A Review of Current and Future Components for Electronic Warfare Receivers

JEFFREY H. COLLINS, FELLOW, IEEE, AND PETER M. GRANT, MEMBER, IEEE

***Abstract*—This paper addresses the role of conventional and new components in passive electronic warfare (EW) receivers. The various areas of EW are defined before restricting the discussion predominantly to the radar intercept problem at microwave frequencies. The operational parameters of conventional components are then reviewed including the multiplexer; crystal video, instantaneous frequency measurement (IFM), and scanning superheterodyne receivers. The significance of modularity, digital control, and hybrid combinations of components is highlighted. A brief description follows of the operational Cutlass EW equipment. New components based on surface-acoustic waves (SAW) and acoustooptic (AO) Bragg cells are then presented and their particular importance in channelized receivers, IFM's, and microscan receivers noted. Finally, a number of conclusions are drawn covering likely trends in EW receivers and the need for continuing development of large-scale integrated (LSI) circuits for signal sorting and overall digital management.**

I. Introduction

THIS PAPER is dedicated to a review of both conventional (current) and new (future) componentry for deployment in electronic warfare (EW) systems and specifically to the key function of electronic support measures (ESM). The scenarios and definitions within EW are given in Section II. This is followed in Section III by a brief description of ESM requirements and architecture. Section IV delineates the properties of conventional components for ESM receivers. Their utilization is illustrated in Section V for a typical ESM equipment, namely the shipboard Decca Cutlass system. Section VI reviews the advantages and disadvantages of the new SAW and acoustooptic (AO) componentry for use in intercept receivers. Finally, Section VII draws conclusions covering likely trends and the need for continuing development of large-scale integrated (LSI) circuits for signal processing and digital management in ESM equipments.

II. Electronic Warfare—Scenario and Definitions

Modern military planning now includes provisions to protect men and equipment from electromagnetically controlled weapon threats. Investment in electronic warfare (EW) techniques for this purpose is colossal as witnessed by the expenditure of over two billion dollars by the non-Communist world in 1976. EW takes many forms, such as degrading the performance of a hostile radar, intercepting and disrupting enemy communications, decoying aircraft and ordinance—and the newer science of degrading the enemy's perception of the tactical area. Spurred by the recent wars in South-East Asia and the Middle East, EW has matured out of the "black box" stage to become a vital element in military strategy when used in concert with the other assets at the disposal of military commanders.

There are three basic subsets to the overall discipline of EW, namely: electronic support measures (ESM), electronic countermeasures (ECM), and electronic counter countermeasures (ECCM). These may be defined as follows [1].

ESM: Actions taken to search for, intercept and locate, and analyze radiated electromagnetic energy for the purpose of exploiting these in support of military operations. ESM encompasses electronic intelligence (ELINT), for example, information gathering on weapon threats; communications intelligence (COMINT); signal intelligence (SIGINT), a generic term including ELINT and COMINT; and radiation intelligence (RADINT) derived from spurious emissions, such as missile flares. ESM is entirely passive being confined to signal reception.

ECM: Actions taken to prevent or reduce an enemy's effective use of the electromagnetic spectrum. ECM includes jamming and deception, both manipulative and imitative.

ECCM: Actions taken to retain the use of the electromagnetic spectrum despite a hostile force's use of ECM techniques.

EW techniques are applied throughout land, airborne, and shipborne environments. The electromagnetic spectrum commonly covered ranges from HF to microwave frequencies of 40 GHz and above, and now encompasses optical frequencies with the advent of infrared-controlled weapons. The scope and nature of EW necessarily demands that this paper is highly restrictive and unclassified. However, ESM receivers are key to all EW suites. Therefore, the primary aim of the paper is to review the impact of newer componentry, based on surface-acoustic waves (SAW) and acoustooptic (AO) Bragg cells, in relation to "in-service" componentry for utilization in digitally controlled ESM receivers for ELINT purposes operating up to 18 GHz.

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The authors are with the Department of Electrical Engineering, University of Edinburgh, Edinburgh EH9 3JL, Scotland, UK.

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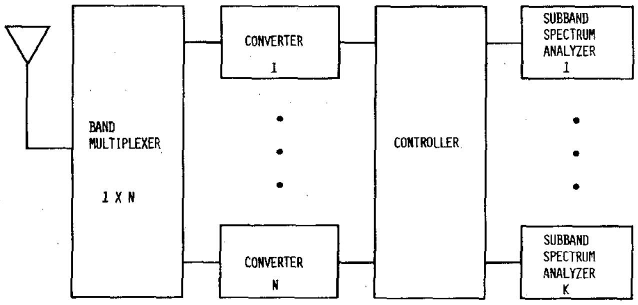


Fig. 1. Typical ESM intercept receiver architecture.

III. ESM Receiver Requirements and Architecture

The requirements on modern ESM receivers [2] are formidable. For radar intercept they must have an instantaneous frequency coverage of 0.5 to 18 GHz, a sensitivity of better than -60 dBm, an instantaneous dynamic range of >50 dB and a frequency resolution of order 1 MHz. A diversity of signals must be handled with high probability of intercept (POI) and low false alarm rate (FAR). These signals include pulsed, CW (Doppler), frequency agile, pulse repetition interval (PRI) agile, and intrapulse modulation (chirp, biphase, and spread spectrum). Cost, size, and complexity considerations dictate that as many tasks as possible be handled by one receiver. These tasks include threat warning, threat analysis, signal analysis, and direction finding. In addition, the receiver must be able to selectively filter a dense signal environment to allow the processing of relevant signals at optimum efficiency. Ideally, ESM receivers should have a hardware design independent of the threat scenario but with adaptive software and modularity of construction, to accommodate system growth and maturing technologies.

The architecture of a typical ESM receiver is shown in Fig. 1. The frequency band is divided into N sub-bands by power dividers and multiplexers followed by down conversion to a common IF frequency. Each sub-band is directed by a controller to one of K spectrum analyzers to obtain the necessary frequency resolution.

IV. Conventional Componentry for ESM Equipments

A. Aim

This section delineates componentry based on established technologies that is now being, or about to be, applied in the receivers of ESM equipments for signal and spectrum analysis. Following the essential multiplexers, the basic receiver components such as crystal video, instantaneous frequency measurement (IFM), and the scanning superhet are discussed and their relative merits identified. Some observations are made on the IFM-steered superhet for signal selection under computer control and the impact that both microwave integrated circuits (MIC's) and LSI circuits are having on receiver miniaturization.

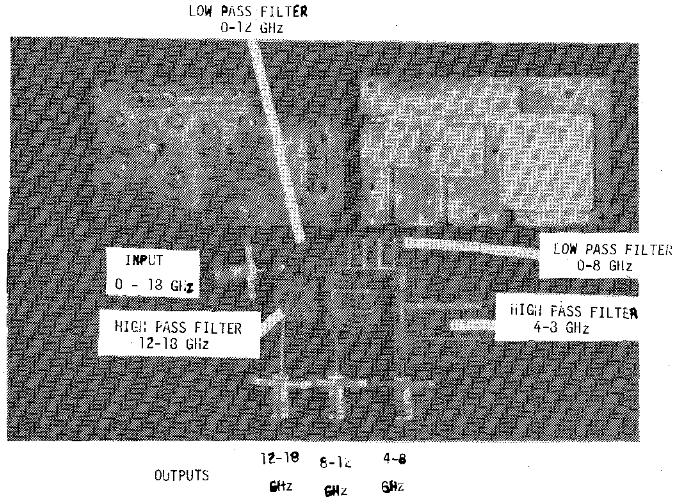


Fig. 2. Contiguous triplexer for 4–8, 8–12, and 12–18-GHz bands realized in suspended substrate stripline. (Photograph courtesy of Filtronic Components, Ltd., Leeds, UK.)

B. Multiplexers

Multiplexers provide the front-end key to signal sorting in ESM systems. Realizations are readily available in coaxial-line technology. However, due to the frequent requirement for accurate matching between components, great skill is necessary in their assembly and alignment. Recently, low-temperature coefficient suspended substrate stripline configurations have been built [3] using printed-circuit board techniques. The substrate used is 0.005-in RT/Duroid 5880. A triplexer, Fig. 2, covering the bands 4–8, 8–12, and 12–18 GHz has been made by the accepted architecture of the "diplexer cascade" [4] with high-pass and low-pass filters providing frequency crossovers at 12 and 18 GHz. To minimize impedance variations the odd-degree generalized Chebyshev prototype is used. The triplexer characteristics are input VSWR<1.8 from 4–18 GHz; passband insertion loss <1 dB, out-of-band rejection>40 dB, except within 5 percent of crossover frequencies where the insertion loss is 4.5 dB. This triplexer is packaged into $2.4\times1.45\times0.5$ in. Tests on the 8-GHz low pass have shown an acceptable ±0.3-percent variation in crossover frequency for a temperature change of 100°C. This stable result can be ascribed to the filter's resonators being essentially in air.

C. Crystal Video

The wide-open crystal video receiver consists of a low-noise RF preamplifier, a video detector (square law), and a log video amplifier. Advantages are high POI, simplicity, and compactness. Its disadvantages are inability to discrimate between different frequencies, rapid degradation in dense signal environments, and susceptibility to jamming. Upgrading by adding a tunable yttrium iron garnet (YIG) filter to TRF crystal video gives a frequency resolution between 5 and 70 MHz. However, POI and FAR are traded as the YIG filter is switched in and out. Also phase

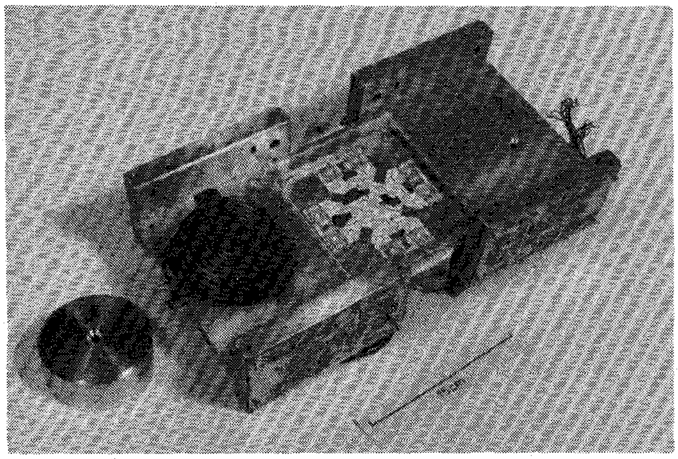


Fig. 3. Detail of microwave integrated circuit and one cable delay path for digital instantaneous frequency measurement (DIFM) component. (Photograph courtesy of Phillips Research Laboratories, Redhill, UK.)

and frequency modulation present in exotic signals go undetected.

D. Instantaneous Frequency Measurement (IFM)

The IFM (Fig. 3) is akin to crystal video except that a bank of MIC-based delay-line discriminators [5], preferably temperature compensated, are employed to obtain frequency information. The IFM is preceded by a limiting RF amplifier to increase sensitivity and dynamic range. Harmonics of a single signal generated by limiting are removed by bandpass filters. In the dual-signal case, there is some signal suppression and the intermodulation components generated are suppressed by normal discriminator action, due to the high degree of spectral symmetry.

Typical IFM throughput delay is 150 ns with pulsewidth measurement down to 60 ns. Advantages are wide instantaneous bandwidth, POI approaching 100 percent, and an ability to detect frequency agile and chirped signals. Inherent disadvantages are high FAR in dense signal environments and CW susceptibility. These may be modified by suitable receiver design [6]. The compact digital IFM (DIFM) is now emerging. One arrangement [7] for the 2- to 4-GHz band uses a bank of six discriminators followed by video amplifiers and analog digital (A/D) conversion. Three channels of high-speed parallel conversion develop a Gray-coded digital frequency word to format into an 11-bit number and output the signal frequency to an accuracy of 2.5 MHz. This processing is realizable in LSI bipolar technology. Designs are underway to integrate this DIFM into a 64-in^3 package.

E. Scanning Superhet

The scanning superheterodyne receiver, the workhorse of ESM receivers, commonly consists of a YIG preselector followed by local oscillator (LO) based downconversion, IF amplification, and demodulation. Advantages are high sensitivity, low FAR, good frequency resolution, flexibility to new threats, and reasonable jamming immunity. Disadvantages are poor POI to single pulses, unless fast-scan or smart-scan techniques are used, and blindness to frequency agile signals. Fast-scanning techniques are limited by IF filter response, LO, and preselector sweep rates; and further frequency resolution can be sacrificed. Typical scan rates are 100 MHz/ms for a YIG preselector and 100 MHz/100 ns (10^4 times faster than a YIG) for a varactor-tuned LO. Smart-scan techniques depend on preprogrammed search techniques to determine threats with minimal acquisition times.

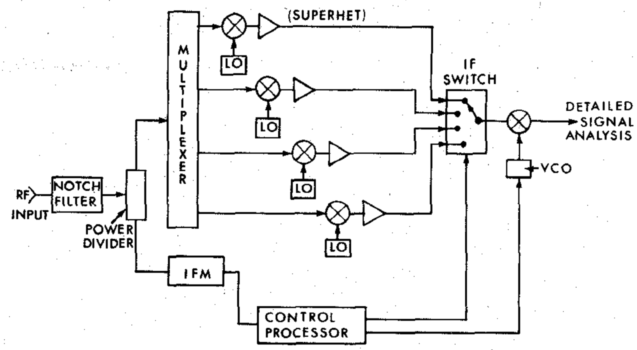


Fig. 4. Schematic of digital IFM steered superheterodyne receiver. The addition of IFM gives enhanced intercept probability over stand-alone superheterodyne receivers.

A recently reported [8] miniaturized receiver for 0.5 to 18 GHz employs an instantaneous IF bandwidth of 500 MHz, linearized varactor-tuned GaAs FET LO's, and all MIC construction. It is projected to occupy <100 in^3 and to have power consumption <20 W. Frequency accuracy is better than ± 0.5 percent. This receiver has poor frequency accuracy, is prone to spurious signals in high level, high signal density environments, and has little immunity to jamming. However, it could constitute a significant front end for the SAW modules described in Section VI.

F. DIFM Steered Superhets

It has recently been recognized that the different shortcomings of the DIFM and superheterodyne receiver may be largely overcome by deploying them in combination. The solution adopted, Fig. 4, uses a power divider to simultaneously feed one DIFM and a channelized bank of four superhets. The output from the signal excited superhet channel is rapidly switchable (<40 ns), by command from a preprogrammed processor actuated by the DIFM output, into a single downconverter employing a fast tuning and set-on VCO. The detailed parameters of unknown signals are thereby extracted. This approach avoids the extreme loss of sensitivity and multiple ambiguities associated with folding multiple RF bands into the same signal processing path.

Four further points are worthy of note. First, CW capture of the DIFM is overcome using an automatically tunable notch filter at the signal input port. Second, the trend towards modularity (see Section III), or "common processing modules," has led to downconverting all signals into a standard wide IF such as 2 to 4 GHz and operating the system on a time-shared basis. Third, advances in GaAs FET amplifier technology, in regard to low noise figure and high intercept point, have led to their wide usage in such modules. Finally, the key to operating this ESM system is "digital management" made possible by the advent of the microprocessor.

This "modular" ESM system [8] has a sensitivity of −85 dBm, a dynamic range of 70 dB, frequency accuracy of a few megahertz, pulsewidth resolution to 100 ns, and a resolution of 30 MHz for two signals differing in power by 50 dB. The throughput rate is 1 million pulses per second.

V. The Cutlass ESM System

The unprecedented growth in complex naval weapon systems over the past decade has convinced most naval planners that even in a Third World environment of fast strike craft and frigates, the survivability of surface ships is now in question. The Decca Cutlass ESM system [9] (see Fig. 5), operating over 1–18 GHz, is designed on a cost conscious basis for this dense signal EW scenario. It is of modular construction and integrates an advanced jamming capability together with the firing of chaff.

Bearing to 5° rms accuracy is measured using a six-port amplitude comparison system. Each port consists of a pair of spiral antennas covering 1 to 4 GHz and 4 to 18 GHz. The outputs from the antennas are multiplexed into the frequency bands 1 to 2 GHz, 2 to 4 GHz, 4 to 8 GHz, 8 to 12 GHz, and 12 to 18 GHz, and fed to crystal video detectors. p-i-n diode modulators are used to enable bearing measurement on CW signals. The bearing resolver provides digital bearing, amplitude, and pulsewidth.

The frequency of incoming signals is measured by a DIFM using an omnidirectional antenna unit. Signals in each band are fed into limiting amplifiers and on to digital frequency discriminators which output a digital word representing incoming RF. The frequency discriminators also detect and measure CW signals.

The first stage of signal de-interleaving is carried out using the parameters of frequency, bearing, and pulsewidth. Where frequency or other parameters are not sufficiently well defined for de-interleaving, pulses pass on to the next stage where association on a simple time of arrival (TOA) basis is attempted. The TOA of every pulse is compared with all subsequent pulses and arithmetic subtractions are made to establish pulsetrains of fixed pulse interval. Pulses which have not been so recognized are fed to the complex de-interleaving stage, where a computer is used to examine for any cyclic characteristics in the group of pulses. This stage is used in order to recognize pulse trains from radars using ECCM techniques such as staggered or jittered pulse interval or frequency agility.

The amplitude of pulses in a pulsetrain from a particular radar will vary cyclically in a way dependent upon the scan type. The processor is used to identify those and to measure the scan period or the frame rate of a complex scan.

Successfully de-interleaved pulses are given a track number. The input to the radar identification unit consists of track number, frequency, bearing, amplitude, pulsewidth, pulse interval, agility, scan period, and scan type. The output from the unit is an identification of radar type, its threat significance, and the confidence level of the identification. These outputs are achieved by comparing the input parameters with a store of known radar types and their parameters, which are loaded into the computer core store from a tape reader. The tracking store has a capacity of 150 detected radars. Normally, details of the 25 most serious threats are displayed automatically. The maximum incident pulse density for 100-percent POI is 130 000/s.

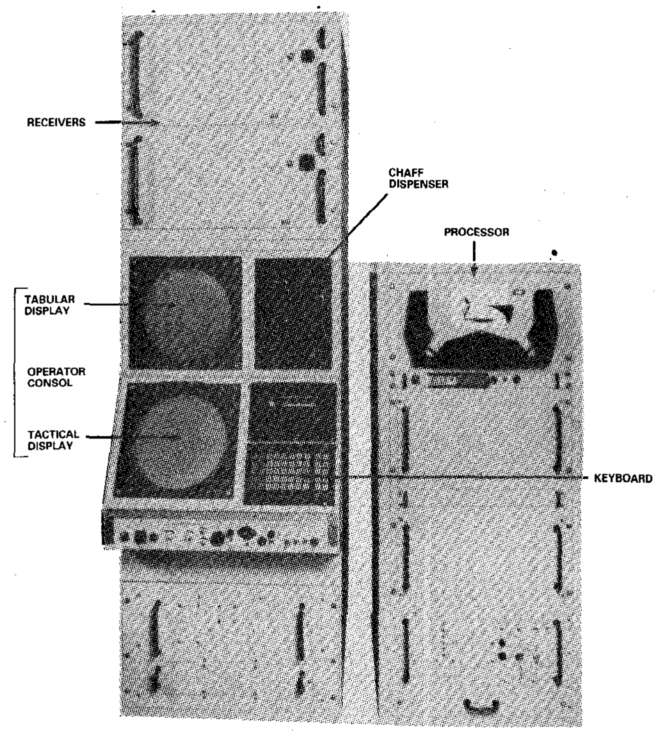


Fig. 5. The operators console of the Cutlass ESM equipment. (Photograph courtesy of Racal Decca Radar, Hersham, UK.)

VI. New Componentry for ESM Receivers

A. Introduction

Surface acoustic wave (SAW) devices offer many advantages for the realization of ESM receivers [10]. The small physical size of SAW bandpass filters permits compact IF channelized modules to be designed using contiguous filter banks, where 4–32 filters are fabricated on one substrate and mounted in a single package which need be no larger than a TO3 header. Sophistication in the filter design can be used to implement SAW IFM's within the filterbank. SAW techniques can also be used to extend the scanning superhet approach into a microscan or compressive receiver, for fast, e.g., 1 μs, spectrum analysis over wide >100-MHz bandwidths. Although compressive receiver techniques have been understood for some 15 yr, it is the recent development of SAW dispersive delay lines providing chirp bandwidths of 1 to >250 MHz with dispersive delays from <1 to >100 μs and center frequencies from 10 MHz to 1 GHz which has rekindled interest in these techniques. The unique attribute of SAW is versatile controllable design coupled with planar microelectronic-based manufacturing techniques, ensuring both high precision performance and reproducibility. Before the advent of SAW, favored dispersive delay lines were HF/VHF acoustic realizations [11] based on steel strip or perpendicular diffraction/wedge structures in fused quartz and the electromagnetic realization at microwave frequencies based on the folded-tape meander line [12]. Each of these had distinct design, operational, and manufacturing difficulties. As a result, SAW technology has now taken over as the preferred realization of dispersive delay lines notably for radar pulse compression and for specialized range of compressive receivers.

This section reviews SAW channelized and compressive receiver design techniques in addition to studying the emerging spectrum analyzers based on acoustooptic Bragg-cell diffractors.

B. SAW Channelized Receiver

In a channelized receiver the received signal is input in parallel to a bank of bandpass filters each designed to operate at a different center frequency. Filters are normally designed as a contiguous bank with individual filter crossovers at the 3-dB points (Fig. 6). Sampling the filter outputs, at a rate comparable to the reciprocal of the filter bandwidths, provides a direct measurement of the input frequencies. SAW filterbanks [13], Table I, have been designed on high coupling lithium niobate substrates using either frequency-selective reflective arrays [14] or multistrip couplers [15] for integral multiplexing but recently attention has focussed on the more temperature-stable (e.g., quartz substrates) filters. The problems of multiplexing the input into the individual filter [16] also limits the maximum number of discrete filters in each module to typically 16 or 32, when the overall insertion loss and amplifier requirements are taken into account. SAW techniques can readily realize individual filters [17] with <1- to >50-MHz bandwidth operating at VHF/UHF. Fig. 6 shows the composite response of an 8-channel SAW filterbank, which is compared in Table I with other reported SAW channelizers. Dynamic ranges are typically 40–60 dB.

Particular problems which impact ESM receivers are the wide variation in input signal types, e.g., CW, pulsed, spread spectrum, coded, etc. For high resolution analyzers, these latter signals can result in detection not only in the channel appropriate to the center frequency but also on adjacent channels due to the spectral energy spread. One method to avoid pulsed signals being detected as multiple inputs is to design the SAW filter with a resolution appropriate to the shortest expected pulsewidth. SAW IFM techniques, see Section VI-D, may then be used within the filterbank for accurate center-frequency measurement of longer duration pulses.

Two filterbank design techniques, based on banks of wide- and narrow-band filters [18] on identical center frequencies, also exist for overcoming this multiple detection problem. In the guard band approach [19], the two

Fig. 6. Composite response of 8-channel SAW filterbank. Vertical scale: 10 dB/div. Horizontal scale: 10 MHz/div. (Courtesy of Hughes Aircraft Company, Fullerton, CA.)

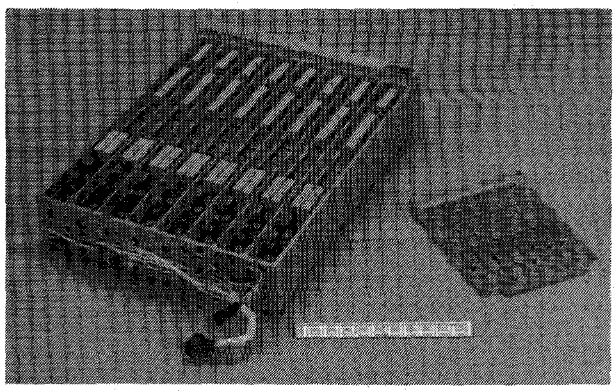


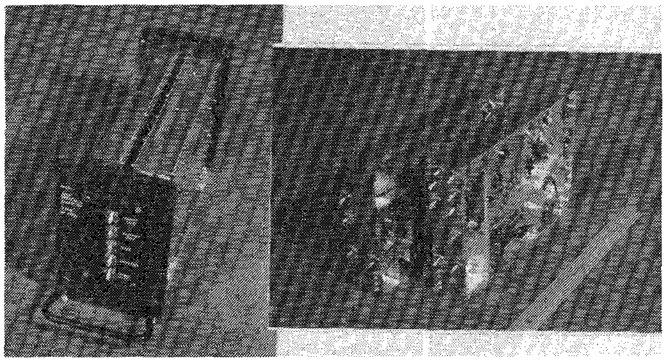
Fig. 7. 8-channel filterbank receiver module showing, on left, initial version based on miniaturized *LC* filters and, on the right, the equivalent module when SAW frequency filters are incorporated. This module covers an 80-MHz bandwidth centered on a 280-MHz IF, and incorporates the guard band design technique [18] within the channelizer. Sixteen such modules may be used in parallel to obtain 1-GHz instantaneous bandwidth. (Photograph courtesy of Watkins Johnson Co., Palo Alto, CA.)

TABLE I
COMPARISON OF TYPICAL PARAMETER FOR SAW FILTERBANKS

References	[18]	Fig. 6	[19]	[29]	[30]
Center Frequency, in megahertz	325	266	234	350	625
Number of Filters	16×2	8	4	12	9
3-dB Filter Bandwidths, in megahertz	10 or 20	9	4	9	31.25
Nominal Insertion Loss, in decibels	20	36	20		15
Variation Insertion Loss Between Filters, in decibels	±2	±1.5	±1	±2	
Out-of-Band Rejection, in decibels	>50	40	50	40–50	40

filterbanks are connected in parallel and the outputs of both wide- and narrow-band filters for each frequency are separately detected and fed into a comparator [18]. This suppresses the detected output when the signal still falls within the passband of the wide-band filter but is outside the passband of the narrow-band filter. Thus detection only occurs for spectral components within the passband of the narrow-band filter. This requires three banks of N SAW filters plus amplifiers, limiters, detectors, and comparators to realize an N-channel receiver. Fig. 7 shows the typical hardware involved in constructing such an 8-channel filterbank. The alternative approach [20], which uses only two banks of N SAW filters, connects each of the individual wide-band filters into a limiting amplifier prior to entering the respective narrow-band filters. With suitable choice of filter center frequencies and bandwidths [20] adjacent channel comparisons from N such channels identifies the input frequency to an accuracy of $\Delta F/2$, where ΔF is the bandwidth of the individual narrow-band channelizer filters. This provides a consequent resolution improvement of two over the earlier guard band approach and also gives more efficient utilization of SAW hardware.

A SAW ESM receiver operating over the radar bands would require an instantaneous bandwidth of ~1 GHz with a resolution approaching 1 MHz. This cannot presently be achieved with a single 1000-channel filterbank and hence a modular approach is envisaged (Fig. 1) where the input frequencies are separately down-converted into a number of identical IF modules each covering a bandwidth of approximately 100 MHz. The multiplexing of the input channels [21] can take many distinct approaches, and the precise receiver configuration [20] is dependent on application. For ground-based equipments where cost, size, and weight are less important then all channels can be implemented in hardware to give full 100-percent POI. Alternatively, bandfolding can be adopted to reduce the number of IF analyzer modules, at the expense of reduced sensitivity [22]. In some signal environments, the individual analyzer modules can be time-multiplexed via a call switch to overcome the reduced sensitivity of bandfolding. Airborne equipment normally requires some choice between the options, and the precise configuration is heavily dependent on the EW scenario.



(a) (b)

Fig. 8. SAW compressive receiver with B=25-MHz bandwidth and 50-kHz resolution. Photograph (a) shows the receiver in $\frac{1}{2}$ ATR case with cover removed while (b) illustrates the detailed construction of the two subassemblies. (Photographs courtesy of Racal-MESL, Ltd., Edinburgh, UK.)

TABLE II
RACAL-MESL 1748 SAW SPECTRUM ANALYZER SPECIFICATION

Bandwidth (1 dB)	25 MHz
Resolution (3 dB)	50 kHz
Spectral ripple	1 dB peak to peak
Maximum input signal level	−16 dBm
Dynamic range (sidelobe limited)	35 dB
Dynamic range (noise limited)	60 dB
Maximum output signal	1.28-V peak
Input-signal sample duration	40 μs
Output data rate	1 MHz/μs
Duty cycle	50 percent
Temperature range	−10°C to +50°C
Power consumption	16 W
Weight	5.4 kg
Size	125×195×330 mm ($\frac{1}{2}$ ATR short)

C. SAW Microscan Receiver

The compressive receiver [23] accomplishes spectrum analysis or Fourier-transform processing via the chirp transform algorithm [24], where a discrete time sample of input signal is multiplied by a chirp waveform and either the sum or difference product term is convolved in another dispersive chirp filter. There are two basic types of analyzer, one where the multiplying chirp is of shorter duration than the convolver [25] and the second where the multiplier is longer [23].

For communications ESM (COMINT), where signals comprise either CW or slow frequency hopped waveforms and resolution close to the 25- or $12\frac{1}{2}$-kHz channel spacing is desired, the second approach is favored as it gives the highest resolution and can be easily weighted for sidelobe suppression. For radar ESM (ELINT), where there is a high percentage of pulsed emitters, it is necessary to incorporate a preconvolver into the long multiplier configuration [26], and hence the short multiplier offers a simpler hardware realization. However, the practical implementation of weighting, for sidelobe suppression, does present significant problems [24].

A key advantage of these compressive receivers is their relative simplicity as they are equivalent to 30–1000 channel filterbanks operating at IF's in the range 20–500 MHz covering bandwidths of 1–>200 MHz with a resolution of 25 kHz–2 MHz. Any one SAW implementation will have parameters constrained by precise chirp filter performance within these bounds. Fig. 8 shows the compact size of a SAW compressive receiver which offers 25-MHz bandwidth and 50-kHz resolution, i.e., it is equivalent to a 500-channel filterbank. Full receiver specification is given in Table II. SAW compressive receivers typically offer 60–80-dB noise-limited dynamic range [26] but compressed pulse sidelobes limit the dynamic range to 35–45 dB in channels close to (i.e., within a few resolution cells) a detected signal.

A difficulty with the compressive receiver is the single fast serial readout of frequency, which places severe demands on the speed, cost, and power of the analog-to-digital converter and other digital interface circuits in the pulse sort processor. In fact, limitations on the speed of LSI interface circuits currently restrict this receiver to bandwidths of 50–100 MHz which is less than the current capabilities of SAW devices. Since the compressive receiver uses a discrete time sampled input, additional hardware is required to provide asynchronous operation and 100-percent POI.

One advantage of the compressive receiver is that high-level narrow-band jammers can be suppressed by time-domain processing such as gating [10] or soft limiting. When such techniques are incorporated between a forward and reverse transform processor [24] they can give 20–40-dB rejection of narrow-band jammers [10] with only minimal degradation to other signals. Multiple transform processing based on SAW techniques has many other applications [24] but the power cepstrum [27] is particularly interesting in ESM for detection and classification of coded pulsed emitters. The SAW implementation now extends this established audio and seismic signal-processing technique to 10's of megahertz bandwidths. In the future, SAW-based complex cepstrum processing could offer the possibility of recovering radar waveforms which are distorted by multipath and reverberation.

D. *SAW IFM*

In comparison with current IFM's, which are wide open microwave components with several gigahertz bandwidth, the SAW discriminator or IFM is an IF bandpass device whose bandwidth is controlled by SAW filter capabilities [17]. The simplest SAW IFM [28] comprises two bandpass filters with a small differential delay between filters. Feeding the outputs into a double balanced mixer provides a direct analog measurement of fine frequency. Alternatively, with twice the SAW hardware, the filter outputs can be summed and differenced at IF prior to detection and comparison to yield a digital output giving course frequency measurement [28] with wider input dynamic range. Extension with additional three or four discriminators whose delays are integer multiples of the first IFM can output a digital truth table defining fine frequency [22], [29], [30]. Such banks of SAW IFM's are capable of providing resolution into the range 10 MHz–50 kHz. Due to the inability of IFM's to unambiguously handle multiple-input signals, such SAW discriminators would have to be incorporated into the output of a SAW channelizer or compressive filter.

E. *Acoustooptic Bragg Cells*

Another approach to the design of ESM receivers is to use acoustooptic (AO) techniques [31] to implement the Fourier analyzer. These processors, which are based on the AO Bragg cell [32], interact a propagating acoustic wave with a focused optical beam to give a diffracted output, Fig. 9, whose deflection is dependent on frequency and whose amplitude is proportional to the intensities of the signals present in the acoustic wave. The Bragg cell frequency resolution is approximately equal to the reciprocal of the acoustic transmit time through the crystal. Detection is performed after focusing the deflected optical beam on to a photodetector array, which normally utilizes CCD components.

Two distinct implementations of the AO Bragg cell analyzer are possible, the bulk [33] and the integrated [34]. The approach using a bulk acoustic wave has been studied for a number of years and it is available today in commercial equipment [35]. These AO analyzers [33] can typically handle 5- to >500-MHz bandwidth in a processor which is equivalent to a 100–1000-point transform giving resolutions in the range 20 kHz to 1 MHz. The precise bandwidth and resolution is governed by the detailed cell de-

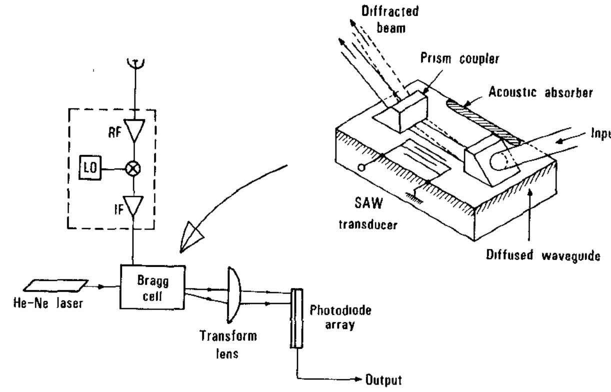


Fig. 9. Schematic of Bragg-cell receiver and illustration of planar device. (Courtesy of Standard Telecommunication Laboratories, Harlow, UK.)

sign, in particular the acoustic propagation medium. Lithium niobate L100, gallium phosphide L110, and tellurium dioxide L001, are all applicable to analysis for ELINT where resolution of 1 MHz is required. Conversely, the lower velocity tellurium oxide S110 gives the improved 20-kHz resolution required in COMINT.

The operating parameters for these AO Bragg cells are broadly similar to SAW filterbanks and compressive receivers but problems are experienced in obtaining good amplitude weighting of the input acoustic beam to give comparable spectral sidelobe suppression, to that achievable with SAW components. Cell efficiency and photodetector sensitivity is currently limiting dynamic ranges to typically 30 dB. These deficiencies apart, the wide bandwidth and simplicity of these AO components has already resulted in their being used commercially.

Current bulk Bragg cell analyzers incorporate integrating photodetectors with $\frac{1}{2}$–1-ms periods which introduce slower receiver response and reduced sensitivity for pulsed and other low-duty-cycle signals when compared with SAW-based receivers. Integrating detectors also introduce problems when measuring the characteristics of individual pulsed emitters in dense ELINT scenarios. Development is now aimed at overcoming this limitation with a peak detecting array.

In order to simplify the readout from the photodetectors, there is a trend to interface them with a digital buffer store [36] which performs data manipulation on a detector-by-detector basis to give a digital output which is compensated for cell calibration errors and gain variations. The trend towards peak detecting arrays will require a considerable increase in speed and hence power of this digital interface processor.

Although the bulk analyzer is small compared to digital equipments there is still a thrust to develop rugged guided wave hybrid or integrated AO analyzers [34] where ultimately the laser, focusing optics, acoustic propagation, and detection are all integrated onto a single substrate. The goal is to develop an analyzer with 1-GHz bandwidth and 1-MHz resolution for airborne radar ESM. Substrate choice for a hybrid approach would favor $LiNbO_3$ which has well proven acoustic properties, while for an integrated analyzer

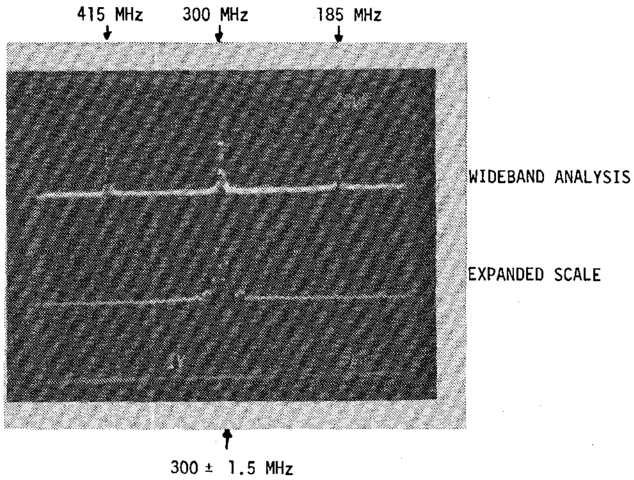


Fig. 10. Output from Bragg-cell receiver with tone inputs. Upper trace shows four tones at 415, 298.5, 301.5, and 185 MHz. Lower trace shows an expanded scale resolution of adjacent tones at 298.5 and 301.5 MHz. Horizontal scale: upper trace—35 MHz/div; lower trace—8 MHz/div. (Photograph courtesy of Standard Telecommunication Laboratories, Harlow, UK.)

silicon on sapphire (SOS) [34] is currently attractive for detector fabrication.

With $LiNbO_3$, the optical waveguide is formed by diffusion of materials, such as titanium, to give a surface film with a differential refractive index. Focusing requires diffraction-limited geodesic lenses which are etched into the substrate by an ultrasonic machining process. In the SOS substrates, the optical beam propagates in a sputtered glass waveguide on the surface. The acoustic transduction requires a piezoelectric zinc oxide film overlay, and the Bragg cell is realized by a tantalum pentoxide (Ta_2O_5) diffusion. Focusing is achieved by deposition of a similar Ta_2O_5 film onto the optical waveguide to implement a Luneberg lens. Both these approaches require a tilted SAW transducer array [31] comprising several sections operating at different center frequencies to maintain the optimum Bragg angle with frequency and to give the required flat response over the 1-GHz design bandwidth. Fig. 10 shows the typical output from a surface-wave Bragg cell analyzer employing an integrated optical waveguide. The electrical output is obtained with a 1024-element CCD photodetector which clearly shows the four CW VHF/UHF inputs which cover a 230-MHz bandwidth.

Currently, both approaches are hybrid, requiring an external coherent laser source to be butt-edge coupled into the analyzer. (In the lithium niobate substrate approach the detectors must also be coupled at the output.) Ultimately, the substrate is likely to be replaced by gallium arsenide, which is piezoelectric and also offers the possibility of integrating the laser to realize a true monolithic spectrum analyzer.

VII. Conclusions

This paper has addressed conventional and new componentry for ESM receivers with emphasis on ELINT where frequency resolution of a few megahertz is required. It is apparent that, even with the trend to modular construction, there will be no single combination of componentry which satisfies all EW scenarios. Nevertheless, modularity promises widespread usage, optimized performance against specification, and ready availability of hardware.

The newer componentry based on SAW implies that the channelized receiver can become a reality in ELINT while the SAW microscan seems more naturally fitted to COMINT. SAW IFM's impact both application areas. However, the SAW microscan approach leads to formidable high serial data rate signal sorters and their ultimate realization in LSI technology. Acoustooptic Bragg cells again have the significant ability to implement a spatial channelizer (typically 1000 channels) and, by choice of material, frequency resolutions can be made compatible with either ELINT or COMINT. However, its main problem lies in poor sensitivity to pulse signals and relatively long response times.

Space has precluded discussion of the new form of YIG componentry utilizing magnetostatic wave (MSW) propagation in epitaxial YIG films. This planar technology is akin to SAW in realizing nonrecursive transversal filters yet advantageously [37] it offers tunable properties directly at microwave frequencies. Thus in the future, MSW might well impact ESM receivers through channelized filters, IFM's, and microscan.

It is apparent that major advances in hybrid integration will take place irrespective of the componentry deployed in "common modules." These will encompass MIC's, custom LSI/VLSI for both analog and digital signal processing, on-board computers, microprocessor command and control; and the newer componentry of SAW acoustooptics and MSW. However, the difficulties in economically using conventional receivers to cover the band 18–40 GHz in $\frac{1}{2}$- or 1-GHz steps while still maintaining high POI is recognized. Finally, ESM receivers for threats at millimetric-wave frequencies and infrared seem destined to receive significant emphasis.

Since the preparation of this paper, an expanded manuscript has been published [38] which covers in greater detail the requirements and capabilities of current EW receivers in the specific scenarios of communications (COMINT) and radar (ELINT). In addition, this paper contains further comparisons of the technical capabilities of SAW channelizers, compressive receivers, and acoustooptic Bragg cells.

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