receiver processing rate of one microsecond or less is required. The "false alarm" rate must be extremely low. Furthermore, if certain unavoidable conditions as to the quality of the output data exist, the receiver must be able to recognize it and indicate that fact. It must be capable of determining all of the conventional monopulse parameters including pulse width, pulse amplitude, frequency (all frequencies contained within a pulse), time-of-arrival and direction of arrival. It also must be capable of handling and correctly identifying multiple simultaneous pulse events. In addition, the receiver must also exhibit a high sensitivity (comparable to the conventional superheterodyne receiver) in order to detect emitter side and backlobe radiation. Finally, a high dynamic range is required, particularly in relation to multiple signal intermodulation products, so that the processor may spend its time analyzing real signals and not spurious products. In short, the receiver must be a high quality, rf-to-digital monopulse converter operating with a wide instantaneous field of view in both azimuth and frequency.

Signal Acquisition Receivers

Historically, any treatment of state-of-the-art receiver technology has dealt with one or both aspects of the intended use or application. These include tactical or threat-reactive ECM applications and strategic intelligence applications. In strategic applications, the objective is the collection of detailed technical intelligence. Included within the applications which are tactical in nature are passive Electronic Support Measures (ESM) as well. Common to both tactical and strategic applications is the fact that both the density and the complexity of signals is increasing.

Equipment for tactical applications has been designed to provide maximum probability of intercept, rapid acquisition and identification of intercepted signals and usually provide or stimulate some type of active response to those intercepted signals. Such a typical application might be set-on spot noise jamming, barrage noise jamming or deceptive countermeasures, where speed of response is very important. Even in ESM applications (e.g. direction-finding or homing and warning) speed of response is very important.

Now consider the environmental problem statement for these applications in the years around the 1980 time frame. Out of an extremely high density of emitters, the EW system must first identify those emitters which pose a serious threat and then determine an appropriate response — whether it be of an ECM nature or an evasive or strike action. Whichever the response, the receiver must detect and process all incoming pulsed rf signals with an instantaneous bandwidth consistent with the requirement for a high probability of intercept of exotic emitter types.

Similarly, equipment belonging to strategic applications has been designed to collect detailed signal intelligence. Therefore, precise measurement of signal parameters is of paramount importance. A typical application might be an attempt to determine the operating mode parameters of a signal known to exist, but which has been difficult to detect. Under this condition, the probability of detection is critical to collecting new and interesting data on signals known to exist. Again, consider the problem statement in the 1980 time frame. In a very dense environment, the receiving system must identify and collect data on signals that are new in nature and collect data on operating modes of known signals which may be exotic or complex in nature.

Both applications, therefore, require receivers with high probability of intercept in terms of wide instantaneous rf bandwidth, very high capacity throughput or processing rate and high sensitivity. Even in strategic applications, a high probability of intercept is needed to ensure a high probability of signal detection. Real time processing becomes necessary due to the tremendous amount of data that need to be sorted out. In addition, a high probability of intercept system may serve to set-on other receivers for detailed signal analysis. Conventional approaches that limit data rates by means of buffers, low sensitivity thresholding actions or by using directional antennas, only avoid the real issues which must be addressed if future EW problems are to be solved.

Limitations of Conventional Technology

A result of the projected increase in signal density is the high incidence of accidental signal pulse overlap as shown in Figure 1a. Resolution of such time-overlapped signals on a pulse-by-pulse basis is not possible using conventional receiver technology. Even with the well-known Instantaneous Frequency Measure-

ment (IFM) technique, the result will be a phasor sum voltage output corresponding to a nonexistent or false signal at the receiver output. Resolution of the ambiguity may be achieved, of course, by allowing one signal to "walk through" the other, but this requires more pulses and additional time delay which future systems cannot tolerate. Furthermore, in future rf environments it is possible to postulate that a significant (greater than 10%) number of pulses arriving at the receiver will be time overlapped with other signals. This identification problem is made even more complicated since certain time-overlapped pulsed rf events may be interlocked, Figures 1b and 1c. Detection of interlocked (non-random) rf signals means that no identification of the signal will be possible unless the ambiguity can be resolved—at least to the extent of determining the carrier frequencies of each pulse.

Another limitation of current conventional receiver technology occurs because some radiators emit only a few pulses. Conventional techniques use receivers which demand a number of pulsed rf events in order to establish a better signal-to-noise ratio for processing or to center the IF passband on the signal in the specific case of a superheterodyne receiver. A monopulse technique that will correctly encode all pulsed rf parameters on an individual basis is required for future systems.

Another emitter signal that is difficult to detect is a frequency hopper, Figure 1d, particularly with the sweeping receiver having a narrow instantaneous passband. Of course, the very necessity to open up the instantaneous bandwidth of the receiver introduces some of the problems previously cited so that the solution becomes even more difficult.

The chirped rf signal is an emitter class of particular interest. During

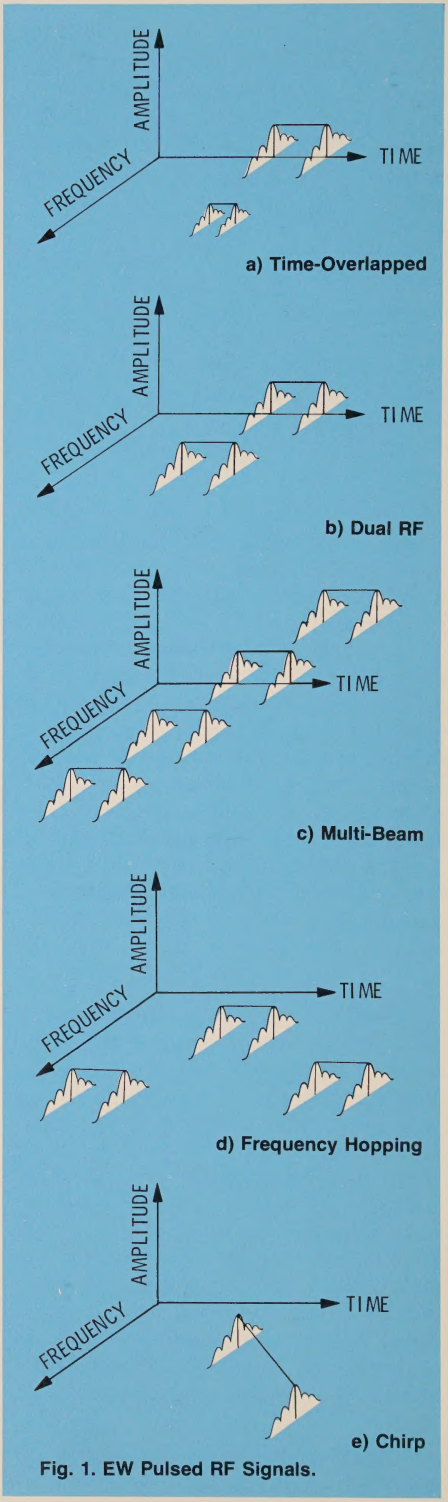


Fig. 1. EW Pulsed RF Signals.

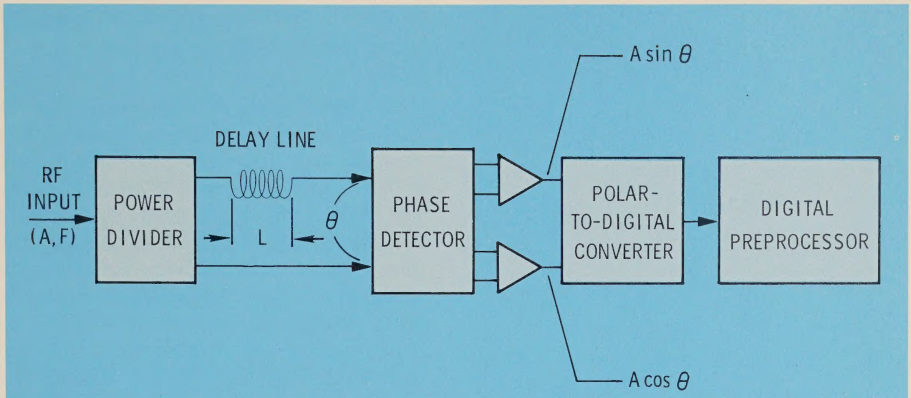


Fig. 2. Instantaneous Frequency Measurement (IFM) Receiver Technique.

the pulsed rf event, the carrier frequency is rapidly swept over a wide frequency bandwidth, as shown in Figure 1e. For the emitting radar, sweeping the carrier frequency results in improved resolution*. However, for the reconnaissance receiver, a problem of probability of detection arises. Unless the instantaneous receiver bandwidth corresponds to the chirp bandwidth of the signal, it will be distorted and probably not recognized.

Suffice it to say that conventional receiver technology, whether it be superheterodyne, Tuned Radio Frequency (TRF) or crystal video, is incapable of coping with and adequately responding to future high-density rf environments.

Advanced Receiver Technology

Only two major receiver techniques have an inherent capacity for high probability of intercept in the future densely populated rf environment. These are Microscan and Channelization. Either of these techniques can be employed to approach, if necessary, a 100% probability of intercept. Each approach achieves a high system sensitivity. Furthermore, each technique is compatible with high data throughput rates and each is capable of operating in a dense environment.

First, however, a description of the Instantaneous Frequency Measurement (IFM) technique will explain why this approach will not exhibit a high probability of intercept in future rf environments.

The input to the IFM receiver is split into two parallel rf paths—one path containing a delay line, Figure 2. These two paths feed a phase detector. The phase detector output signals are proportional to the rf input amplitude (A) and the sine or cosine of the phase difference between the two phase detector input ports. The delay line length (L) causes the phase angle (θ) to be proportional to the rf input frequency — F. When a pulsed rf input signal is applied, simultaneous video pulses proportional to the sine and cosine of the rf frequency are generated. Thus, the information contained within output signals A Sin θ and A Cos θ may then be digitized and passed on to a preprocessor or computer.

This type of receiver is basically a large frequency discriminator receiver. As such, it provides a simple means of measuring frequency in a low-density rf environment. However, because it depends entirely on a frequency/voltage transfer function to derive the frequency data, it is not possible for the receiver to respond to two rf signals simultaneously since the phase detector out-

*Reference No. 3

puts cannot assume two voltage values simultaneously. Thus, the very effect that provides its simplicity is a basic drawback to its use in a high-density rf signal environment since the false alarm data that are created cannot be eliminated. A second disadvantage of the IFM technique is that it cannot recognize time-overlapped signals. The use of notch filters to suppress high duty cycle signals is a partial solution, but the problem of detecting pulse overlap (either random or dual rf) is severe.

The principle of using a frequency discriminator is a valid technique. However, the difficulty in its use arises when it is employed in applications which cover large rf portions of the spectrum simultaneously. For precise measurements over a limited frequency range, the discriminator function is a valuable technique since it permits interpolation of a frequency range.

The discriminator function need not be formed by a frequency discriminator as is typically done in IFM technology. An alternate technique is the use of two filters, displaced in center frequency, with the filter outputs compared after detection to form a conventional discriminator response. This approach does have advantages. It is compatible with high-selectivity filters and channelized approaches and permits higher frequency accuracy than does channelization by itself. Another advantage of this approach is that the two filters which form the discriminator function provide inherent selectivity to the output response. Thus, false alarm responses do not result, except within the narrow filter response range.

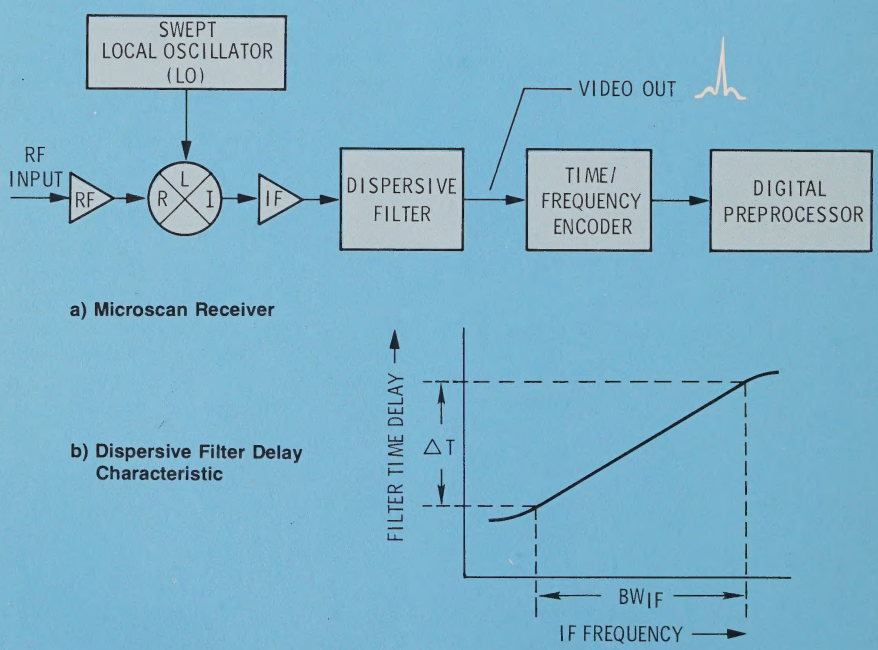


Fig. 3. Microscan Receiver Technique outputs a time-compressed pulse for each frequency component of the RF Input.

Microscan or Compressive Receiver

The microscan or compressive receiver is derived from Chirp radar technology. A dispersive filter is used to compress a linearly frequency-modulated pulse into a much shorter pulse. A block diagram of the compressive receiver is shown in Figure 3a. The RF Input band is mixed with a linearly swept LO (such as a Voltage Controlled Oscillator) and down-converted to the IF band. During the LO sweep, each frequency component present in the RF Input band moves across the IF band and appears at the dispersive filter as a linear FM or chirped-frequency signal. When the sweep rate of the LO is equal to the dispersive filter's delay slope, a time-compressed pulse occurs at the filter output for every frequency component of the input. The result is a spectrum analysis or impulse response of the input signal. If the dispersive filter delay-versus-frequency characteristic is as shown in Figure 3b, a proper slope match is obtained when the IF signal descends in frequency, moving across the filter's dispersive bandwidth, BW_{IF}, in ΔT seconds.

The sequence of events for a single receiver scan is shown in Figure 4. The rf signal bandwidth BW_{RF} of Figure 4a is down-converted by the linear sweep oscillator to an IF band (Figure 4b) which overlaps the compressive filter's dispersive bandwidth, BW_{IF}. As each signal (e.g. F_s) is swept across the IF bandwidth, BW_{IF}, the response appears at the detected video output as shown in Figure 4c. The timing of the compressed response relative to the beginning of the LO sweep denotes the absolute frequency of F_s. For multiple simultaneous signal inputs, the separation of pulses denotes relative frequency of the signals. In Figure 4b, the dispersive filter's bandwidth is arbitrarily taken

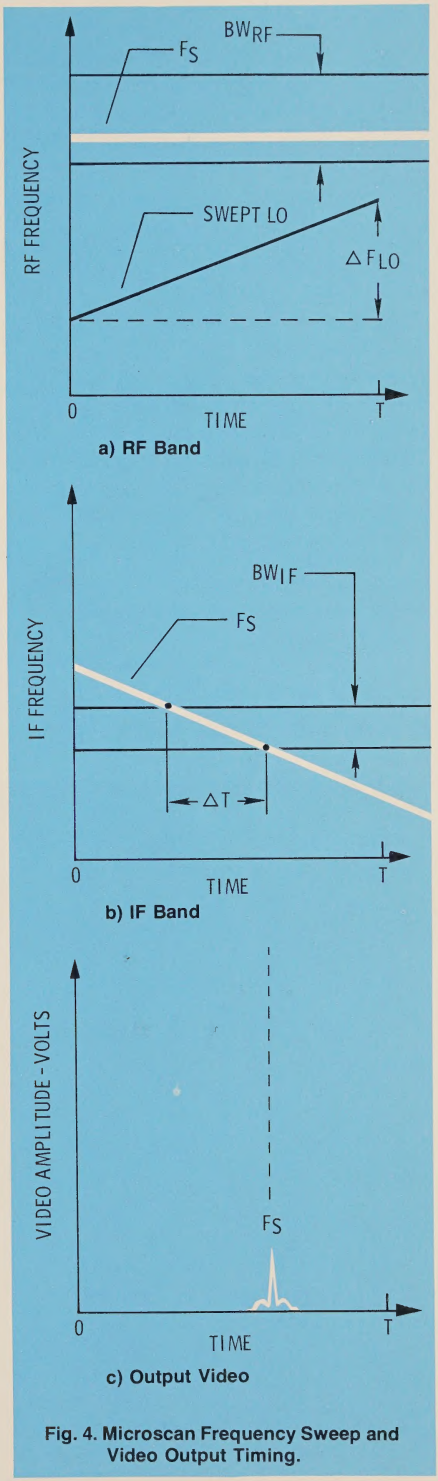


Fig. 4. Microscan Frequency Sweep and Video Output Timing.

to be a small portion of the rf signal bandwidth, $BW_{IF} << BW_{RF}$. Some resultant distortion of the output response naturally occurs. Also, information on the pulsed signal width may be lost using this receiver technique.

The time to scan a band, particularly in a pulsed microwave environment, is an important consideration. The objective is to scan bandwidth BW_{RF} in a time less than the minimum expected pulse width in order to maintain 100% probability of intercept. The microscan receiver can scan its required resolution bandwidth Δf in a time approximately equal to the reciprocal of this bandwidth, $1/\Delta f$. Thus, covering a signal bandwidth of

$$BW_{RF} \text{ requires } \frac{BW_{RF}}{\Delta f^2} \text{ seconds.}$$

Some of the disadvantages of this approach are immediately apparent. First, if high-frequency resolution (small Δf) is required, then a relatively large amount of acoustic delay (large ΔT) is required which limits the data handling rate of the receiver for high-density applications. Secondly, compressive acoustic delay devices exhibit a relatively large amount of insertion loss which limits the attainable system noise figure. In addition, the system sensitivity is further limited by the wide-open front-end required and this also gives rise to spurious intermodulation products.

Channelization Technique

The channelized receiver employs banks of contiguous filters and fixed-tuned local oscillators in order to down-convert the rf spectrum. This type of receiver does not require any tuning in the conventional sense; each bank of filters is wide open to the rf spectrum. However, some form of time sharing and/or frequency band multiplexing is ordinarily used to

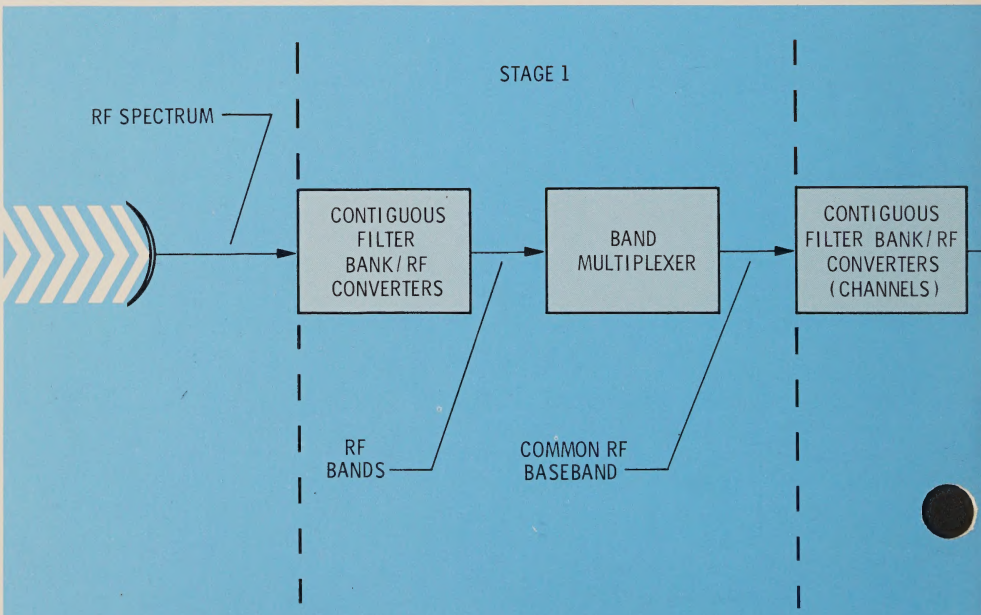


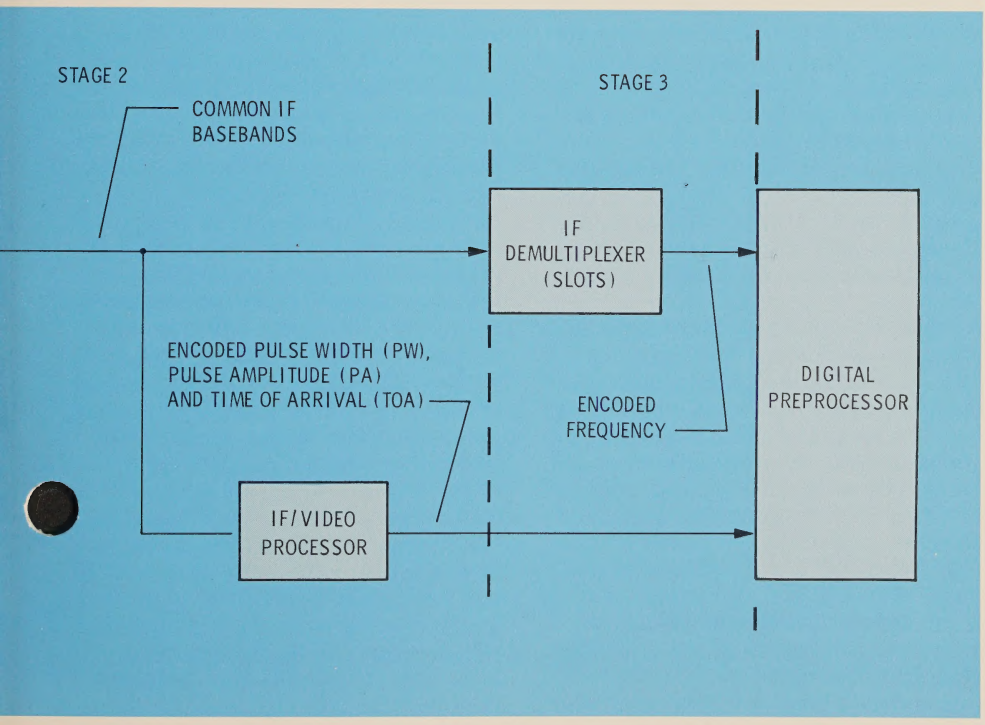
Fig. 5. Three Stage Channelization Technique converts the RF Spectrum into very narrow band IF bandwidth.

reduce the complexity of the receiver. The channelization or filtering of the rf spectrum usually occurs at several stages within the channelized receiver as shown in Figure 5.

• Stage 1. The first stage of channelization divides the RF Spectrum of interest into a number of RF Bands and then down-converts each band to a Common RF Baseband. A contiguous set of matched filters is used in order to separate the input spectrum into bands, whereas, wideband balanced mixer-preamps with high power LO drivers perform the band conversions. Normally the Common RF Baseband frequency is chosen in the E- and F-band range (2-4 GHz). This stage of the receiver is usually referred to as a "channelizer" or channelized frequency downconverter and may be used independently of the following stages to form E- and F-band baseband inputs for other types of analysis receivers, such as the superheterodyne receiver. Conversion to E or F band takes advantage of the high performance technology available, even in system configurations in which high probability of intercept is not yet required.

• Stage 2. The second stage of channelization occurs at the Common RF Baseband. Again, a contiguous filter bank and mixer-preamps are introduced to form a set of contiguous IF output "channels". Each channel operates at a Common IF Baseband range—typically above 60 MHz but lower than 500 MHz—and covers the entire Common RF Baseband range.

• Stage 3. The last stage of channelization divides each Common IF Baseband channel into very narrow band IF "slots". These narrow band slots are formed by an array of contiguous filters and detectors (IF Demultiplexer) and are placed across each channel of the Common IF Baseband.



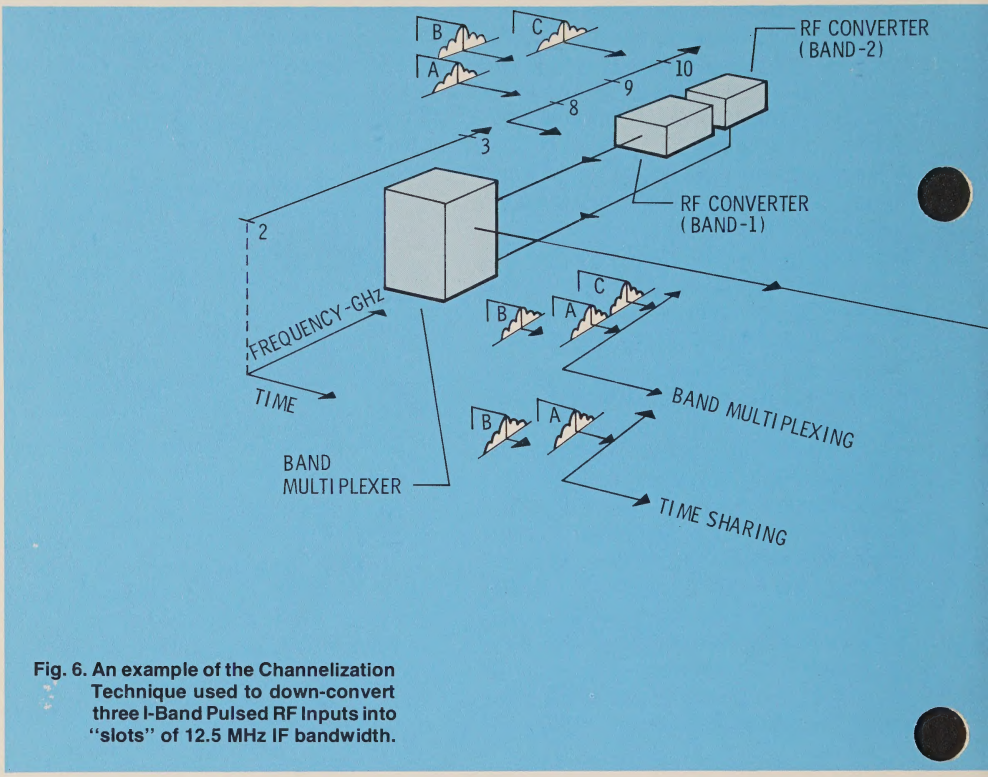


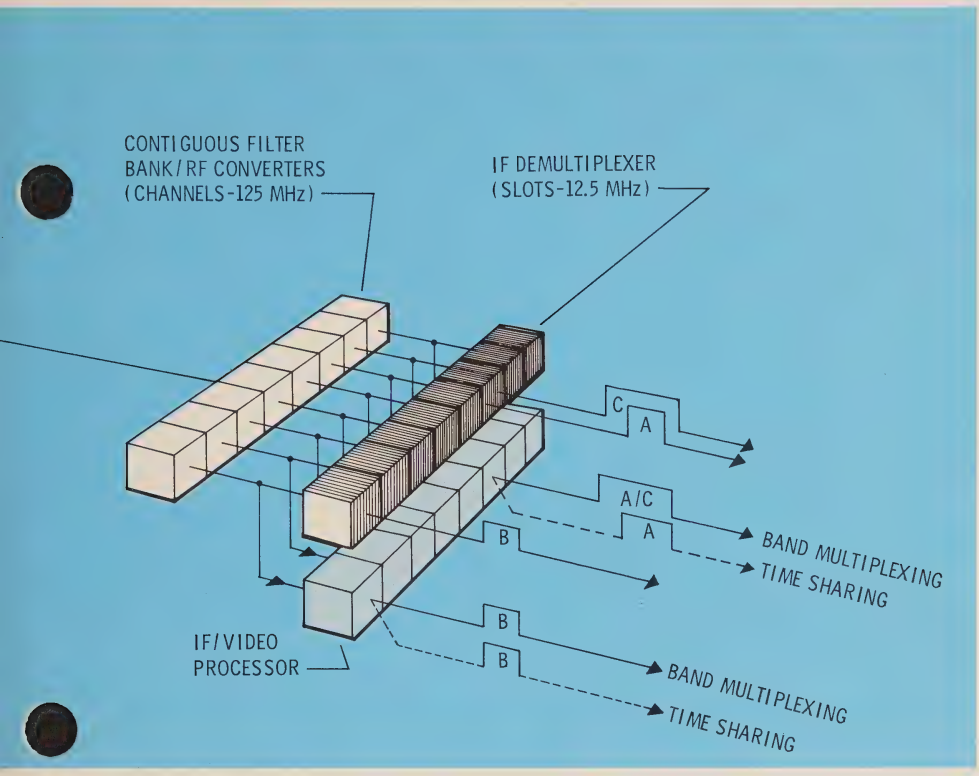
Fig. 6. An example of the Channelization Technique used to down-convert three I-Band Pulsed RF Inputs into "slots" of 12.5 MHz IF bandwidth.

An example of the channelization operation for three I-band (8-10 GHz) RF inputs is shown in Figure 6. In this example, pulsed rf inputs A and C are time coincident. RF conversion of Band-1 and Band-2 inputs can place either a time-shared or frequency multiplexed Common RF Baseband (1 GHz) at the second stage of channelization or channel inputs.

A set of eight contiguous channels for example, is chosen to divide the 1 GHz Common RF Baseband into eight Common IF Baseband channel outputs, each 125 MHz wide. At the third stage, a very narrow IF bandwidth of 12.5 MHz is achieved by dividing each Common IF Baseband channel output by an array of ten (125 MHz/12.5 MHz) slots.

It is important that the first stage of channelization achieve good definition, that is, good selectivity and minimum in-band insertion loss. The selectivity will aid, along with subsequent mixer suppression, in discriminating against spurious responses which would otherwise excite false signals in other rf bands. Wideband balanced mixer-preamps driven by LO power as high as 20 dBm is essential to achieve a 70-80 dB dynamic range with the receiver operated wide-open to rf inputs. It is also essential for the mixer-preamp to maintain a low noise figure to retain or achieve high system sensitivity without the absolute necessity of rf preamps at the input. Placing rf preamps prior to the rf conversion limits the dynamic range magnitude. Also, careful analysis of the frequency conversion process is mandatory to avert spurious responses; particularly in-band spurious responses**. Thus, it is essential to provide good discrimination against spurious responses so that the down-stream processor spends its time analyzing real signals.

**Three dynamic ranges are important; 1 dB compression or "linear" dynamic range, single-signal spurious-free and two-signal intermodulation products.



During receiver operation, a decision occurs as to whether the receiver be operated on a purely wide-open basis or to use some form of time sharing, or both. Frequency multiplexing (summing) of all the Common IF Baseband channels will accomplish the goal of wide-open operation, however, several potential problems are introduced. First, the system sensitivity is degraded since the noise from all rf bands is added. Secondly, an ambiguity problem is introduced in the case of time-coincident rf pulses arriving from different rf bands. Activity detectors associated with each rf converter can serve to identify which bands are active. However, it will not be possible to identify whether Band-1 or Band-2 rf converter contained the time-coincident rf pulse A or C. Several solutions are possible, however, if more than 1 pulse event is allowed to occur before attempting to resolve the signal.

The time-shared operation can be implemented on either a programmable switching basis or by means of fast (nanosecond) switching based upon the signal activity. Again, the receiver outputs at Common IF Baseband are useful for IF processing schemes other than strict channelization. A pure phase discriminator or IFM technique may be introduced to process each of the parallel wideband Common IF Baseband outputs, Figure 5, either on a simultaneous basis (sum again at IF) or by means of time-sharing. The point to be made here is that the first two stages of channelization are compatible with other IF processing techniques.

Critical to the third stage performance is how to prevent all the slots from being activated when a narrow pulse is incident on the receiver. Also, what happens when simultaneous pulse events (such as A and C) occur at

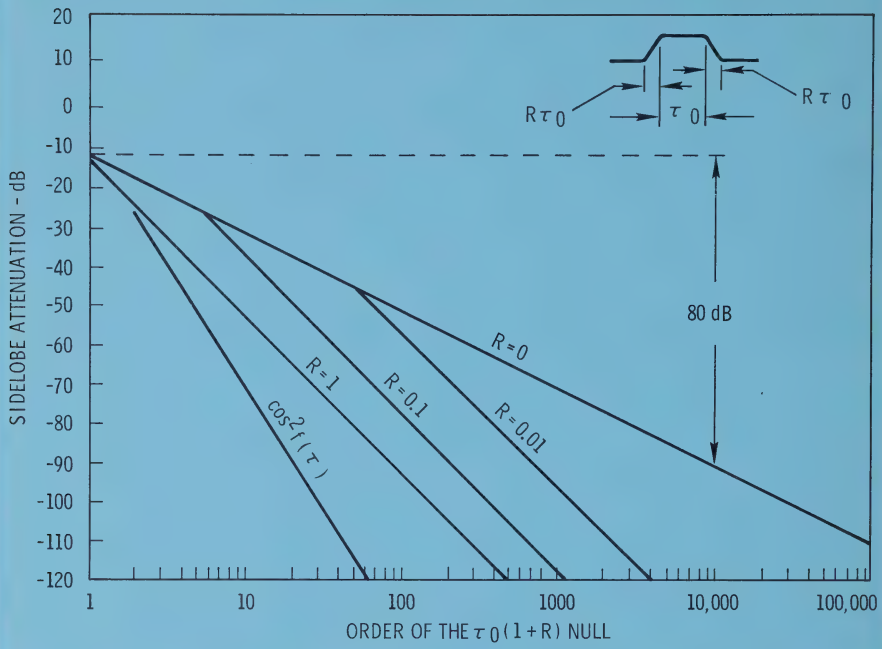


Fig. 7. The Sideband Power Distribution for the Pulsed RF Signal Spectrum.

different slot frequencies? Using conventional filtering techniques at this level has serious disadvantages—particularly if a high instantaneous dynamic range is desired. A conventional filter array across the Common IF Baseband with signal activity based upon amplitude response does not work. Even if high "Q" filters are used in order to approach an "ideal" rectangular passband, it will be self-defeating because the filters will ring.

A technique for implementing these filters has been employed at W-J which dramatically solves these problems. An ideal rectangular passband is synthesized using non-ideal filters with the result that a slot is excited if and only if the carrier frequency lies within the filter passband. This is true for narrow pulses—and wide dynamic ranges. Each slot on its own determines if the signal is present or not without reference to any other slot or to input signal amplitude. If the spectral content of one signal does not hide the carrier frequency of another signal, then both signal frequencies can be correctly resolved. Hence, the ultimate resolution for simultaneous pulse events approaches the ideal.

The response characteristics of the slot filter array can be determined by a plot of the sideband power distribution versus pulsed rf signal spectrum as shown in Figure 7. The curves are normalized to the order of the pulse width null in order to allow various pulsewidths (τ_0) and pulse shapes ($R\tau_0$) to be plotted. Each order of magnitude on the horizontal axis corresponds to a frequency scale of a decade relative to the pulsed signal center carrier frequency. The frequency spectral definition may be approximated by the inverse pulsed signal pulsewidth or $\frac{1}{\tau_0}$.

As an example, for a rectangular pulse (R = 0 or zero rise and fall times), the spectral fall-off is the conventional $\left(\frac{\text{Sin } x}{x}\right)^2$ envelope with the first sidelobe peak occuring at a null of 1.5, and is down 13 dB from the spectrum peak or 0 dB. For a pulsed rf signal with a 0.1 microsecond pulsewidth (0.1×10^{-6} sec.), it can be approximated that the sideband energy is detectable for a frequency range extending ±100 GHz

$$\left(\frac{10^4}{0.1 \times 10^{-6} \text{ sec.}}\right)$$

on either side of the center frequency. The dynamic range of the sideband energy corresponding to four frequency decades is 80 dB.

Real pulses do not exhibit the characteristic of zero rise and fall times. The degenerative case of trapezoidal pulses (R = 0 and finite rise times) improves the spectral power response. The ultimate rate of spectral power fall-off for these pulse shapes is −40 dB per decade, compared to −20 dB for rectangular pulse shapes. For a pulsed signal with 0.1 microsecond pulsewidth in the shape of a trapezoid with equal rise and fall times (triangular shape with R = 1), the spectral power range is reduced and occupies ±1 GHz on either side of the center frequency. These curves can be used for predicting the spectral power range for a pulsed signal whose pulsewidth is wide compared to the rise time.

Sideband power for real pulse shapes tend to fall-off at −60 dB per decade as indicated by the Cos^2 curve. This curve gives a more realistic relation since the derivatives of the leading and trailing edges of the pulse are not discontinuous as they are for the trapezoidal pulse. There may also exist some incidental FM that results in both non-symmetry of the power distribution and additional sideband power. However, for the purpose of analysis, the Cos^2 function forms a valid starting point. For a pulsed signal under the condition of Cos^2 spectral power distribution, the sideband energy is detectable for a frequency range approaching 200 MHz over a 90 dB dynamic range. This potential sidelobe power distribution then forms the limiting condition under which two signals can be detected simultaneously. Two signals, each exhibiting 0.1 microsecond pulse width, time overlapped and differing in power levels by 50 dB, cannot be separately detected if the frequency separation is less than 50 MHz.

By similar reasoning, this sidelobe power distribution determines the response characteristic of channel filters arrayed contiguously if conventional bandpass filters are employed. A single pulsed signal with 0.1 microsecond pulsewidth, will cause a filter that is 50 MHz removed from the pulse center frequency to respond as a result of the sideband energy content, independent of the selectivity of the filter. For filters with a low-Q value (as needed to obtain a distortionless pulse transient response), the actual spectral width response is greater than the sideband energy of the pulse spectra. It is also dependent on the transient response of the filter to impulse functions and to the convolution of the filter passband characteristics with the signal-sideband energy. In a conventional filter bank channelized receiver, this would result in many filters responding to the 0.1 microsecond pulse signal. This type of response poses severe problems in processing and encoding the data from a conventional channelized filter.

The use of guard filters significantly improves this situation. Guard filters employed at each filter frequency (IF

Demultiplexer in Figure 5) allow a simple digital encoding technique to be used. Each individual filter response is compared to its own guard filter response to determine whether the center of the pulsed signal power distribution lies within the filter bandwidth. This technique, currently in use at W-J, results in a significant improvement for reducing the number of filters that respond to pulsed input signals.

Summary

Further development of channelized receivers at Watkins-Johnson will define the specific form to which the channelized receiver will adhere. The redundant modularity concept inherent in the channelized receiver should prove to be advantagous when Microwave Integrated Circuit (MIC) implementaion is accomplished. MIC implementation is imperative and essential to bringing down cost. For example, interdigital filter techniques, integrated mixer-preamp assemblies and derivation of the LO inputs from a common crystal-controlled source by harmonic multiplication or successive stages of up-conversion are necessary. Once this on-going effort provides MIC functional modules with acceptable rf performance, the use of microwave integrated circuitry will result in low-cost production and a high degree of reproducibility.

Acoustic surface wave devices are another critical aspect of the successful implementation of the channelized receiver. Small IF delay modules are required to permit rapid switching of an rf multiplexer to the appropriate rf channel. This high speed switching can retain a high probability of intercept while reducing complexity. Delay modules utilized as channelized filters is another area under investigation. Finally, a look at Large Scale Integration (LSI) is being taken to provide the control structures necessary for microsecond video processing. In summary, the channelized receiver offers the optimum capability to combine rapid recognition/reaction time, high probability of intercept, and high quality data required for future EW receiving systems.

Author: Terry Harper
Mr. Harper is also the author of the Airborne Rotary DF Antenna Systems article which appeared in the March/April 1975 issue of Tech-notes. His biography describes his extensive experience in the antenna and ECM areas and can be found in the March/April issue.

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