# Very Fast Signal Processors as a Result of the Coupling of Surface Acoustic Wave and Digital Technologies

HERVÉ GAUTIER AND P. TOURNOIS, MEMBER, IEEE

*Abstract*—**The recent progress of the digital and the surface acoustic wave (SAW) technologies have made them compatible; and it is now possible to design signal-processing modules which benefit from the flexibility of the digital techniques and the very high computation speed of the SAW techniques. Very fast signal processors can now be built which are able to process several tens of megasamples per second and whose volume and power consumption are limited. This paper shows the compatibility of these technologies and the advantages yielded by their joint use. Several examples are described which relate to one- and two-dimensional Fourier and correlation processors.**

## I. Introduction

MODERN SIGNAL PROCESSORS require higher and higher processing speeds: 10 to 100 megasamples per second rates are now common in electronic counter measure systems where the radar environment is very dense, and in spread spectrum telecommunications operating over several tens of megahertz instantaneous bandwidths. But high rates are also necessary in low-frequency multichannel equipment like sonar systems, and in real-time two-dimensional signal analyzers. To build such processors, a multiplexed digital technology had to be employed and resulted in often prohibitive volume and power consumption.

The existence of surface acoustic wave (SAW) computation modules now allows for very fast complex computations to be performed in real time and at rates corresponding to 10- to 500-MHz bandwidths. For examples, the speed of Acoustic Fourier Transform modules corresponds to that a one-butterfly digital FFT circuit with a 2-ns butterfly time; and acoustic convolvers can perform more than $10^{10}$ analog multiplications per second. In both cases, 12-bit dynamic range and 6- to 8-bit accuracy are obtained. Analog systems like radars have made use of these components for some years. But their field of application has been limited because 1) digital post-processing must generally follow and it was unable to extract the information at these speeds, 2) series multiplexing was not powerful enough and one could only process one-dimensional information with high rates, and over limited time slots, directly compatible with the SAW devices, 3) finally, the lack of memory required that the signals to be compared be quasi-simultaneous and only instantaneous processing was possible.

The performances of digital components such as samplers/digitizers, multiplexers, digital modulators, and memories are now compatible to those of the SAW technology. The speed of the computation modules like multipliers, correlators, FFT's is not comparable. To perform these complex functions, acoustic wave components should, therefore, be employed and coupled to fast I/O and store digital components. The flexibility of the digital techniques is thus associated to the high processing speed of the SAW components. Reduction in volume, power consumption, cost, and hence improved reliability would result. A simple technological answer has, therefore, been found to the question of fast processors stated earlier.

This paper will show the compatibility of the two technologies in presence and the advantages which can result from their joint use. Several examples are described which deal with one- and two-dimensional systems. Fourier transform processors (sea-bottom imaging sonars and two-dimensional acoustic beamforming) and correlation processors (signal sorting or filtering and two-dimensional map correlation) are discussed.

## II. Fundamentals of SAW-to-Digital Coupling

A very wide variety of components and subsystems can be realized using these two basic technologies. This presentation will be restricted to a few. The major surface wave components of interest here are the dispersive delay lines which can employ the reflective array technology [1] or the interdigital transducer technique [2], and the convolvers which may be of the piezoelectric [3] or semiconductor type [4]. These components are the basic building blocks for Fourier transform [5] and convolution correlation [4] modules. And with adequate interfaces, these analog processors can be coupled to digital circuits.

The digital components and interfaces referred to throughout this paper are the sampling and digitizing circuits (A/D converters), the digitally controlled modulators (D/A converters), and the memories. Channel multiplexing circuits should also be added to this list; they are in fact digitally controlled switches. Computation circuits like multipliers or analyzers are purposely left out for their speed is relatively low.

Manuscript received February 12, 1980; revised November 25, 1980.
The authors are with Thomson-CSF, Centre de Cagnes-sur-Mer, 06802 Cagnes-sur-Mer, France.

0018-9480/81/0500-0404$00.75 ©1981 IEEE

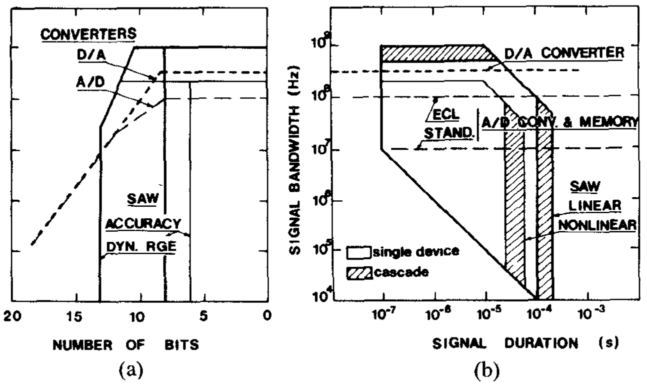



Fig. 1. Performance bands of SAW and digital components.

### *A. Compatibility of the Two Technologies*

These classes of components can be employed together provided their performance bands overlap. In the analog processing vocabulary, these performances can be signal bandwidth and duration on the one hand, and accuracy and dynamic range on the other. Translations into the digital processing language are sampling or access speed and number of bits. Comparison of the various performance bands is graphically represented in Fig. 1(a) and (b).

In the signal duration versus bandwidth plane, the linear SAW device area is rather well known [6], [7]. Its upper bounds are 200-$\mu$s duration and 1-GHz bandwidth; these figures being reached by device cascading or frequency multiplication. The maximum time–bandwidth product is $10^4$ at the present time. Nonlinear components, like convolvers, exhibit more limited performances although the technological bounds are not so well known.

The notion of signal duration is meaningless when dealing with the digital components listed above, because one can, in principle, assume the memory size is unlimited. Clock frequency and access time are then the only factors to be considered when setting the bandwidth limits.

The fastest available A/D converters and memories employ the ECL technology (GaAs and $I^2L$ technologies are being developed [8]). It allows for gate propagation time of less than 1 ns and memory access time of 10 to 20 ns. Hence the maximum operation bandwidth is around 100 MHz. More standard and less power-consuming technologies (CMOS and low-power Schottky) set this limit at 10 MHz. Performances of the D/A converters always are higher because they only require logic gates, and direct modulation of the carrier is possible [9]. A good compatibility, therefore, exists for signal bandwidth and duration up to 100 MHz and 100–200 $\mu$s, respectively.

The dynamic range and *absolute* precision of digital circuits are not independent; they are functions of the number of bits in the coding. Further, the maximum number of bits of A/D converters is an inverse function of speed. Converters of the parallel type using ECL comparators and logic gates can operate at 200 MHz over 7 bits. Slower circuits with larger number of bits, e.g., 12 bits at 20 MHz, would employ the successive approximation technique [9]. For the D/A converters, 60- to 80-dB isolation, hence dynamic range at 500 MHz, is possible with ECL gates or Schottky-diode modulators directly controlled by the binary information.

In contrast to digital components, acoustic components are characterized by their *relative* accuracy which is independent of dynamic range. Hence two equivalent numbers of bits should be defined. On the basis of 6 dB per bit, and considering the SAW components show typical dynamic ranges of 60 to 80 dB depending on frequency, the number of "dynamic range bits" varies from 10 to 13. On the other hand, computation accuracy relates to frequency or spatial uniformity and spurious suppression. It also depends on the type of signals being processed, for different averaging effects can occur. Linear devices, like the dispersive filters, show down to 0.2-dB amplitude and 1° rms phase errors, which allow for 35- to 45-dB sidelobe suppression with weighting techniques. The equivalent number of accuracy type bits is, therefore, of the order of 8. The slightly degraded performances of nonlinear devices, such as convolvers (0.5 dB and 10° ripples) lead to a minimum number of bits of approximately 6. In all cases, this number of bits is independent of signal amplitude. Coupling of the SAW and digital technologies is, therefore, possible and it will not degrade the performances of either technology.

### *B. Advantages Yielded by the Coupling of Technologies*

Flexibility is the major advantage of digital techniques. It is provided by the existence of memories and variable clocks which allows memory and time expansion/compression to be easily realized and which greatly simplifies data processing [9]–[11]. Further, absolute accuracy can be arbitrarily high. But difficulties arise when high computation speed or large capacity is required; for in either case, volume, power consumption, and cost increase very rapidly and make the use of digital circuits rather impractical. This is where complex calculations and processing should be performed in SAW devices, provided appropriate interfacing circuits are incorporated. Gain in volume, power, and simplicity will result; and in some instances, net improvement in speed is obtained over all-digital solutions. Two characteristic examples are the acoustic Fourier transformers and correlators.

Acoustic Fourier transformers employ the chirp transform scheme [5] whose principle is recalled in Fig. 2. The signal slots to be analyzed have a duration $T_s$, and a bandwidth $B_s$. The result of their premultiplication by a frequency ramp with duration $T_p = T_s$ and frequency excursion $B_p$ is analyzed in a dispersive filter of dispersion $T_f$, bandwidth $B_f = B_p + B_s$ matched to the premultiplying ramp, i.e., $B_f/T_f = B_p/T_p$. Post multiplication is added when the phase information is needed. Such a module can, therefore, analyze $N = B_s T_s$ points in a time $T_c = T_f - T_s$.

The previous equations yield $T_f = T_s/(1 - B_s/B_f)$. The fastest analyzer configuration is obtained by choosing a convolution filter with a minimum dispersion time $T_f$. With the present limitation on filters ($T_f < 200$ $\mu$s, $B_f < 1$ GHz, and $B_f T_f < 10^4$). Fig. 3 gives plots of the minimum time of analysis of $N$ points for various signal length $T_s$.

This is to be compared to the computation time of an FFT digital circuit employing one butterfly with a process-

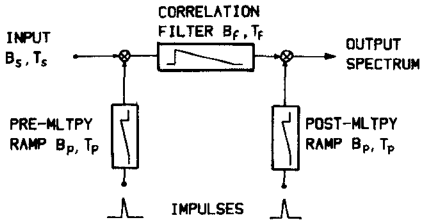



Fig. 2. Schematic of the SAW chirp transform spectrum analyzer.

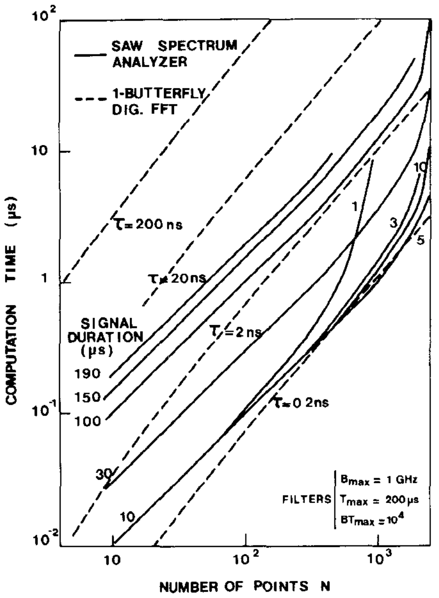



Fig. 3. Comparative plots of the processing speeds of SAW and digital Fourier analyzers.

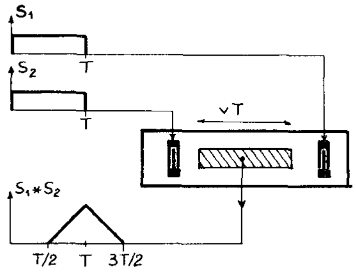



Fig. 4. Schematic of a piezoelectric SAW convolver.

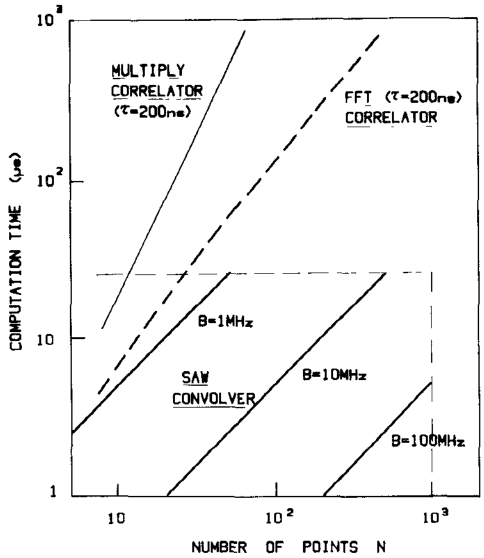



Fig. 5. Comparative plots of the processing speeds of SAW and digital correlators.

ing time $\tau$; i.e., $N(\tau/2)\log_2 N$. The lower butterfly time is 200 ns and a more common value is 1 $\mu$s. Curve fitting of Fig. 3 by the FFT law shows that the equivalent time $\tau$ of an SAW Fourier transformer for signal durations of 1 to 50 $\mu$s varies between 0.2 and 2 ns, hence a $10^2$ to $10^3$ gain in speed over digital circuits.

Most SAW analyzers have the same volume and power consumption. For example, an experimental unit able to analyze 450 points in 15 $\mu$s fills a volume of 0.2 l for a 1-W consumption. By comparison, a digital analyzer built around one 200-ns butterfly (hence 100 times slower) would fill a volume of 0.3 l and dissipate 20 W. It is to be noticed that system reliability is an inverse function of dissipated power.

The acoustic convolvers are a second interesting case. The simplest devices are composed of two identical transducers and a uniform output electrode [3] (see Fig. 4). If $T$ is the propagation time under the electrode, optimum performances are obtained when convolving two simultaneous signals of duration $T$. The computation time is then $T/2$.

Plots of the processing times versus number of points and input signal bandwidth are given in Fig. 5; they are compared to those of digital correlators made of multipliers or better of FFT circuits with 200-ns elementary butterfly time. Acoustic systems are $10^2$ to $10^3$ times faster. Existing acoustic units (with input and output amplifier) able to process 500 points in 5 $\mu$s only fill a volume of 0. 15 l and the power consumption is equal to a few watts. By comparison, 200 times slower digital correlators (512 points in 1 ms) would require a volume of 1 l and dissipate 100 W. In order to show the capacity and the feasibility of hybrid systems employing the two technologies, several practical systems are now described. The basic processors are Fourier transformers and correlators.

## III. Fast Fourier Analysis Applied to Sea-Bottom Imaging Sonar Systems

One of the many applications of spectrum analysis is beamforming. In the case of sea-bottom imaging sonars, antennas are generally linear arrays of periodically spaced transducers. The relative bandwidth of these active sonars is rather narrow so that beamforming may be achieved by Fourier transformation [12] of the signal made of the time multiplexed sequences of complex (amplitude and phase) samples of all transducer signals. Correct sampling of each transducer requires that the sampling frequency be much larger than the operation bandwidth; hence the need for fast switches. The Fourier transformation can advantageously be performed by one SAW chirp transform module

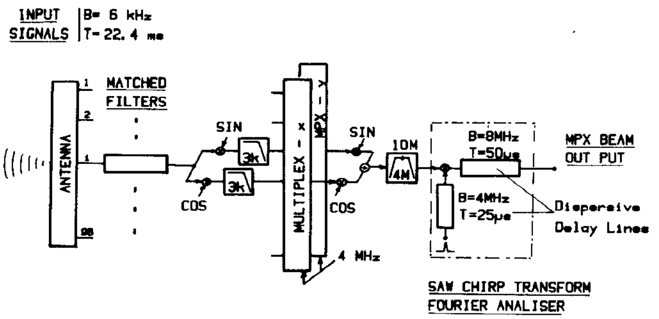



Fig. 6. Example of beamforming in a sea-bottom imaging sonar via fast multiplexing and Fourier transformation.

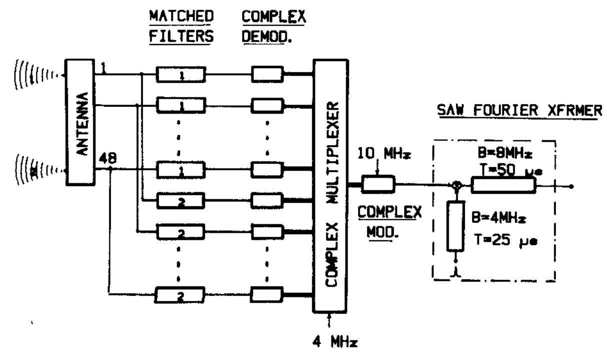



Fig. 7. Generalized beamforming technique in the case of two-illuminator antennas.

of the type described previously.

Fig. 6 shows an example of a sonar system with 96 receiving transducers and one illuminator. FM pulses with 22.4-ms duration and 6-kHz bandwidth are transmitted. After reception, matched filtering is performed by CCD means [13]. Complex demodulation follows; the real and imaginary signals of each channel are next sampled and time multiplexed at a 4-MHz rate; complex modulation of a carrier frequency generates 4-MHz bandwidth, 25-$\mu$s duration signals which can easily be analyzed by an SAW module.

The output is the beamformed signal corresponding to a given range cell. The next sampling of the transducers, 50–100 $\mu$s later, yields the information concerning the next range cell. It is worth noting that SAW processing of sonar signals does not here require any time compression or storage. Interfacing is simply achieved through fast sampling of the many parallel inputs.

Another substantial advantage of this beamforming technique is the possibility to generalize it to systems making use of several illuminators, in order to increase the angular resolution of a given antenna. The simple example depicted in Fig. 7 shows a 48-element antenna with one illuminator at each end, transmitting orthogonal codes with the same duration and bandwidth as previously. After reception, matched filters isolate the echoes associated with each illuminator. The 96 resulting signals are then multiplexed to synthesize the aperture of a 96-element antenna. The output is processed by means of the same Fourier analyzer as before.

Comparison of Figs. 6 and 7 shows that the same number of electronic circuits is necessary. The filters are only of two types. The angular resolution is unchanged; but the antenna length has been divided by 2. This gain very often justifies the slight loss in signal-to-noise ratio of some 3 dB which also results if the radiated power is unchanged.

## IV. Two-Dimensional Fourier Transformers

A field of application where SAW-to-digital coupling is necessary to yield speed, simplicity, and performances is that of a two-dimensional transforms. Among them, the Fourier transform is particularly useful and simple to implement. All that is required are one-dimensional Fourier transformers and an intermediary memory where the information is written in along lines and readout along rows. The capacity and dynamic range of analog memories being too low, digital memories have to be chosen: the SAW and digital technologies must again be married.

The schematic of a digital-in–digital-out $512\times512$ point transformer is shown in Fig. 8. This analyzer can process in real time 4-MHz baseband signals (TV standard). The input digital information is coded over 8 complex bits. It is converted into a real 8-MHz bandwidth signal with a 64-$\mu$s line time and next processed in two acoustic analyzers made of filters with dispersions 64 $\mu$s$\times$8 MHz and 128 $\mu$s$\times$16 MHz; due to the 27-dB processing gain, logarithmic amplifiers must follow them to compress the output dynamic range and keep an 8-bit coding. Complex coding is achieved through complex demodulation and A/D conversion. The intermediary memory is composed of 80 64-kbit RAM packages. To be compatible, the converters must operate at 10 MHz and the memory must show an effective access time of 100 ns.

As it stands, such a subsystem may be directly inserted in existing digital information processing or computation systems, where it would replace dual FFT logic circuits. In some instances, like the video processors, input or output converters are not required, and simplifications follow. Full two-dimensional ensembles have not yet been built but research groups are already working on one-dimensional fully digitally compatible Fourier analyzers [14], [15].

Referring again to the imaging field, one can find direct applications of these units to front plane two-dimensional imaging sonars [16]. The antenna is composed of a square matrix of narrow-band transducers with one illuminator. Two-dimensional beamforming is to be performed in a time corresponding to the system depth of focus to limit the background reverberation noise. A high resolution sonar with a $100\times100$ element antenna might, for instance, require a depth of focus of 5 to 8 m and integration time should then be limited to 5 ms. The maximum scan rate would then be 200 images/s.

Beamforming may again be performed by Fourier analysis of the fast sampled inputs (see Fig. 9). A set of 100 parallel low-speed multiplex switches connects each line of transducers to complex demodulators. Fast 4-MHz multi-

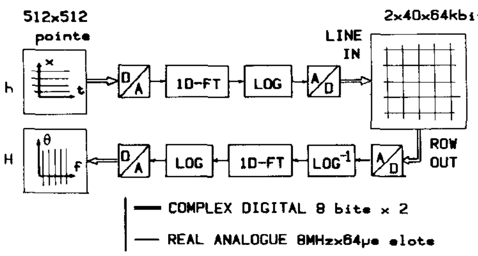



Fig. 8. Example of implementation of a 512×512 8-bit two-dimensional hybrid Fourier transformer.

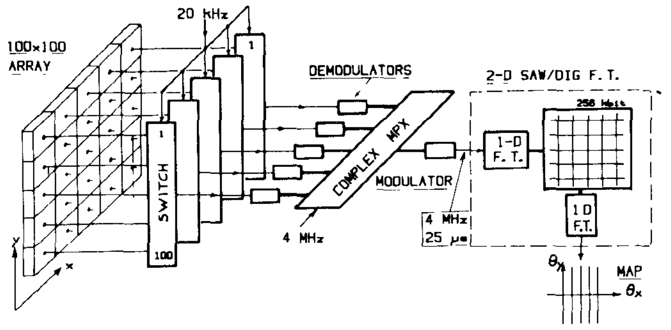



Fig. 9. Application of two-dimensional Fourier transformer to two-dimensional beamforming in imaging sonars.

plexing and HF modulation results in 4-MHz bandwidth, 25-$\mu$s duration line signals which are inputs to an SAW–digital two-dimensional Fourier transformer. This transformer requires a 256-kbit memory size with a 200-ns access time and 5-MHz clock rate converters.

Following the same principles as those presented in Section II it is possible to reduce the size of the antenna with no increase in angular resolution and system complexity. For instance, one may employ a 50×50 element antenna with one illuminator at each corner, transmitting orthogonal signals. Matched filters isolate the received signals and reconstitute 100×100 received signals. The gain in antenna volume and complexity is even more drastic in this case and it allows for large antenna to be synthetized with a fairly limited loss in range.

## V. Correlation Processing

This label groups the processing techniques where any two signals are convolved or correlated. Although the same basic function is performed, a wide range of applications exists. The "sidelooking" synthetic aperture radar [17] requires matched filtering of the signals corresponding to the different range cells. In spread-spectrum telecommunications [18], one talks of fast demodulation. Other receivers compare incoming signals to a known library, the aim being identification or sorting [19]. Finally, imaging systems need two-dimensional processors capable of correlating maps or images to allow for route alignment or identification. And there are many more applications. When very fast processing is compulsory, acoustic convolvers give simple answers to these questions; but they often need a digital backing as the following examples will demonstrate.

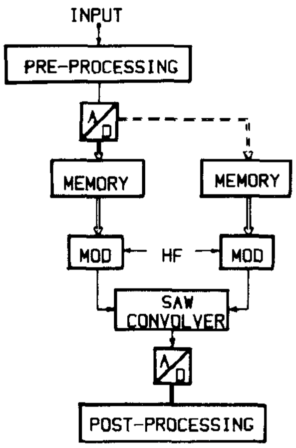



Fig. 10. General scheme of correlation receivers.

### A. *General One-Dimensional Correlation Receivers*

To make an efficient use of an acoustic convolver, the signals to be processed should appear at time differing by less than a few microseconds and should be wide band. These are the two reasons why input memories are generally necessary: they act as buffers and/or time–bandwidth transformers.

The most general type of receiver is represented in Fig. 10. Incoming signals are stored in digital memories and successive signal slots are later compared to previously stored or library signals. For that purpose, the memory contents modulate a carrier and the resulting signals are combined in a convolver. The output is stored and/or further processed.

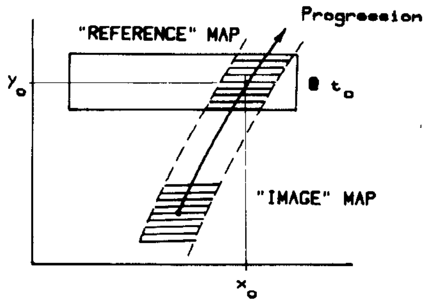
Various particular organizations exist depending on the application (acquisition, sorting, filtering). Signals can be directly fed into the acoustic device (e.g., radar IFF). However, an input memory may act as a time compressor [10], [11] to match the signal characteristics to those of the convolver and be able to perform a large number of correlations in one repetition cycle.

In a synthetic aperature radar, the received signal is stored during the plane progression and its duration corresponds to the time a point target spends crossing the antenna beam (e.g., approximately 1 s). To use a 10-$\mu$s convolver, the input memory must perform a $10^5$: 1 time compression (the readout frequency must be of the order of 10 MHz if the maximum number of samples per range cell is 100). Hence up to $10^5$ range cells can be processed real time in one device! All the computation circuits would fill a volume of 0.3 l and dissipate 5 W [9]. This does not include the memory which is present in all configurations.

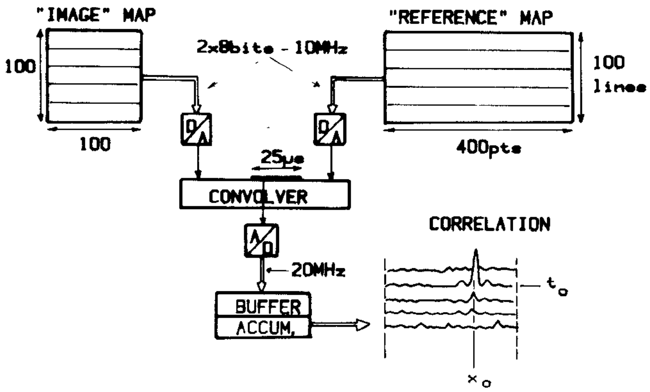
### B. *Two-Dimensional Correlation Schemas*

Since the two-dimensional correlation is not a separable function, it is not possible to perform it by means of two cascaded one-dimensional processors. Interesting solutions yet exist which require one convolver and one digital accumulator. One of them, depicted in Fig. 11, applies to on-board map alignment.

A plane reads the portion of ground which it flies over




(a)




(b)

Fig. 11. Principle and example of implementation of a two-dimensional map correlation system.

and stores the last $N$ lines scanned (see Fig. 11(a)). The map of the ground strip located around ordinate $y_o$ is also stored on-board. The processor should correlate this "reference" map to the "image" map in order to determine the date $t_o$ and abscissa $x_o$ when and where the plane ordinate is $y_o$.

One possible system uses one acoustic convolver and two memories as shown in Fig. 11(b). To be meaningful, the number $P$ of points per line in the reference map should be greater than that of the image map, $M$. Choosing $P=400$, $M=N=100$, the memories can be accessed at a 10-MHz frequency and the line-by-line correlation functions can be performed in a convolver with a 25-$\mu$s processing time. The 100 outputs are added by means of a digital accumulator and one line of the two-dimensional correlation function is obtained after 100 intermediary line correlation, i.e., in a minimum time of 5 ms. Real time processing is, therefore, possible provided the line scan time is greater than 5 ms which corresponds to a 3-m progression at speed Mach 2.

## VI. Conclusion

The digital and SAW technologies have progressed independently for some fifteen years and they have long been assumed noncompatible. This barrier is now falling and coupling these two technologies is not a laboratory exercise any more. It offers new perspectives to ultrafast and real-time signal processing. This paper has attempted to show the feasibility and the advantages of processors built in this way. The list of examples presented was by far not exhaustive.

Most SAW devices applied to signal processing are still being developed. But future needs in digital components and interfaces are already clear. To use the full capacity of the acoustic components it would thus be worth increasing the operation frequency of A/D converters and memories. Sampling frequencies of 500 to 1000 MHz for an 8-bit coding and 1- to 10-ns memory access times are interesting goals. Reduction in memory size and power consumption will remain another major objective, especially when compared to the performances of the acoustic components in this respect.

It is to be remembered that, although of limited use because of their present low speed, analog memories are best suited to acoustic processing (analog samples are stored and memories can be digitally controlled). The ideal processor would be composed of analog memories, acoustic "calculators," and digital control and post-processing units.

## References


[1] R. C. Williamson, "Properties and applications of reflective array devices," *Proc. IEEE*, vol. 64, pp. 702–710, 1976.
[2] M. B. N. Butler, *SAW Devices for Signal Processing*. IEE Pub. no. 180, pp. 21–33, 1979.
[3] P. Defranould and C. Maerfeld, "A SAW planar piezoelectric convolver," *Proc. IEEE*, vol. 64, no. 5, pp. 748–751, 1976.
[4] S. A Reible, J. H. Cafarella, R. W. Ralston, and E. Stern, "Convolvers for DPSK demodulation of spread spectrum signals," in *Proc. 1976 IEEE Ultrasonics Symp.*, pp. 451–455, 1976.
[5] T. W. Bristol, *Review of Spectrum Analysis with SAW Chirp Transforms and Filterbanks*. IEE Conf. Pub. no. 180, pp. 226–231, 1979.
[6] M. G. Holland and L. T. Clairborne, "Practical surface acoustic wave devices," *Proc. IEEE*, vol. 62, pp. 582–611, 1974.
[7] J. D. Maines and E. G. S. Paige, "Surface acoustic wave devices for signal processing applications," *Proc. IEEE*, vol. 64, pp. 639–652, 1976.
[8] *Proc. 1979 MTT-S International Microwave Symp.* (1st Specialist Conf. on Gigabit Logic for Microwave Systems, Orlando, FL, May 3–4 1979).
[9] T. Beauvais, R. Carre, and H. Gautier, *Interfacing and Comparison of Surface Acoustic Wave and Digital Technologies*. IEE Conf. Pub. no. 144, 1976.
[10] P. Tournois and J. Bertheas, "Use of dispersive delay lines for signal processing in underwater acoustics," *J. Acoust. Soc. Amer.*, vol. 46, pp. 517–531, 1969.
[11] J. Bertheas and P. Tournois, *Applications of Microwave Acoustic Components to Sonar Signal Processing*. IEE Conf. Pub. no. 109, pp. 287–298, 1973.
[12] J. R. Williams, "Fast beamforming algorithm," *J. Acoust. Soc. Amer.*, vol. 44, pp. 1454–1455, 1968.
[13] H. Gautier and P. Tournois, "Signal processing using SAW and digital components," *Proc. Inst. Elec. Eng.*, vol. 127, pt. F, pp. 92–98, 1980.
[14] V. S. Dolat, M. B. Schulz, L. A. Veilleux, G. R. McCully, and R. C. Williamson, "High performance hybrid SAW chirp-Fourier-transform system," in *Proc. 1978 IEEE Ultrasonics Symp.*, pp. 527–532, 1978.
[15] C. Lardat, private communication.
[16] P. Rudnik, "Digital beamforming in the frequency domain," *J. Acoust. Soc. Amer.*, vol. 46 (pt I), pp. 1089–1090, 1969.
[17] A. W. Rihaczek, *Principles of High Resolution Radar*. New York: McGraw-Hill, 1969, ch. 13.
[18] R. C. Dixon, *Spread Spectrum System*. New York: Wiley, 1976.
[19] P. Anthouard and T. Beauvais, "Application d'un convoluteur piézoélectrique au traitement du signal radar," in *AGARD Conf. Proc.*, no. 230, paper 5.4, 1977.