Potential Applications of Acoustic Matched Filters to Air-Traffic Control Systems

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Invited Paper

Abstract—**The potential role of acoustic matched filters in the demanding field of civil and military air-traffic control (ATC) systems is examined. Highlighted are the problems of current ATC systems and the significant aspects of acoustic matched filters and their expeditious usage in modems employing band spreading for a multisubscriber environment and certain envisaged ATC systems deemed necessary for future traffic growth that could benefit materially from acoustic technology.**

I. Introduction

THE long-term applications of acoustic matched filters to the demanding field of civil and military air-traffic control (ATC) systems are examined. Highlighted is the fact that at current levels of air traffic, existing systems possess a capability just in excess of that required to handle the peak load of today, and further that although projected growth is to be handled in the short term by upgrading and supplementing present systems, particularly with computer complexes, such an approach does not represent a viable long-term solution. In logical sequence this paper contains three parts: current ATC systems in the United States, Great Britain, and Europe, and their basic deficiencies and lessons for future designs (Sections II through V); the significant and unique features of acoustic matched filters and their performance status as devices and in modem usage (Section VI); and envisaged ATC systems which are necessary to meet forecast traffic requirements emphasizing these systems that acoustic technology impacts (Sections VII and VIII). Liberal deployment of references for existing ATC systems serves to minimize the length of the paper, and the Appendix contains a glossary of commonly used ATC abbreviations.

II. Current ATC Procedures

Following the first powered flight of the Wright brothers on December 17, 1903, air traffic soon reached a congested state necessitating the imposition of procedural rules [1]. The control of air traffic requires the use of a multitude of equipment hardware encompassing ground-based surveillance and identification equipment to enable the controller to know the position and identity of aircraft, accurate onboard navigation equipment for pilot position determination, and voice communication equipment to handle message transfers between pilot and traffic control. The procedures adopted for civil ATC have evolved over many years through international cooperation [2] of government control bodies (e.g., the FAA and CAA) aided by the intrinsic global nature of air traffic. For example, European air-traffic handling systems have evolved by consultation between the major European organizations resulting in the Eurocontrol authority with exclusive responsibility for the upper airspace.

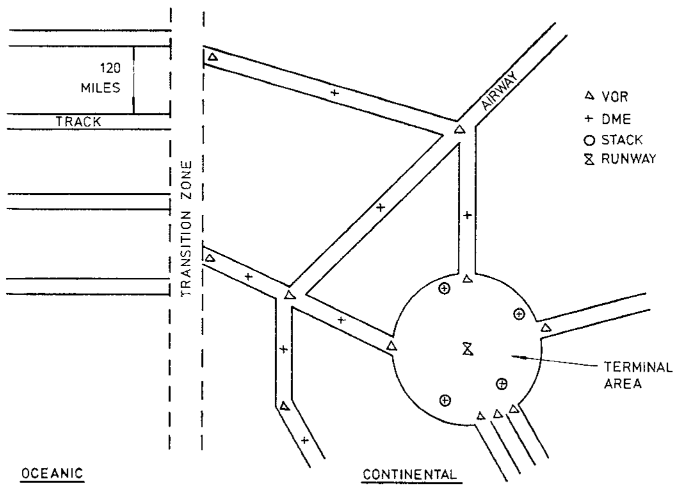

Fig. 1. Typical example of present airways system.

Current civil ATC can be subdivided into terminal, continental (overland), and oceanic areas (Fig. 1), all of which have a ground-based controller. Before entering an ATC system the airline must file a flight plan to enable the routing of each aircraft through the control network. Accepted flight plans are then entered as flight progress strips to enable controller monitoring of progress against schedule. Terminal area procedures [3] involve the scheduling of takeoffs and landings of aircraft to meet the available capacity. En route control [4] overland is accomplished by constraining the aircraft to fly along agreed airways. Transoceanic control involves a two-way structure of tracks or air corridors that are exclusively allocated across the North Atlantic by the oceanic planners [5]. Separation standards for all three areas are maintained by the ground-based controllers who possess exclusive ATC authority.

Military ATC [6] involves a more comprehensive surveillance facility requiring tracking of both friendly and enemy aircraft. With large areas of airspace reserved for military use there are fewer constraints on the pilot who exercises exclusive control requiring the incorporation of navigation, surveillance, and communication equipment of increased accuracy to meet the demanding requirements of intercept and strike maneuvers.

III. Classification, Functional Capability, and Operating Limitations of Existing ATC Systems

A. *Classification and Functional Capability*

Tables I and II detail current ATC equipments and frequency allocations in the three main areas of communications, navigation, and surveillance.

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TABLE I
CLASSIFICATION OF EXISTING ATC EQUIPMENT

	Communications	Navigation		Surveillance
		Radio	Other Techniques	
Line of Sight Short range (continental)	VHF radio	TACAN ILS DME VOR DECCA ADF console	compass sextant altimeter area navigation inertial	radar IFF/SSR ARTS/MEDIATOR MADAP
Long range (oceanic)	HF radio	LORAN OMEGA Doppler	inertial	onboard radio position reporting

TABLE II
FREQUENCY ALLOCATIONS FOR ATC EQUIPMENTS

Equipment	Frequency Allocation	Reference
OMEGA	10–14 kHz	[8], [9]
LORAN C/DECCA	90–110 kHz	[7]–[9]
ADF/CONSOL	200–1800 kHz	[9]
LORAN A	1.7–2.0 MHz	[7], [8]
HF communications	3–30 MHz	[7]
VHF FM communications	30–70 MHz	[7]
ILS (localizer)	108–112 MHz	[7]
VOR	108–118 MHz	[9]
VHF (civil)	118–136 MHz	[7]
UHF (military)	225–400 MHz	[7]
ILS (glide)	330–335 MHz	[7]
TACAN/DME	960–1210 MHz	[10]
IFF/SSR	1030–1090 MHz	[16]
SATCOM/radio navigation	1535–1660 MHz	[28]
Collision avoidance	1592–1622 MHz	[32]
Radar	2.75–3.60 GHz	[15]
Radio altimeter	4.2–4.4 GHz	[9]
MLS	5.0–5.25 GHz	[14]
Radar	9.07–9.50 GHz	[15]
Doppler navigation	8.75–9.50 GHz	[12]
MLS	15.4–15.7 GHz	[14]

Communications are handled by voice procedures on either a VHF or HF net [7] depending on the range to the ground-based antenna. DECCA, LORAN, and OMEGA are all examples of external reference hyperbolic navigation systems [7], [8] that utilize one-way ground-derived signal transmissions. The civil DME [9] and military TACAN [10] overland equipments operate by two-way interrogation of a ground-sited transponding beacon. Inertial [11] and Doppler [12] are examples of self-contained navigation equipments, although more expensive, inertial navigation systems are currently fitted as standard in the 747 [13] and are superseding Doppler equipment in 707 and DC8 aircraft. Primary [15] and secondary radar [16] (SSR for civil and IFF for military applications) are the fundamental equipments used for continental, en route, and terminal surveillance (Fig. 2).

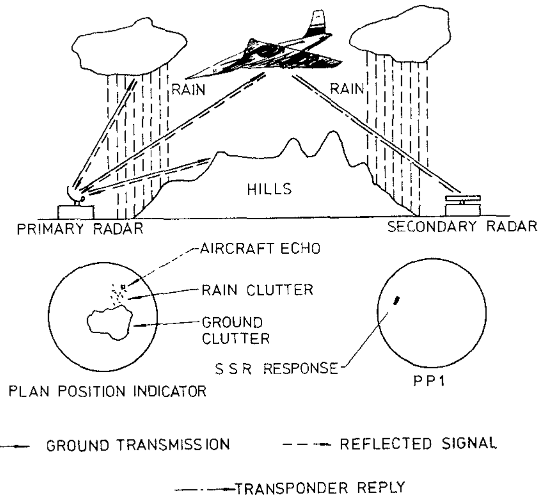


Fig. 2. Principles of primary and secondary radar.

Both civil computer-aided congested area (terminal control) systems, i.e., ARTS and MEDIATOR [17], and military systems, SAGE (United States) and LINESMAN (Great Britain) make extensive use of secondary radar to obtain accurate identification and authentication of primary radar returns.

B. Operational Limitations

Primary radar, whose coverage cannot extend to oceanic crossings like the Atlantic, is particularly subject to rain and ground clutter. Rain clutter can be reduced either by using an MTI system or with a wider bandwidth chirp waveform and pulse compression [18], thus reducing the range cell. Modest compression ratios, e.g., 25, are adequate, and surface acoustic wave (SAW) technology is readily applicable, particularly in airborne radar where size and weight are more significant.

Secondary radar [16] is not affected by clutter. Here an airborne transponder replies to the transmitted signal at a different frequency (Fig. 3). Confusion due to "fruit" and "garble," i.e., unwanted replies, is presently reduced by plot extraction on a PPI, although an alternative method using selective address (ADSEL or DABS) is also under development [19].

HF radio communication links over the North Atlantic are presently marginally reliable, provided a suitable "family" of channels is available to overcome propagation effects. The requirement for improved voice and data link facilities is apparent [20] due to the increase in subsonic air traffic and the introduction of supersonic aircraft. This necessitates consideration of new systems employing satellite repeaters [21].

Due to the requirement for high reliability in airborne equipment there is a built-in redundancy both of equipments

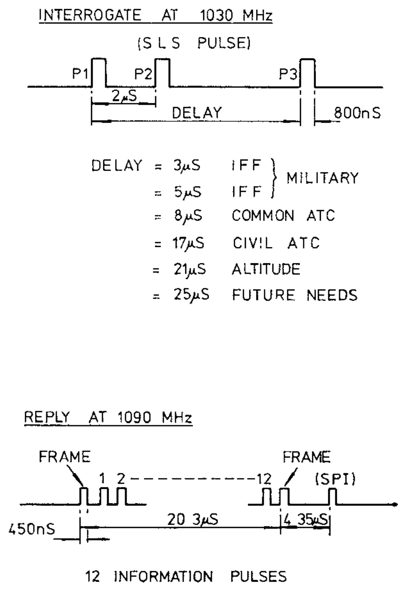


Fig. 3. Present SSR signal format.

and systems hardware, placing heavy pressure on both controllers and aircrew who must perform constant display monitoring. Several alternative schemes are under consideration to perform a level of integration of these equipments and displays in both military and civil environments.

IV. Projected Growth of Civil Air Traffic Indicating Further Deficiencies in Existing Systems

In the United States the projected aircraft fleet for the year 2000 is approximately 1 million, with the peak airborne count exceeding 50 000 [22]. Here there is a preponderance of private fliers which results in a mix of VFR and IFR, as the private aircraft are not all equipped with SSR. Problems of congestion can be overcome either by installing onboard collision avoidance equipment or by imposing a discipline to restrict private aircraft from using congested areas.

The main problem in Europe, where air traffic is double the estimates of 5 years ago, covers the preponderance of protected areas resulting in congestion of the upper airspace, where route crossings now exceed 20 per hour. The MADAP system [23] situated near Brussels is a data processing system to handle the flight plans and SSR returns from aircraft in the upper airspace over Belgium, Luxemburg, The Netherlands, and West Germany. Although just commissioned, it is already inadequate to handle existing traffic.

The North Atlantic ATC system with its large peak summer load (524 crossings in one day in 1971) is becoming severely congested. A quarter million annual flights are forecast by 1980 [24] with 160 aircraft simultaneously outside line-of-sight communications. The high accuracy of inertial navigation equipment, which is currently fitted on most aircraft (Section III-A) that use the North Atlantic track system, can permit the use of composite tracks with reduced separations.

V. Design Considerations Relevant to Future ATC Systems

A. Procedures

It is helpful to comment on possible modifications to ATC procedures and to review design considerations for ATC systems before discussing the relevance of acoustic matched filters. Existing control procedures rely on a ground-based controller with total responsibility for the aircraft in his sector. Systems, such as the McDonnel Douglas EROS, Bendix IMAGE, and RCA SECANT [25], [26] provide the pilot directly with air-derived collision avoidance information placing the onus on him to make an avoiding maneuver without consulting any ground controller. The advent of area navigation on overland routes involves consideration of systems such as intermittent positive control (IPC) [19] that sends positive commands from the ground to selected low priority aircraft to avoid potential collisions.

B. Satellite Hardware Considerations

Microwave satellite repeaters with their demonstrated capability and reliability for communications [27] are under active consideration for the functions of communication, navigation, and surveillance [28] in ATC systems. A synchronous satellite provides an area of coverage well in excess of that obtained from a single ground station. This enables a single repeater to operate, for example, over the majority of the United States without the mutual interference currently experienced from the many ground stations deploying SSR systems [16]. In RF link design the usual prime consideration is bandwidth conservation for optimum utilization of the available spectrum. Fixed ground-to-ground and satellite-to-ground microwave communications are essentially directional links employing high-gain narrow-beamwidth antennas. Here, bandwidth conservancy is not of prime importance as spuriously radiated spectral products are acceptably small. Links between aircraft and satellites are generally omnidirectional, which often results in critical power budgeting requirements because of the low antenna gains. One solution for optimizing the signal-to-noise ratio is to allocate many distinct exclusively assigned frequency channels in the satellite repeater. This complication of expensive satellite hardware is unnecessary when a single wide-band channel is utilized into which all subscribers are accessed on a code selection basis [28]. This is a natural application for matched filter reception techniques based on acoustic technology.

Consideration must be given also to interrelating the oscillator stability requirements with the Doppler shift expected on signals transmitted between a supersonic aircraft and ground terminal or synchronous satellite. The Doppler shift encountered on a 1.6-GHz L-band link with an aircraft flying at Mach 3.5 is typically 5 kHz [29], demanding an oscillator frequency stability better than 3×10^{-6}. This is a formidable requirement for microwave solid-state sources. These observations predicate the use of wide channel allocations (>100 kHz) with simultaneous access of several subscribers for optimal channel utilization.

C. Propagation Effects

Propagation effects such as atmospheric distortion, attenuation, and ducting are broad-band phenomena. Further, a severe problem in communicating with an aircraft over sea on a satellite link is the sea-reflected multipath return [29]. The separation of the direct and multipath return can be accomplished with antenna directivity, suitable antenna polarization, or spread spectrum coding of the transmitted signal [29], which again predicates acoustic matched filter techniques. However, practical measurements to establish the magnitude of the multipath return [30] are inconclusive.

D. *Examples of Integration of ATC Equipments or Signals*

An important consideration in the implementation of new systems involves the proposed level of equipment integration, particularly in military environments. Table II shows that aircraft currently contain a multitude of equipments. Equipment simplification starts with a progressive integration of the outputs of the existing equipments onto a common data processing system with a single sophisticated display, and progresses through integration of equipment operating in the same frequency band to the combination of the functions of communication, navigation, and identification into a single signal format. The totally integrated ICNI system [31], detailed in Section VII-C, is envisaged primarily for military applications where high security is mandatory. Its inherently high accuracy (typical positional errors less than 10 ft) solves the problem of providing a single navigation equipment for both terminal and en route control, a factor also of considerable interest to civil operators. Such equipment redesign will enable a vast reduction in the onboard power consumption, number of antennas required, spectral occupation, operation and maintenance costs, and will give increased accuracy, reliability, security, and interference protection. These latter features again point towards acoustic matched filter techniques. The collision avoidance surveillance (CAS) [25], [26] systems that involve the processing of air-derived signals to compute position of all aircraft within the system are intended primarily for the private pilot and thus price of usage is his key consideration. These systems position the expensive hardware in satellite-sited repeaters and ground processors to avoid avionics equipment costs.

E. *Voice and Data Link Considerations*

ATC reporting based on short messages (<600 bit) does not justify the use of the voice link, which is already becoming overloaded. Instead all these could be accommodated on a single data channel [20] with a message format containing aircraft identity (30 bit), flight level (12 bit), and present position (44 bit). ATC messages necessitate a very high integrity data link as a single bit error can potentially result in a collision, particularly in a congested terminal area. The allocation of exclusive time slots (TDMA) for each aircraft represents a complicated and expensive solution to this problem, due to the necessity for accurate onboard clocks. The design of a novel completely asynchronous system which includes a message addressing capability [33] is described in Section VIII.

New techniques to provide a multiple access capability for voice traffic over, for example, the North Atlantic are also under consideration [21], [34]. Short messages with low channel occupancy preclude the use of uneconomic FDMA and TDMA systems which use a large bandwidth when the system accommodates a large number of aircraft. A random access discrete address (RADA) system [35] might represent a better technique where multiple access of a large number of subscribers is required. To realize a RADA system the baseband (vocoded) transmissions from each aircraft are bandspread by encoding each digit with a distinctive IF signature. The IF signature is used for both address and modulation. The design of the system, discussed in Section VI, results in interference which is proportional to the number of active subscribers. A given optimum usage can be designed into the system.

F. *Summary*

It is preferable to finalize ATC procedures prior to concluding the final design of new ATC systems such as those detailed in Sections VII and VIII. Future deployment of satellites is predicted to obtain the maximum possible area coverage with a single system further accentuating the movement of ATC functions from VHF into microwave communications [14]. Band spreading, in preference to conventional FDMA, techniques are becoming attractive with the advent of acoustic matched filters and the need to cope with multipath environments. The areas of partial replacement of voice by data links and the integration of both ATC signal formats and equipments are justifying increased emphasis in the light of predicted overloading for existing ATC systems.

The necessary complexity in both signal formats and equipment hardware can be partially offset by the application of novel flexible signal processing techniques, especially by those realizable in SAW devices. Thus, it is considered relevant to examine briefly the significant and unique features of SAW technology.

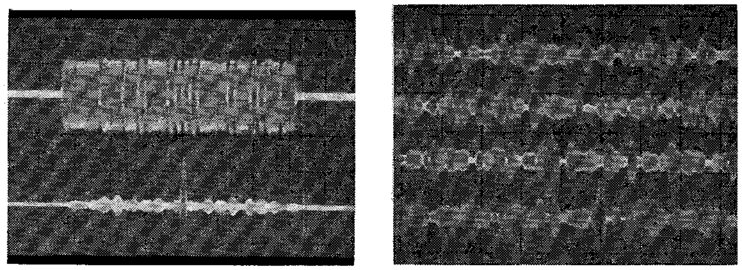
VI. Performance and Modem Design with Acoustic Matched Filters

A. *Introduction*

Communication with low error rate in the presence of noise and interference is achieved efficiently by signal processing [36] prior to transmission and the corresponding inverse process at the receiver. This encoding and decoding involves the assignment of a particular code word (signature) to each message. The code word is selected from an appropriate "alphabet" of signal waveforms chosen such that their transmission makes the *best* use of the given noisy channel. Coded waveforms have also proved attractive for radar systems [18] where the definitions of noise and interference must be extended to include clutter. The signal waveforms after transmission through the channel arrive at the receiver in a corrupted form where an estimate (decoding) must be made in optimum fashion as to which message was sent. This involves the taking of a decision on the presence or absence of the received RF signals. These results are governed by the setting of a decision threshold that must be designed for a minimum probability of error. For any required maximum error rate with a specified signature and signal-to-noise ratio there exists an upper and lower threshold bound. Lower thresholds result in a higher probability of *false alarms* (noise voltages exceeding the threshold), and higher thresholds result in a greater probability of *missing* a received signature. Therefore, an acceptable compromise must balance the *false-alarm* rate and the *miss* rate. Now, if the signal-to-noise ratio at the threshold stage input is increased, the threshold can be raised for a given *false-alarm* probability. On the basis of maximizing both output signal-to-noise ratio and probability of detection for a linear filter, when the additive part of the channel disturbance is stationary, white, and Gaussian, the matched filter is the optimum primary signal processor [37].

B. *Performance of Acoustic Matched Filters*

Impulsing a matched filter generates the time-reversed replica of the matched signal. Hence, the encoding and decoding operations can be accomplished, within certain technology bounds, with conjugate matched filter pairs. Fig. 4(a) (upper trace) shows a phase-shift keyed (PSK) IF signature gen-



(a) (b)

Fig. 4. (a) Top trace: Impulse response of AMF binary phase coded with 31-chip *m* sequence at 5-MHz chip rate on 90-MHz carrier (1 μs/large-scale div.). Lower trace: Aperiodic autocorrelation with same device (2 μs/large-scale div.). (b) Demonstration of synchronization acquisition for periodic autocorrelation functions of parent 31-chip *m* sequence with 4 distinct 7-chip subsequences.

TABLE III
SUMMARY OF KEY ADVANTAGES OF ACOUSTIC MATCHED FILTERS

Feature	Radar	Communications
Processing gain (provided prior to detection in devices)	reduced peak power for same range power: can be compatible with communications	increased signal to noise in band-spreading system
Band spreading	increased resolution increased jamming immunity	multipath resolution interference rejection increased jamming immunity less LO stability required
Waveform flexibility[a]	optimize for best clutter rejection	multiple addresses and signatures
Passive generation[a]	simple realizations of complex waveform	easy frequency hopping
Passive detection	permits truly asynchronous operation	permits truly asynchronous systems
Programmability[a]	electromagnetic compatibility, reduce crosstalk	random access by variable address (RADA) improved security

Note: Asynchronous tailor-made passive devices performing linear filtering.
[a] Features possessed particularly by surface acoustic wave devices.

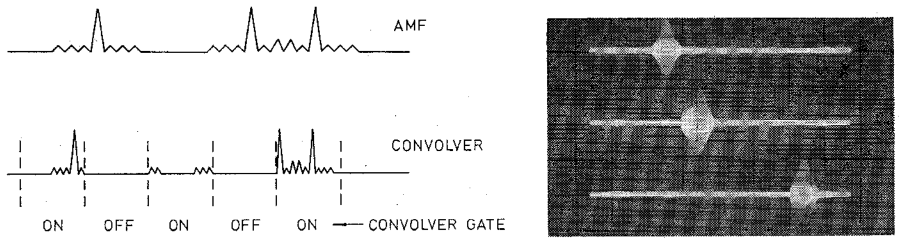
TABLE IV
OPERATING RANGES AND PRACTICAL DATA FOR MATCHED FILTERS

		Operating Ranges			Practical Data			
	Device	f_0 (MHz)	T (μs)	B (MHz)	TB	Sidelobe[b] Level (dB)	Insertion[c] Loss (dB)	Reference
Electromagnetic	lumped circuit	0.2– 30	1000–10	0.02– 5	50	−28		[39]
	tapped RF cable[a]	100 – 500	<1	50 – 300	100	−30	50	[40]
	folded tape waveguide	500 –2500	<1	200 –1000	720		24	[41]
Acoustic	magnetostrictive wire (tapped)	0.5– 2	1000–10	0.1 – 2	500		90	[42]
	strip	1 – 30	1000–30	0.1 – 5	64	−23		[43]
	diffraction grating	30 – 500	40– 1	10 – 250	160	−40	29	[44]
	love wave	1 – 100	200–10	0.5 – 100	60	−20	50	[45]
	SAW IDT[a]	20 – 300	50– 2	1 – 50	1000	−25		[46]–[48]
	SAW grooved grating	20 – 300	100– 2	1 – 100	1500		37	[49]
	convolver[a]	20 –1000	40– 2	1 – 100	31	theoretical	90	[50]
Microelectronic	digital[c]	baseband	5000–10	0.1 – 20	127	theoretical	N/A	[51]
	analog[a]	baseband	1000	0.01– 15	13	theoretical	N/A	[52]

[a] Programmable devices.
[b] Sidelobe levels are quoted relative to the correlation peak.
[c] For CW at center frequency.

erated by impulsing surface acoustic wave analog matched filter (SAW AMF) and its detection in the conjugate AMF (lower trace). Coded time-domain signatures, such as PSK and chirp, with flat frequency spectra offer operational advantages when hard limiters are incorporated in receivers enabling subscribers at widely differing ranges to be accommodated.

Table III summarizes the key advantages that can be obtained with suitable waveform design and acoustic matched filter detection. A comparison of the operating ranges and known practical data of various acoustic devices with electromagnetic and microelectronic techniques is given in Table IV. New operating ranges ideal for many important radar and communications systems are reported in this issue of this



(a) (b)

Fig. 5. (a) Schematic showing a received radar signal after processing in a matched filter, and the same signal after processing in convolver operating asynchronously (see Section VI-B). For simplicity, the transmitter pulse is taken as a 7-chip Barker coded waveform, and the three target returns are shown with the same amplitude. (b) Experimental result for an asynchronous convolver using rectangular RF pulses for the signal and reference. The three traces correspond to three values of signal delay, covering a range greater than the propagation delay in the device.

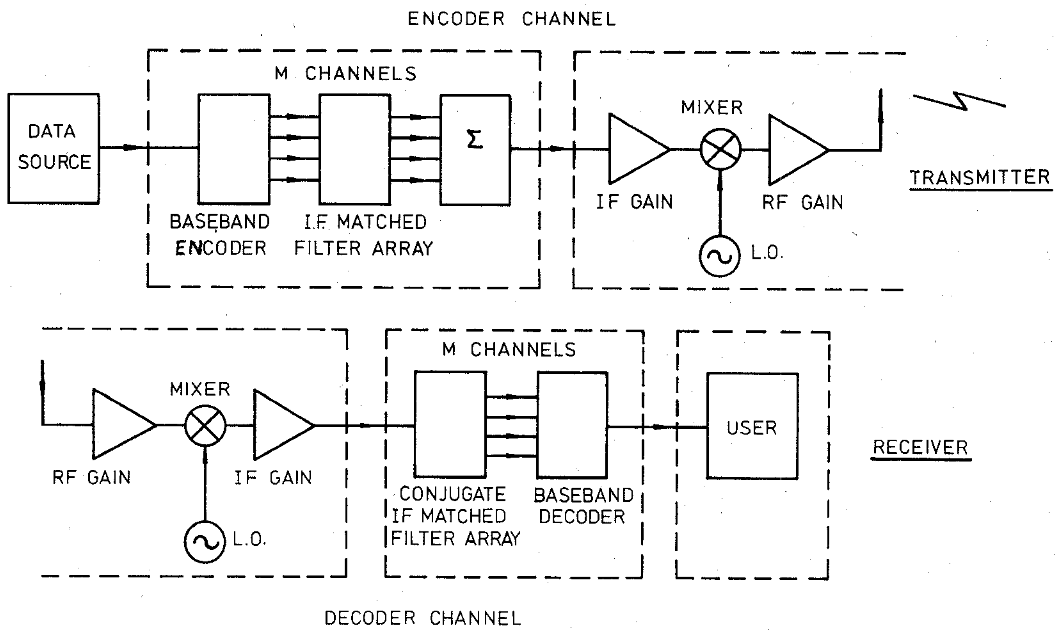


Fig. 6. *M*-ary modem using SAW matched filteis for efficient encoding and decoding operations.

TRANSACTIONS. Further, development is necessary to realize devices for long delays (∽1 ms) with processing gain ∽100 for narrow-band (∽100-kHz) systems; time–bandwidth products in excess of 1000 to reduce search times in synchronization; fast reprogramming (<100-ns) PSK filters processing 10-Mchip/s signals for ICNI; very high chip rate (>100-Mchip/s) devices for secure coded radio altimeter applications.

One crucial advantage of the acoustic filters (especially SAW) is their inherently asynchronous operation at RF, giving rise to fully asynchronous systems (see Sections VI-C and VIII-D) and powerful techniques for synchronization acquisition [53] in secure communications. For, secure spread spectrum applications, programmability is necessary and acoustic devices with the most promising features are the SAW programmable AMF and the nonlinear convolver. Fig. 4(b) illustrates the principle of synchronization acquisition [47] with a 7-tap SAW programmable AMF which is used to correlate four distinct 7-chip subsequences of a 31-chip waveform. Convolvers are not inherently asynchronous owing to the requirement for an accurately timed reference to ensure complete overlap of signal and reference in the region where their interaction is sensed. However, by using a repetitive reference signal and appropriate gating [54], asynchronous operation may be achieved. The output produced is shown schematically in Fig. 5(a). For visual display [Fig. 5(b)] the time segmentation effect is removed by arresting the time base when the output is gated off.

One further problem concerns the timing of the autocorrelation peak that is not directly related to the input signal timing due to the time segmentation effect. True timing is obtained in a *real-time recovery* unit using the reference timing information. Additional hardware is therefore required for applications that require asynchronous operation and true timing output. For comparison, a programmable PSK filter, although having limited programmability compared with the convolver, requires only tap switching circuitry and a read-only memory for code vector selection.

C. Definition and Characteristics of Band-Spread Communications Modems

It is now possible to indicate how matched filters might fit into communication systems by investigation of a simple modem (Fig. 6). Consider the encoder and decoder processors split into baseband and IF sections. At the transmitter, digital data from a source (e.g., computer terminal or vocoder) is fed into a baseband encoder. Each message is assigned one or more of M code words generated first at IF, by impulsing

TABLE V
EFFECT OF TIME–BANDWIDTH PRODUCT ON MINIMUM SIGNAL-TO-(NOISE PLUS INTERFERENCE) RATIO

$B_S T$	min $(S/I+N)_{i/p}$ dB	Relative Improvement (dB)
1	11.5	0
13	0.4	11.1
31	−3.4	14.9
127	−9.5	21.0
511	−15.5	27.0

Note: P upper bound $=10^{-5}$ for $\gamma=1$.

the appropriate matched filter, and then translated to RF by mixing with a local oscillator. Each matched filter has a distinct *signature*, or code word, characterized by 1) waveform, e.g., phase-shift-modulated sequences such as the pseudonoise [55] and Barker [56] sequences, or frequency-modulated signals such as the linear chirp [18]; 2) center, or carrier frequency and modulation bandwidth; 3) relative delay (the delay is of importance in some frequency hopping schemes).

The choice of signature *alphabet* depends on the system requirements, e.g., number of users, mode of operation, i.e., coordinated or uncoordinated, propagation characteristics of the channel, desired level of message integrity, etc. At the receiver, the incoming signal is down-converted to IF and recognized in a conjugate matched filter array. Following demodulation of the matched filter output, a threshold detector stage makes the required decisions and sends pulses into the baseband decoder, whose output is a reconstruction of the source data stream.

The type of demodulator used can effect the error rate, which is dependent on the received signal-to-noise plus interference and the time–bandwidth product of the transmitted code waveform. In practice, the use of envelope demodulation instead of the preferred [36] phase or synchronous demodulation, which results in an effective 3-dB increase in error rate, is commonly necessary due to the difficulty of extracting phase information. Large time–bandwidth product codes are therefore required to ensure sufficient signal-to-noise ratios for a given false-alarm rate.

In [57], the equation relating false-alarm probability, P to Gaussian disturbances and waveform time–bandwidth product for an envelope detector in the worst case situation, where the bandwidths of signal B_S and interference B_I are equal, is

$$P = \exp - \left[\gamma^2 B_S T \left(\frac{S}{I+N}\right)\right] \tag{1}$$

where γ is a normalizing threshold constant and S, N, and I are the signal, noise, and interference powers, respectively. Table V shows the minimum input signal-to-(noise plus interference) ratio which can be tolerated to obtain a false-alarm probability not exceeding 10^{-5} for various values of time–bandwidth product, taking $\gamma=1$.

D. Experiments on a Simple M-ary SAW AMF Modem

We have shown experimentally [58] that a matched filter expansion–compression loop offers a useful improvement in detection probability for a signal in noise and strong interference. However, in practice a simple loop does not make best use of the given channel. The M-ary system (Fig. 6) increases the efficiency of the communications channel. To illustrate the

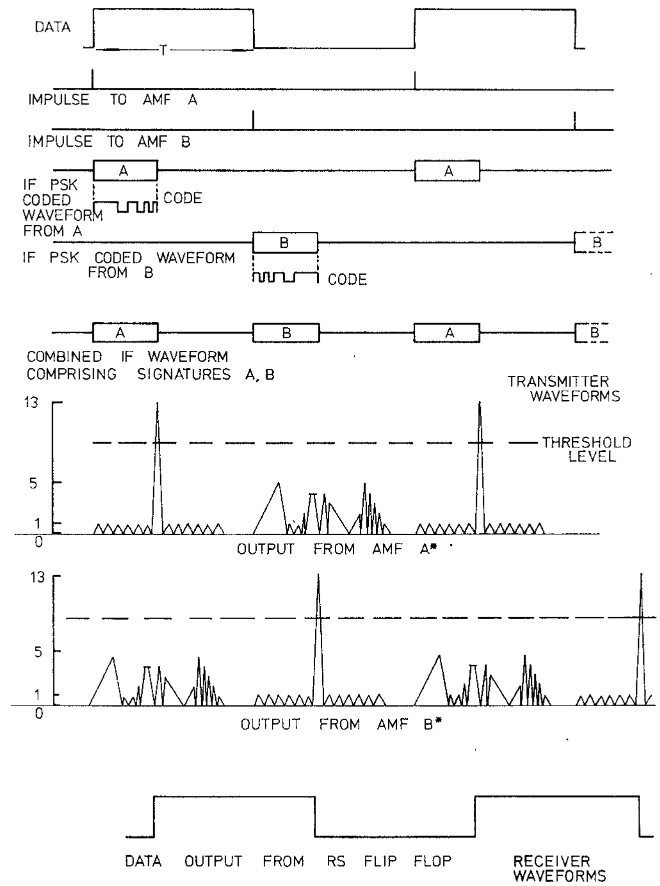


Fig. 7. Waveform diagram for simple two-signature M-ary SAW AMF modem.

M-ary principle, experiments were conducted for the simple case where $M=2$. Thus, in each T s one binary digit is transmitted and the corresponding data rate, $1/T$ bit/s, is subject to the maximum rate, $2B_S$, given by the sampling theorem.

The waveforms corresponding to the modem experiment are indicated in Fig. 7. For convenience four identical 13-chip Barker coded devices are used. Thus the two signatures generated (A and B) were simply the Barker Code (1111100110101) and its time reverse (1010110011111). The cross correlation with the time-reverse sequence has peaks of relative height (5:13). These cross-correlation peaks arise from the imbalance of "1" and "0" states in the sequence and are not representative of the best autocorrelation and cross-correlation functions obtainable with selected binary PSK sequences [59]. In the receiver, the conjugate matched filters A^* and B^* have maximum response to codes A and B, respectively. However, unlike the simple loop experiment, the threshold must be set halfway between the top of the autocorrelation peak and the top of the cross-correlation peak. This causes a degradation in performance because of the reduction in usable threshold range. The outputs of the threshold detectors are connected to set and reset a flip-flop which regenerates the data stream. Thus it is noted that a significant feature of SAW matched filters is their ability to retrieve data without synchronization preambles, enabling the construction of a truely asynchronous data detection system (as detailed in Section VIII).

The transfer of data (a 7-bit pseudonoise sequence) has been demonstrated at a clock rate of 25 kHz with low error rate ($<10^{-7}$) in a noise and interference free coaxial wire link.

Error rates of less than 10^{-4} have been measured for simultaneous signal-to-noise and signal-to-"in-band" interference ratios of +8 dB. Selected signatures would enable the threshold to be lowered to the optimum [58] level and hence the error rate could be minimized.

The number of usable signatures and frequency slots is usually not sufficient in a simple M-ary system to provide random and simultaneous multiple access to a large number of subscribers. In Section VII the problems of selecting a sufficient number of codes with bounded cross correlations is highlighted in range differencing surveillance systems. The following two subsections indicate briefly certain possible implementations of SAW matched filters to previously published multiple access systems.

E. Time-Domain Multiple Access

Reed and Blasbalg [60] described a time-domain multiple access (TDMA) M-ary system using the (7, 2) octal Reed–Solomon [61] code to generate a time–frequency pattern for each signal waveform. These codes exhibit orthogonality with an almost flat power spectrum, in addition, pseudorandom frequency hopping into eight channels is employed to combat multipath. The seven subpulses of each signature are *uncoded* 1.8-μs bursts of RF selected from eight possible frequency slots, the total message bandwidth being 5 MHz and the total RF bandwidth 40 MHz. A synchronized receiver first removes the pseudorandom frequency hop, then each subpulse is detected by its appropriate matched filter and maximum likelihood decoding extracts the data. This multiple frequency-shift keyed (FSK) system accommodates 4000 users at a data rate of 100 bit/s per user.

SAW matched filters can be used both to generate and detect the uncoded subpulses for the time–frequency pattern. Further, programmable AMF's duplicated in each of the eight pseudorandomly selected frequency slots would remove the synthesized local oscillator and only involve synchronous baseband gating of the matched filter outputs.

F. Random Access Discrete Address (RADA) Modem Implementation

In address communication systems (Section V-E) a number of individual signatures constitute an address resulting in many different combinations providing a large address alphabet. Many subscribers can send arbitrary messages over a common wide-band channel at the same time and in the same geographical area by addressing each communication. The transmitted waveform has to carry both address and modulation. The most promising addressing technique is the exclusive allocation of a time–frequency pattern to each receiver, and possible modulation techniques are the digital delta modulation, quantized pulse position modulation (PPM), pulse code modulation, and analog PPM or pulse frequency modulation.

The number of addresses is determined inherently by the size of the time–frequency matrix. The selection of addresses depends on the system details. Certain solutions are outlined in the paper by Blasbalg *et al.* [62]. They propose a multiple FSK pseudonoise addressing modem, into which SAW matched filters could be fitted. A guide to the number of *unique* addresses A, obtained from a time–frequency matrix, is given by Magnuski [35]

$$A = \frac{F!}{(F-N)!N!} \times \frac{(T-1)!}{(T-N)!} \qquad (2)$$

where F denotes the number of frequency slots, T the number of time slots, and N the number of coded sequences transmitted in the address. As a simple example, consider four frequency slots ($F=4$), five time slots ($T=5$), and three identical code sequences per address ($N=3$), yielding 48 unique addresses. These addresses are *quasi-orthogonal* in that two addresses may coincide in more than one time–frequency box. Their resolution becomes increasingly difficult as the mutual cochannel interference increases. A solution has been proposed by Chesler [63] combining M-ary and RADA techniques. A number of addresses M are assigned to each receiver providing an optimum value of M for which a minimum probability of error is obtained for each matrix size and channel utilization.

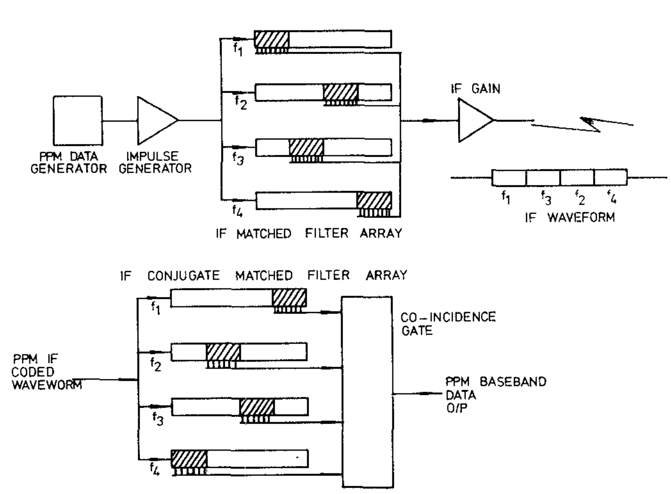


Fig. 8. Random access discrete address using SAW AMF's and SAW delay lines for encoding and decoding addressed PPM data.

TABLE VI
FUTURE ATC SYSTEMS

	Simple ←———	———→	Comprehensive
Ground-based and onboard equipment	radar (primary and secondary)	air-derived collision avoidance (SECANT)	ICNI
Satellite transponder systems	inertial navigation reporting	AEROSAT	collision avoidance range differencing system

A simple realization of a RADA modem for transferring PPM data is shown in Fig. 8. The recognition of both coded IF waveforms and the time–frequency pattern is necessary as this represents the receiver's address. For short coded waveforms, recognition of the time–frequency pattern may be accomplished through expeditious use of SAW delay lines to ensure that correct correlation in each frequency slot occurs in the same time slot. A coincidence gate performs the baseband decoding necessary to regenerate the PPM signal.

VII. POSSIBLE FUTURE ATC SYSTEMS

A. Classification

Following the review of properties, obtainable parameters, and advantages of utilizing acoustic matched filters in ATC, this section discusses certain representative new ATC systems under development for possible implementation in the late 1970's and beyond. These systems are classified in Table VI via a matrix scheme comprising simple though comprehensive

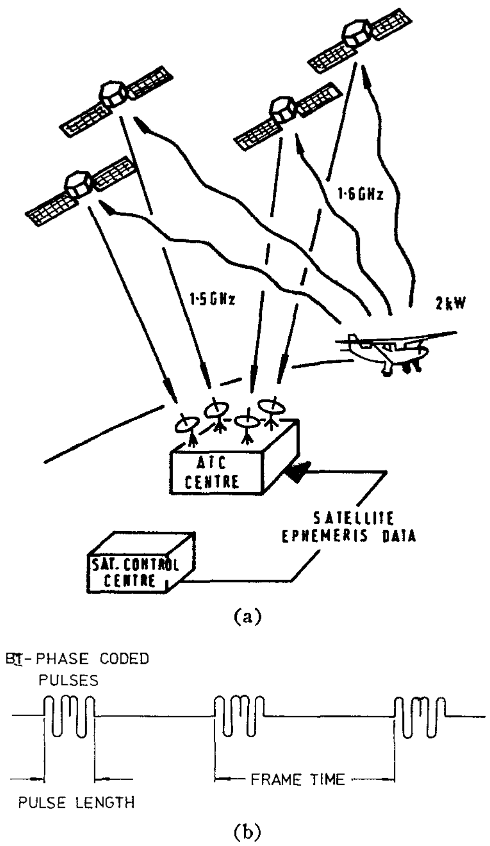


Fig. 9. Satellite range differencing systems. (a) Inclined eccentric orbiting satellites with ATC transponders. (b) Signal format.

systems. Space limitations preclude discussions of the important military IFF area where widespread interest in SAW matched filter techniques is currently being shown.

B. Range Differencing Surveillance Systems

These systems [28] which are primarily intended for use in the continental United States (CONUS) have as an essential requirement the inclusion of all aircraft. The proposed method of operation involves a one-way ranging system, for bandwidth conservancy, where each aircraft is equipped with a beacon transponder which generates a unique coded ranging signal [32]. The use of an upper hemispherical coverage antenna enables routing of the transmitted signal through several widely spaced satellites back to a ground-based control center (Fig. 9). As no synchronization exists between the aircraft and the ground station, the use of four or more satellites enables calculation of absolute user position. For accurate receiver timing and separation of the returns from the many aircraft in the system, it is proposed to biphase modulate the transmissions with a coded sequence. This enables usage of a matched filter in the receiver to extract the required signal from among the multiple retransmitted satellite signals and to provide a timing accuracy equal to 1 chip of modulating code. The system ranging accuracy is therefore governed by the bandwidth of the transmitted signal. However, it is impossible to obtain the required 100 000 codes [59] for unique identification of each aircraft. Proposals have been submitted by TRW, Boeing, and Autonetics [28] to generate these identities using unique combinations of codes, pulse repetition rates, pulse placements, and transmission frequencies (Table VII).

The TRW LIT system [32] utilizes a single transmission

TABLE VII
RANGE DIFFERENCING CAS SYSTEMS

Parameters of System	TRW	Boeing	Autonetics
Pulse length (μ/s)	51.1	255	20 (for 1 pulse)
Modulation rate (MHz)	10	2	10
Code length (chips)	511	511	200
Number of codes	25	16	10
Number of frequencies	1	1	10
Frame time (s)	1.0–1.1	1.0–1.3	N/A
Frame spacings (μs)	10	50	N/A
Number of frame addresses	10 K	6 K	100×100
Number of identifications	$\frac{1}{4}$ million	100 K	1 million
Accuracy of position (ft)	250	300	260
Transmitter peak power (kW)	3.5	2	1

frequency of 1.6 GHz with a modulation rate of 10 MHz and a quarter of a million addresses as detailed in Table VII. The received signals, after recognition and timing, are fed into a PRP analyzing and tracking computer which predicts any likely conflicts. SAW AMF have been fabricated for generation and detection of the coded sequences used in this system. The Boeing proposals feature a similar LIT system of reduced accuracy due to the use of a signal of only 2-MHz bandwidth.

The Autonetics [28] proposal that covers not only simple surveillance but also en route navigation and communication, employs a pulse triplet containing the unique address. Air-to-ground communication messages can be sent 3 bit at a time by using the pulse triplet in a PPM format enabling the accomplishment of ranging and communications on the same signal format. This system represents a more comprehensive update version of the TRW and Boeing systems.

It should be noted that these surveillance systems transmit an identity pulse enabling the calculation of absolute position. However, the installation of accurate inertial navigation equipment offers an alternative surveillance system (discussed in Section VII) which transfers onboard navaid data to a ground controller over an asynchronous data link.

C. Integration of Communications, Navigation, and Identification Equipments

ICNI [31], which was initially discussed in Section V-D, is a military concept requiring a signal format of high security and information fidelity when subjected to multipath returns, interference, jamming, and spoofing signals.

The proposed system utilizes a single communications channel that is common to all users with subscriber allocations organized on a TDMA system [31]. One-way transmission provides bandwidth conservation and removes the self-interference experiences in two-way transmission systems (SSR [16], SECANT [26], etc.). A typical subscriber would utilize one 10-ms slot per 10-s time frame to transmit position, identity, mission, fuel, and ordinance status, etc., with ample provision for error detection and correction, utilizing an onboard clock to time the start of transmission. The single time slot allocation may be used in several modes, accommodating simple time ordered signaling as previously described or discrete address interrogation and reply including data exchange with another subscriber [31].

To combat the problems of jamming and interference, it is intended to utilize a moderate bandwidth (10 MHz) with both pseudorandom band spreading and frequency agile techniques. Band-spread coding with matched filter detection also enables minimization of the transmitter profile reducing the visibility of the transmitted signal and the effectiveness of any

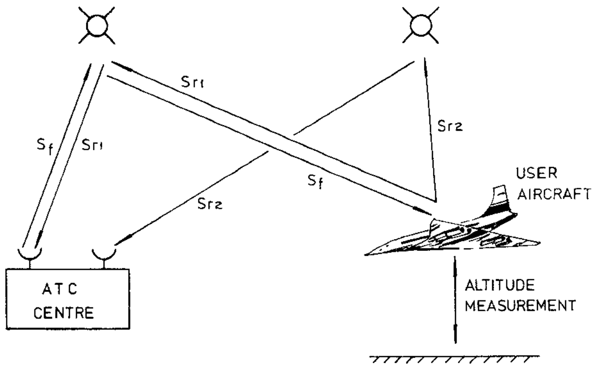


Fig. 10. Active tone ranging system.

hostile monitoring. These coding techniques which exhibit a reasonably flat spectral power density could permit utilization of the previously allocated TACAN band (960–1210 MHz) [10] for coexistence of both signals without any severe mutual interference. The bandwidths proposed for this system are between 10 and 25 MHz, which are easily accommodated by SAW AMF's. These AMF's, which perform rapid synchronization acquisition (Fig. 4), have been constructed to detect the 127-chip synchronization preambles [31]. It is anticipated that distinctly coded preambles will exceed the total currently achievable device delay, requiring a programmable AMF with the capability of changing code within a chip period. SAW matched filters are also expected to find many application in the detection of message data. This system highlights the advantages of a single signal format incorporating the functions of communication and ranging at the same transmitted power level without mutual interference.

D. AEROSAT

The North Atlantic aeronautical satellite system AEROSAT comprises a joint verture by FAA and ESRO to provide an extension of positive ATC surveillance [21], voice, and high data rate functions [64] over the busiest oceanic air-traffic route in the world. In establishing a communications link over the North Atlantic a synchronous satellite represents the optimum choice of signal routing repeater. The specification of L-band transmission for ATC is expedient following the reservation of a substantial band from 1535 to 1660 MHz for aeronautical radio navigation and communication (Table II). The system is to be controlled and accessed through two oceanic control centers, one situated on each side of the Atlantic, with communication facilities to the existing ATC centers at Gander and Shanwick.

The AEROSAT system proposes initially to utilize two satellites, each one placed in synchronous orbit over the ends of the present track system. Surveillance is to be performed with a ranging system of 1-nmi (1σ) accuracy based on chirp [65], multiple tones, or digital ranging techniques [66]. Active ranging (Fig. 10) is accomplished by selectively interrogating the aircraft through one satellite (*Sf*) prior to detection and timing on the reply (*Sr*), containing onboard altitude information, that has been routed through the two satellites. To meet the traffic forecasts it is proposed to design six communications channels, three in each satellite, using simplex operation with narrow-band FM modulation. Systems planning includes one 1.2-kBd DPSK data link to cover the entire area which uses one of the satellite voice channels.

The requirements for each satellite therefore include the capability of simultaneously relaying two surveillance signals, providing three communication channels, accepting and acting on telemetry tracking and command signals, and performing necessary frequency conversions on all signals. Power budgets have been derived for both uplinks and downlinks that highlight the requirement to evaluate the tradeoffs in aircraft installation costs (e.g., antenna phased array designs), spacecraft weight, and transponder reliability.

It is intended to evaluate a preoperational system using the ATS-F satellite in 1974 to ascertain both the optimum voice modem and ranging techniques and also to evaluate fully the problem of multipath returns from sea reflections. The AEROSAT system, which is likely to be the first operational satellite ATC system, as envisaged uses signals with time–bandwidth products that exceed the capabilities of currently existing SAW devices. However, the use of acoustic strip delay lines could present significant technological advantages when performing the signal processing functions. Should the design and construction of onboard electronically steered phase arrays be impossible, then band-spreading techniques with SAW matched filter detectors could represent a significant technique for achieving the required aircraft to satellite power budgets.

VIII. Novel High-Integrity L-Band Data Link for ATC

A. Introduction

Pending the deployment of AEROSAT, no ground-based surveillance exists for the North Atlantic crossing. It was previously stated in Section III-A that all large aircraft will shortly be equipped with sophisticated and accurate inertial navigational equipments. This section describes a simple high-integrity L-band data link to output onboard navaid data which contains SAW matched filters, and the features of fully asynchronous operation with built-in error checking procedures for verification of message authenticity.

B. Accessing Procedures

It is intended to confine reporting of position information to a single communications channel utilizing one-way signal transmissions combined with a selective address system. This differs from the ICNI concept by arranging subscriber accessing on an unsynchronized poled basis to accommodate individual aircraft interrogation rates suitable for both subsonic and SST. Navigation information which is always a message of known length (Section V-E) can therefore be accommodated within a fixed length message format (e.g., 120 bit), which includes address information. High integrity, the probability that a message will be received and outputed correctly, is vital in ATC data links. Throughput, which is a measure of the number of outputed messages for a given number of transmitted messages, is of lesser importance as it can be overcome by further interrogation. High integrity can be achieved for fixed length messages by the application of suitable baseband encoding techniques [33], [67].

C. High-Integrity Encoding–Decoding Procedure

Matched filters giving improved detection probabilities by processing at IF do not provide high integrity without baseband error detection techniques. In a system using binary registers, this is achieved through a high level of message redundancy to avoid the absence of a "1" being interpreted as a "0" in the receiver. The application of tristate receiver logic, described by Parker [67], where reception of either a "1" or "0" data bit always constitutes a change of state, offers a

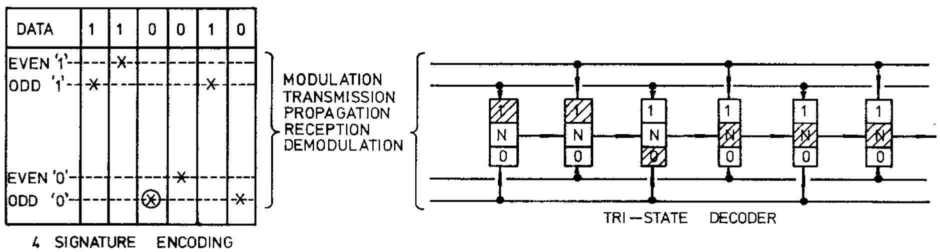


Fig. 11. Four-signature encoding and high-integrity decoding utilizing a tristate logic shift register.

significant improvement. A four-signature data encoding system allows encoding both for data level and for position in the message sequence. Fig. 11 shows the encoding in the transmitter of each data bit into one of four signatures. In the receiver, the detected baseband pulses are present on four wires feeding the decoding register. After clearing the register to the nondeterminate state, the first bit of message, which appears as an odd "0" clocks the first stage only to a "0" (because all other odd stages are inhibited) and removes the inhibit from the second stage. The receiving logic therefore ensures that even bits cannot be entered into odd states and vice versa. If one bit of the message is missing at the receiver the next bit, which possesses the incorrect positional information, is rejected. Then all the following bits are entered two stages in advance of their correct position resulting in a nondeterminate state in the last two stages. The occurrence of an odd and even bit overlap results in a register overflow. A single check bistable is employed to ascertain that no errors have been received before outputing the message onto the display. This illustrates a cheap and efficient method of realizing a self-checking high-integrity data detection system. It is fully asynchronous since the previous data bit provides the decoder shift pulses.

D. *Modulation Format*

The choice of waveforms for the four distinctive signatures will be governed by ease of generation and detection and by other factors influencing the system performance. The four signatures can be readily obtained by using four audio tones within the allocated frequency channel. However, for an L-band channel this involves problems of oscillator stability (Section V-C). Band-spreading techniques using SAW AMF's, which are asynchronous devices, have potential advantages in that discrimination between signatures can be achieved, multipath returns can be resolved, and the system will be less sensitive to interference and jamming (Table IV). Two signatures can be realized with two chirp pulses, one positive slope and the other negative slope. A further pair of chirp waveforms with a different center frequency make up the four signatures. PSK waveforms could also be employed but large time–bandwidth products are necessary to reduce the cross-correlation products to acceptable levels [59].

The overall system operation, which is represented in Fig. 6 with $M=4$, encompasses the feeding of incoming data stream in the transmitter into a four-signature encoder which routes the data on to four busses to impulse the associated filter and generate the required signature [68]. The filter outputs, at IF, are then summed, amplified, and up-converted to L band. In the receiver the down-converted IF signal is fed into the four conjugate chirp filters, each of which gives an output on one of four lines which lead to the tristate decoder.

E. *Conclusions*

The system as described is fully asynchronous and provides significant advantages, in privacy of transmitted signal and high message integrity, over existing and proposed data links. In addition, each of the individual facets of the system (Section VIII-A) uses proven techniques which if married should produce an easily engineered and operated system incorporating additional data link facilities to further reduce the communication channels load. It is concluded that the transmission of real-time navaid data represents a powerful technique for cost-effective surveillance system on oceanic crossings. However, the system as described has many wider areas of application to aircraft and battlefield IFF (high-integrity ADSEL/DABS concept), air-to-air computer dumping, and air-to-ground sonar buoy surveillance.

IX. Conclusions

Implementation of new ATC systems involves cooperation between a large number of parties, implying a long time scale prior to implementation. It is therefore important that device designers and system planners should immediately coordinate their efforts to evaluate the performance of acoustic wave technology in a real-world situation. Highlighted are system philosophies for new microwave ATC systems incorporating matched filters which offer attractive band-spread coding in place of more conventional multiple access techniques. Acoustic matched filters, particularly surface-wave filters, have many advantages, e.g., economics and performance reliability, although strong competition can be expected from LSI semiconductor technology, despite the additional complexity necessary to achieve large dynamic range and asynchronous operation. In the interest of brevity we have excluded discussion of other acoustic devices, such as frequency filters, delay lines, and UHF oscillators for applications such as FDMA data transmission, radio altimeter, and selective address SSR. It can be concluded that ATC systems development has reached a critical phase due to the congestion of air traffic, and that signal processing in acoustic devices can offer significant advantages in the next generation of ATC systems.

Appendix

Glossary of ATC Terminology

ADF	Automatic direction finding.
ADSEL	Address selective SSR.
AEROSAT	Aeronautical satellite system (North Atlantic).
AGARD	Advisory Group for Aerospace Research and Development.
ATC	Air-traffic control.
ARINC	Aeronautical Radio Incorporated.
ARTS	Automated radar terminal system.

ATS	Advanced technology satellite.
CAA	Civil aviation authority (United Kingdom).
CAS	Collision avoidance surveillance.
CONUS	Continental United States.
DABS	Discrete address beacon SSR.
DME	Distance measuring equipment.
EROS	Eliminate range zero system.
ESRO	European Space Research Organization.
FAA	Federal Aviation Administration (United States).
ICAO	International Civil Aviation Organization.
ICNI	Integrated communications navigation and identification.
IFF	Identification friend or foe.
IFR	Instrument flight rules.
ILS	Instrument landing systems.
IMAGE	Intruder monitoring ground equipment.
IPC	Intermittent positive control.
LIT	Location identification transponder.
MADAP	Maastrich automatic data processing equipment.
MLS	Microwave landing systems.
PPI	Plan position indicator.
SAGE	Semiautomatic ground environment.
SECANT	Separation and control of aircraft by nonsynchronous techniques.
SSR	Secondary surveillance radar.
SST	Supersonic transport.
TACAN	Tactical air navigation system.
VFR	Visible flight rules.
VOR	VHF omniranging.

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Short Papers

Surface Elastic Wave Bandpass Filters for Frequency Synthesis

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Abstract—**Surface elastic wave bandpass filter techniques have been applied to the development of a minaturized frequency synthesizer for satellite communications systems. A bandpass filter centered at 247 MHz has been developed exhibiting less than 7-dB insertion loss over a 6-MHz 1-dB band, with sidelobe rejection greater than 45 dB.**

The surface elastic wave bandpass filter is becoming an attractive component for application in communication systems at VHF and UHF frequencies [1]–[8]. The surface wave filter is a fabricationally simple compact planar structure easily integrated into hybrid microelectronic circuitry. It is an extremely versatile component permitting a wide range of desired band shape responses to be developed, because phase and amplitude characteristics can be synthesized independently. It represents a reliable reproducible component that can be produced inexpensively.

Surface-wave bandpass filters were designed, fabricated, and evaluated for use in frequency synthesis for minaturized communications systems.[1] The synthesizer uses frequency multiplication and addition techniques to develop stable coherent reference signals for an ultrasensitive receiver.

The primary requirements for filter performance were a moderate bandpass, low insertion loss, and strong rejection of unwanted sidebands. Equally important requirements were small size and process compatibility and integrability with other hybrid microelectronic circuitry. The surface-wave filter represented an attractive alternative to cascaded high-Q LC networks which would have required shielding and taken up considerable space.

Surface-wave filters were initially developed for evaluation at frequencies of 56, 150, 220, and 244 MHz. The filters were designed with lithium niobate ($LiNbO_3$) as the substrate material. The transducer structure of each filter consisted of a central interdigital electrode having a $\cos^2 x$ apodization with two adjacent electrodes of uniform finger overlap. The interdigital electrodes had equal quarter wavelength linewidths and spacings. The center apodized pattern controlled the main in-band frequency response with the two adjacent patterns having fewer finger pairs and thus a broader band response. The outer patterns also included a separate reflector region spaced by an odd number of quarter wavelengths to test the use of a unidirectional response near band center [9]. The interdigital patterns were photoetched on polished Y-cut plates of $LiNbO_3$ with surface-wave propagation along the Z axis. The electrode metal was evaporated aluminum approximately 2500 Å in thickness.

The four filters were evaluated with the signal input to the center apodized pattern and the output from the adjacent patterns, which were electrically connected together. Series inductors were used to match impedance levels. The insertion loss of the filters was in the range of 5–7 dB. A 3-dB bandwidth of 7 percent was obtained, and the sidelobe rejection was greater than 30 dB. The ripple in the bandpass was less than ± 1 dB.

The filters at 200 and 244 MHz were evaluated using the "quarter wavelength reflectors" to give a unidirectional characteristic to the output transducers. The reflectors were optimized with a series inductance to ground [9]. The beneficial effect of the reflectors was to reduce the loss by an additional 2 dB (a total filter loss as low as 3 dB was obtained) and to reduce the ripple in the bandpass to ± 0.25 dB. There was, however, a decrease in the bandwidth and an additional ripple in the skirt region. The lower sidelobe level outside the bandpass region was unaffected.

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