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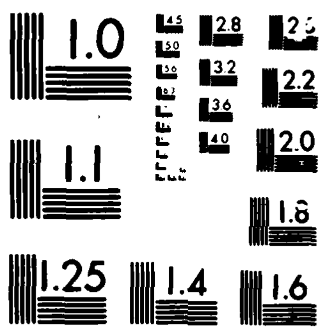

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This research program centered on the investigation of low-accuracy analog opto-electronic methods for processing multi-sensor-array data (e.g., phased array radar, sonar). Two methods were considered for signal orthogonalization in low-accuracy preprocessors, one based on a resonant piezo-electro-optic modulator, the other based on photo-refractive and similar spatial light modulator devices. Neither method appears to offer significant benefits over all-electronic preprocessor methods because of the

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lack of large-scale parallelism. An analog, continuous-time opto-electronic processor for adaptive phased array signal processing was also considered that does exhibit considerable parallelism and shows promise for use as a low-accuracy co-processor in a hybrid analog/digital configuration.

OPTICAL DIGITAL ALGEBRAIC PROCESSING FOR MULTI-SENSOR-ARRAY DATA

FINAL TECHNICAL REPORT ON

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Summary

This research program centered on the investigation of low-accuracy analog opto-electronic methods for processing multi-sensor-array data (e.g., phased array radar, sonar). Two methods were considered for signal orthogonalization in low-accuracy preprocessors, one based on a resonant piezo-electro-optic modulator, the other based on photo-refractive and similar spatial light modulator devices. Neither method appears to offer significant benefits over all-electronic preprocessor methods because of the lack of large-scale parallelism. An analog, continuous-time opto-electronic processor for adaptive phased array signal processing was also considered that does exhibit considerable parallelism and shows promise for use as a low-accuracy co-processor in a hybrid analog/digital configuration.

SUMMARY OF RESEARCH

1. Objectives of Research

The principal objective of this research program was to determine whether low-accuracy analog opto-electronic signal processing methods could be used effectively to pre-process multi-sensor array signal data to improve the overall performance of an analog optical/digital electronic algebraic signal processing system.

2. Background

The Air Force has many signal processing tasks, particularly those associated with multi-sensor-array data, that lie beyond the current capabilities of electronic signal processing systems. The development of highly parallel processing architectures and algorithms, coupled with improvements in VHSIC technologies, will increase significantly the capabilities of electronics for such tasks. Optics, with its high degree of parallelism, enormous bandwidth, and three-dimensional interconnect capability, also offers potential solutions.

Emphasis on optical signal processing research has been placed in recent years on the study of *algebraically-oriented processors* suited for specific operations like direction finding, beam forming, and adaptive noise cancelling, and for more general operations like least-squares solution of sets of linear equations and singular-value decomposition. Often, high accuracy (e.g., 32 or more bits on a digital processor) is required for satisfactory performance. Unfortunately, optical processors are inherently analog in nature, and digital accuracy is obtained only at a significant price in terms of system throughput, complexity, and cost. For example, the SAOBiC processor, at one time under development by GuilTech Research Company [1], though offering in excess of 500×10^6 32-bit floating-point operations per second, was still slow compared to all-electronic processors and far behind the 10^{10}-10^{11} operations per second offered by analog-accuracy optical processors.

One well-established method for increasing the speed of processing systems for data from multi-sensor arrays is through suitable preconditioning of the input signal data. Preprocessing is regularly performed on signal data in adaptive phased array radar signal processors. Significant increases in overall processor speed generally result and, in some cases at least, reduction in system cost as well [2]. The key to increasing convergence rate in these cases is in effect a transformation applied to the input signal correlation matrix that reduces the spread in the eigenvalues of the matrix. This is equivalent to improving the condition number of the matrix, with greater stability resulting for subsequently-applied algorithms. A particularly important aspect of such preprocessing is that it need not be performed with high accuracy: low-accuracy analog preprocessors, effecting, for example, an approximate orthogonalization on the input signal vectors, are regularly used in cascade for adaptive phased array radar signal processing [3].

Two major areas of investigation received emphasis in the research program. One centered on the basic operations required of opto-electronic components for signal orthogonalization and on ways for performing those operations. The other centered on a particular processor for performing adaptive phased array radar signal processing. Both areas are discussed in detail in the following sections.

3. Signal Orthogonalization

One of the most attractive preprocessors for adaptive phased array signal processing is the Gram-Schmidt cascade preprocessor [4], which effectively decorrelates, or orthogonalizes, signals from the antenna array elements. Figure 1 shows a system using the Howells-Applebaum form of adaptive-loop processor for signal orthogonalization. A single adaptive loop is shown in Fig. 2. The purpose of the loop is to compute an output signal $y_j(t)$ that contains only information that is not contained in signal $y_i(t)$, i.e., innovative information. This is accomplished by calculating $y_j(t)$ in accord with the equation

$$Y_j(t) = X_j(t) - \gamma_{ij}(t)y_i(t) \tag{1}$$

where $\gamma_{ij}(t)$ is a correlation coefficient given by

$$\gamma_{ij}(t) = \frac{\langle y_i^*(t)x_j(t)\rangle}{\langle y_i^*(t)y_i(t)\rangle} \tag{2}$$

the angle brackets denoting a time average. It is easily shown that in the steady state, $y_i(t)$ and $y_j(t)$ are uncorrelated, i.e., $\langle y_i^*(t)y_j(t)\rangle = 0$. For the case of interest, $y_i(t)$, $x_j(t)$, etc., represent the complex envelopes of associated narrowband signals.

It is evident from Eq. (1) that an opto-electronic preprocessor of the Gram-Schmidt type must be able to perform three elementary operations: 1) signal multiplication; 2) correlation coefficient calculation, which involves a time average; and 3) signal subtraction.

Two basic approaches to performing these three operations were considered in this program. One involves the use of a resonant piezo-electro-optic

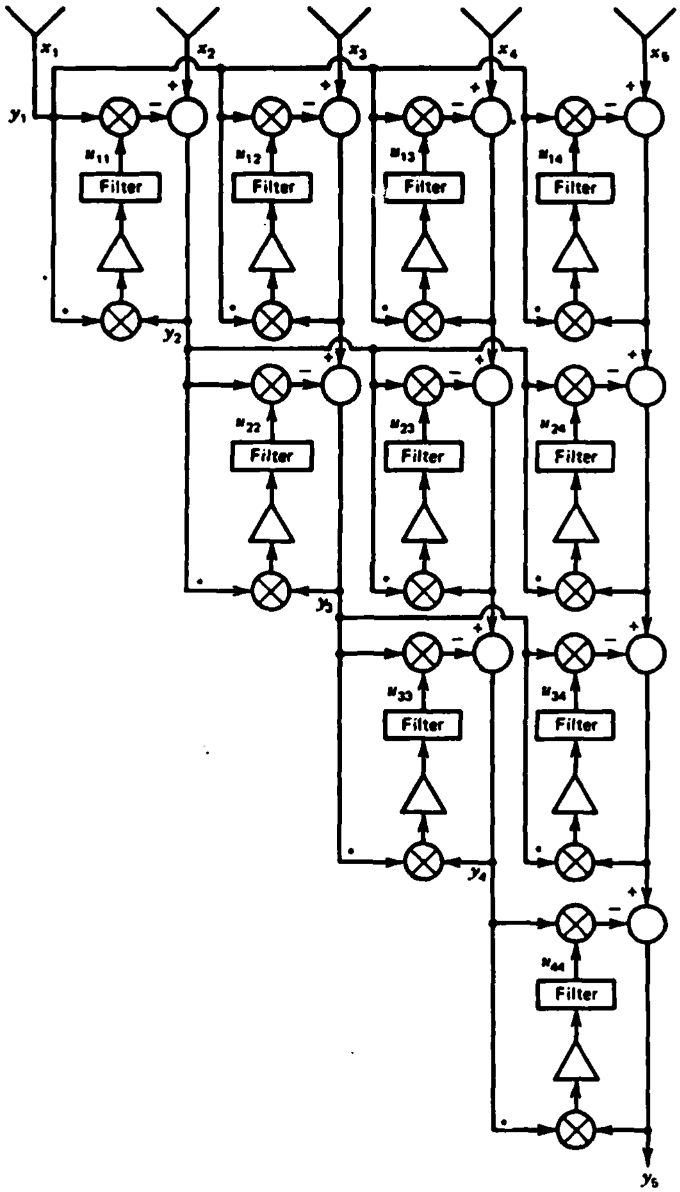

Fig. 1. Gram-Schmidt orthogonalization for a five-element array using Howells-Applebaum adaptive loops. [From Ref. 8.]

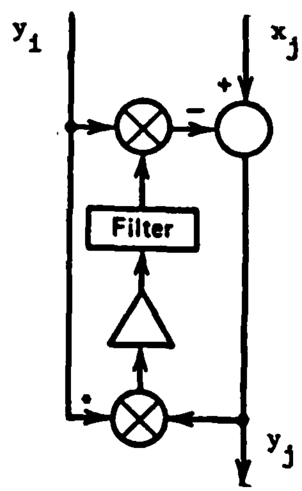

Fig. 2. Single adaptive-loop processor.

modulator device. The other relies on time-averaging characteristics of quasi-real-time, light-addressable spatial light modulators. These two approaches are discussed in the following sections.

3.1. Resonant Piezo-electro-optic Modulator

A resonant piezo-electro-optic modulator [5,6,7] can perform both the multiplication of $y_i(t)$ by $\gamma_{ij}(t)$ in Eq. (1) and the time average needed to calcualte $\gamma_{ij}(t)$.

The device is similar in many respects to an ordinary linear electro-optic modulator, but it is operated in an a.c. mode at the piezo-electric resonance vibration frequency of the crystal. At this frequency, shear and thickness mode vibrations of the crystal result in large sinusoidal fluctuations of the birefringence of the crystal with the application of relatively small a.c. voltages. If placed between crossed polarizers and driven at the resonance frequency ω_o, the modulator produces fluctuations in light intensity transmittance τ in accord with the equation

$$\tau = \sin^2 \left[\frac{1}{2} \Phi \cos \omega_o t \right] \qquad (3)$$

where Φ, the peak birefringent retardation, is directly proportional to the amplitude of the applied sinusoidal voltage. Depending on the crystaline material used, resonant frequencies in the range 0.5 to 500 MHz appear to be easily obtained [5,6]. Because of the mechanical resonance, voltages required to achieve significant changes in transmittance τ are typically several orders of magnitude lower than those required for the d.c. linear electro-optic (Pockels) effect. Specifically, a.c. voltages in the 5-20 volt range are adequate in reported cases for high efficiency modulation.

For optical processing applications device transmittance τ should vary linearly with the applied signal. If the crystal used has some natural birefringence or is illuminated by light of the appropriate elliptical polarization, the operating point of the device can be shifted such that τ has the form

$$\tau = \sin^2 \left[\frac{\pi}{4} + \frac{\Phi}{2} \cos \omega_o t \right] \quad (4)$$

Theoretical considerations show that for an applied driving a.c. voltage V at an arbitrary frequency ω, device response can be written as

$$\tau = \sin^2 \left[\frac{\pi}{4} + \beta \left(\frac{V}{V_o} \right) \cos \omega t \right] \quad (5)$$

where V_o is a constant that appears typically to be in the 1-20 volt range and β is a resonance parameter given (in the vicinity of resonance - far off resonance τ is essentially constant) by the standard resonance function

$$\beta = \beta(\omega) = \left[1 + 4Q^2 \left(\frac{\omega-\omega_o}{\omega_o} \right)^2 \right]^{-\frac{1}{2}} \quad (6)$$

Device Q, unless deliberately reduced, is typically of the order of 10^3, and the reasonance is thus extremely sharp.

So long as the applied voltage V is kept sufficiently small, τ can be written in the form

$$\tau \cong \frac{1}{2} + \beta(\omega) \left(\frac{V}{V_o} \right) \cos \omega t \quad (7)$$

There is a phase shift introduced for $\omega \neq \omega_o$, but this does not affect the results in the applications of interest.

The high-Q resonance just described can be exploited in estimating the correlation coefficient γ of Eq. (2) through the approximation

$$\gamma_{ij}(t) \approx \frac{1}{T} \int_{-\infty}^{t} y_i^*(\xi) y_j(\xi) \exp\left[\frac{t-\xi}{T}\right] d\xi \qquad (8)$$

Figure 3(a) illustrates estimator operation schematically for a single pair of antenna element signals; Fig. 3(b) shows the same operation in complex signal form. In the latter, the resonant filter is represented by the transfer function associated with its baseband equivalent, which is a simple RC filter. The output of the filter is slowly time-varying, with approximate bandwidth 1/T.

It should be emphasized that the high-Q filter of Fig. 3(a) is the electro-optic device itself and that its output is not an electrical signal but rather the modulated light transmittance τ of Eq. (7). Figure 4 models the essential input-output characteristics in terms of a resonant tuned circuit and the electo-optic transfer characteristics. The input signal is the product of the two IF signals of Fig. 3, with the filter tuned to the difference frequency ω_o.

Figure 5 shows a possible configuration of the adaptive loop processor using the resonant piezo-electro-optic modulator, with all signals represented for convenience in complex form. The function $\{b + y_i \exp[j\omega_o t]\}$ represents the light intensity illuminating the resonant piezo-electro-optic modulator, bias b being added to avoid clipping on negative parts of the signal.

The overall Gram-Schmidt signal orthogonalizer would consist of a number of such loops operating in a configuration suggested by Fig. 1. System dynamic range is limited primarily by nonlinear terms not contained in Eq. (7) and by noise associated with the bias.

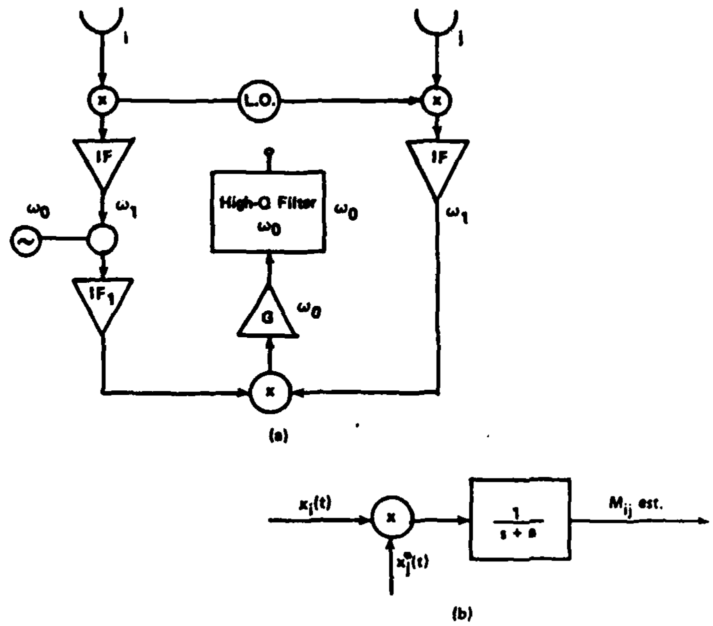

Fig. 3. Estimator operation:
(a) real signal flow diagram;
(b) complex representation.

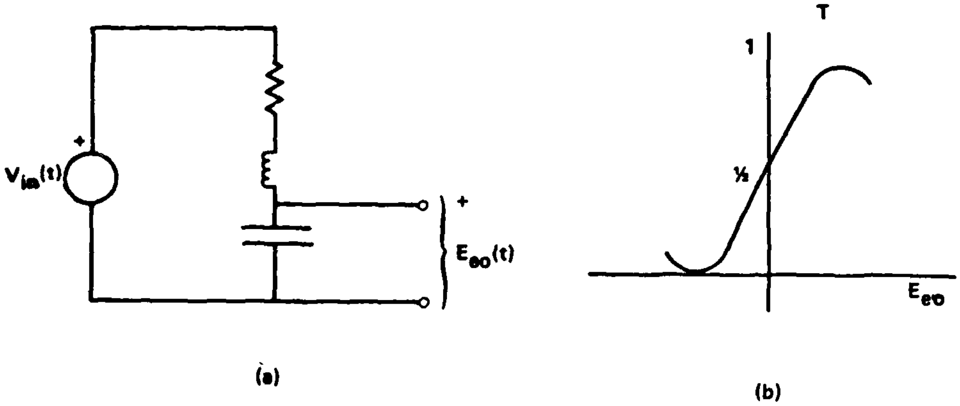

Fig. 4. Resonant tuned circuit model and transfer characteristic.

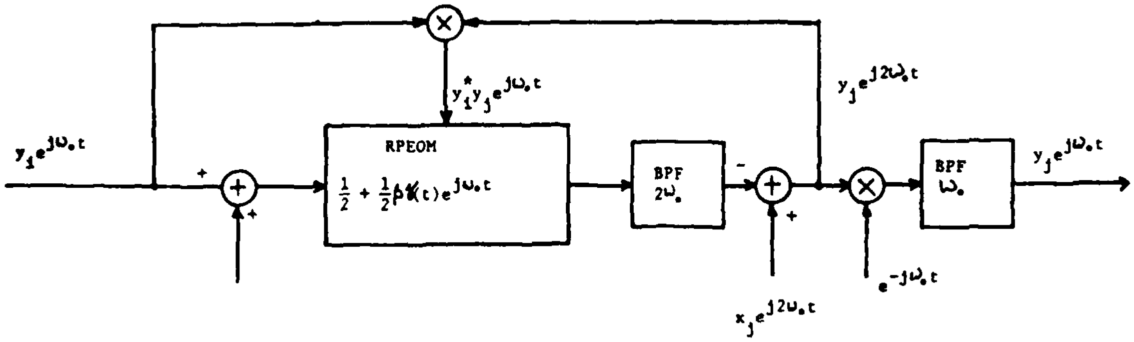

Fig. 5. Possible opto-electronic adaptive loop processor with resonant piezo-electro-optic modulator (RPEOM).

3.2. Photo-Addressable Spatial Light Modulator

As noted earlier, the resonant piezo-electro-optic modulator serves both to calculate the correlation coefficient through its high-Q time-averaging characteristics and to multiply $y_i(t)$ by that coefficient through its a.c. light intensity transmittance. An alternative approach is to use photorefractive or other light-addressable spatial light modulator (SLM) materials.

The idea is based on the observation that Young's interference fringes can be used as a direct measure of the correlation of two optical waves. In particular, if two tilted plane waves with complex amplitudes $y_i(t)$ and $y_j(t)$ are allowed to interfere, the resultant fringe pattern has amplitude proportional to the correlation coefficient γ_{ij} of Eq. (2). If this fringe pattern is used to expose a light-addressable SLM, a grating structure results that can diffract an incident light wave. Assuming linearity, the amplitude of the diffracted wave is proportional to the grating amplitude, which, as noted, is proportional to γ. Thus a wave with amplitude proportional to $\gamma_i y_{ij}(t)$ can be produced.

One possibility is to use a pair of acousto-optic modulators driven by narrowband signals having complex envelopes $y_i(t)$ and $y_j(t)$. These produce a pair of waves, incident on a light-addressable SLM, with complex amplitudes

$$U_i(x,y,t) = Y_i(t) \exp[j2\pi f_o x] \exp[j\omega_o t] \qquad (9a)$$

and

$$U_j(x,y,t) = Y_j(t)\ \exp[j2\pi f_o x]\ \exp[j\omega_o t] \qquad (9b)$$

The interference of these two waves produces an exposing intensity at the SLM of the form

$$I(x,y)\ \alpha\ \text{bias} + |\gamma_{ij}|\ \cos[\omega_o x + \arg\{\gamma_{ij}\}] \qquad (10)$$

where γ_{ij} is the correlation coefficient specific to a time integration over the exposure period.

Assuming a linear response of the SLM to the exposing wave intensity, a complex wave amplitude transmittance of the form

$$t(x,y) = t_b + \alpha[\ \gamma\ \exp[j2\pi f_o x] + \gamma^*\ \exp[-j2\pi f_o x]\ ] \qquad (11)$$

results. If the grating is illuminated with light of complex amplitude $y_i(t)\exp[-j2\pi f_o x]$, a transmitted wave proportional to $y_i(t)\gamma_{ij}$ results, which, with a proper phase relationship, can be subtracted from a wave of amplitude $x_j(t)$.

In Eq. (11) γ is written as a constant. In general, however, γ is a function of time, varying with a bandwidth that may exceed tens or even hundreds of kilohertz. In order for the grating transmittance to vary with time in the proper way, the light-addressable SLM grating must "track" the local time average of the exposure pattern. Specifically, it should have a time constant, both for fringe buildup and decay, in the range from tens of milliseconds to tens of microseconds, depending on the application. Photorefractive materials such as BSO exhibit such characteristics and would be a possible candidate. For photorefractive materials, the rise time for writing differs from the relaxation time for erasure and is, in fact, dependent on the intensity of the writing light distribution, suggesting the need for automatic gain control.

Although the correlation coefficient and the product γy_i can in theory be calculated, this scheme presents too many difficulties to be particularly practical for real-time signal processing tasks. For one thing, the wave field being diffracted by the grating must not seriously perturb the grating structure itself. This means that the diffracted wave field should be incoherent with the two interfering waves, preferably of a wavelength at which the SLM is not sensitive. Probably more serious a limitation is that, unlike for the resonant piezo-electro-optic modulator, complex wave amplitudes bear the signal information. The adaptive loop processor must therefore have the form of an interferometer, capable of modulating, adding, and subtracting wave amplitudes. When this limitation is added to the architectural difficulties discussed, the SLM scheme appears to be impractical for the processing operation of interest here.

3.3. Parallelism Considerations

In the final analysis, although both the resonant piezo-electro-optic modulator scheme and the light-addressable SLM scheme could perform the desired functions, neither appears to be competitive with all-electronic schemes. This conclusion is reached largely through architectural considerations. Simply put, that fraction of an opto-electronic Gram-Schmidt signal orthogonalizer that would be optical is relatively minor and, of much greater importance, it does not exploit optical parallelism in any way. A conclusion reached by many optical signal processing researchers is that an optical processor will not compete with its electronic counterpart unless the optical processor operates with a high degree of parallelism, preferably through global interconnections. The Gram-Schmidt processor requires none of this and there is no reason, in fact, that the integration-multiplication capabilities of the opto-electronic devices discussed should not be replaced by electornic multipliers and integrators.

4. Adaptive Beamforming Processing

One way in which the resonant piezo-electro-optic modulator device can be used with much more optical parallelism is in the direct processing of antenna element signals for adaptive beamforming. There is no longer the sought-for relationship between a low-accuracy analog preprocessor and a high-accuracy digital post-processor. However, it may be possible to use the low-accuracy optical system in a co-processor configuration along the lines recently proposed by Caulfield [10].

The system for performing the radar signal processing calculations is an electro-optical matrix-vector multiplier in an analog feedback system. Related systems have been investigated before [8], but always they have implemented the necessary complex arithmetic using relatively awkward negative-real representations for complex variables. Furthermore, they have operated on an iterative basis rather than the *continuous* basis facilitated by the resonant piezo-electro-optic modulator.

The principal goal of the processor is the calculation of the optimum complex array weighting vector w that satisfies the matrix-vector equation

$$s^* = Mw \qquad (12)$$

where M is the covariance matrix associated with the (complex) signal from the antenna elements and s is the array steering vector. Iterative processors calculate w via the algorithm

$$w_{k+1} = s^* + (I - M)w_k \tag{13}$$

the complex arithmetic being implemented using nonnegative-real (e.g., three-component or biased real-imaginary) representations for the matrix and vectors. Figure 6 illustrates a system for calculating w using dynamic relaxation methods. The integrators in the system can be replaced by simple RC filters if the matrix M (which represents the signal environment in the adaptive phased array radar case) is time-varying. It can be shown that the system is stable if the matrix M is positive-definite, in which case the eigenvalues of M have real parts that are positive. The covariance matrix M of Eq. (12) is indeed positive-definite, and non-oscillatory convergence is assured.

Operation of the system is described in terms of the inversion of the matrix equation

$$y = Mx \tag{14}$$

where x is to be solved for. In the radar case, all vector and matrix components are narrowband signals and can be written in the form

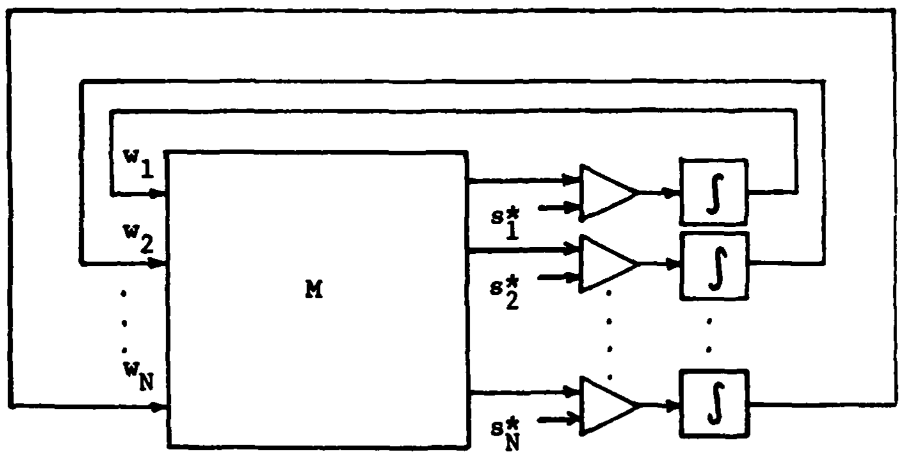

Fig. 6. System for calculating w using continuous relaxation method.

$$|x_i(t)| \cos [\omega_o t + \theta_x(t)] \tag{15}$$

$$|y_i(t)| \cos[\omega_o t + \theta_y(t)] \tag{16}$$

$$|m(t)| \cos[\omega_o t + \theta_{ij}(t)] \tag{17}$$

The key to system operation is an SLM made up of resonant piezo-electro-optic modulator elements exhibiting the time-varying light intensity transmittance

$$\tau_{ij} = b + |m_{ij}| \cos[\omega_o t + \theta_{ij}] \tag{18}$$

where b is a bias. Overall system operation is indicated by the block diagram of Fig. 7. Certain mixer-filter combinations have been made unnecessary by the use of complex representations for the signals. The optical matrix-vector multiplier is in most respects like the system described by Goodman et al. [9] except that the matrix elements m_{ij} are conveyed on a temporal frequency carrier.

The SLM representing M is made up of a 2-D matrix of individual resonant piezo-electro-optic modulators of the type discussed earlier. The input signal to the ijth element is the product of the ith and jth IF signals:

$$V_{ij}(t) = |x_i(t)| \cos[(\omega_1 + \omega_o)t + \theta_i(\tau)] \\ |x_j(t)| \cos[\omega_1 t + \theta_j(t)] \ . \tag{19}$$

with the filter being tuned to the difference frequency ω_o. Processing requires that all signal pair products be calculated and applied to separate

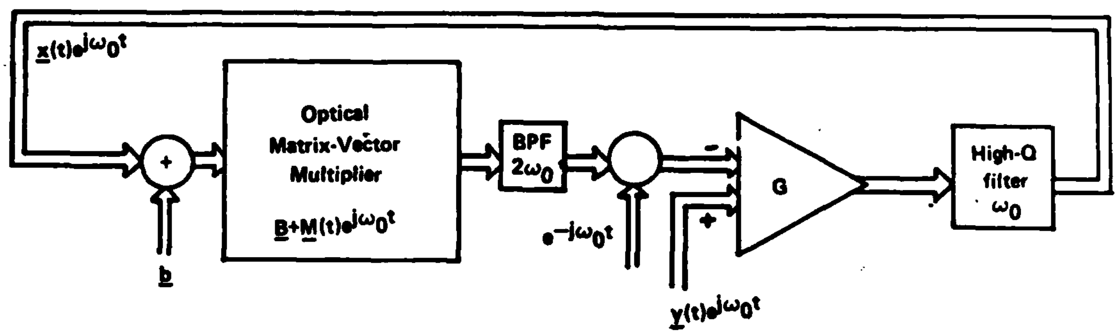

Fig. 7. Block diagram of a.c. electro-optic matrix inversion processor.

electro-optic elements of the matrix SLM.

Assuming the small signal approximation leading to Eq. (7) is satisfied, the transmittance of the ij^{th} cell of the resonant SLM is given by Eq. (18). The transmittance function evolves with a bandwidth approximated by 1/T, whereas the relaxation algorithm converges at a rate governed by the smallest eigenvalue of M.

5. General Conclusions

Low accuracy opto-electronic systems can be used for preprocessing of multi-sensor-array data to reduce the load on high-accuracy post-processors. However, based on architectural considerations of the Gram-Schmidt *preprocessor*, it would appear that there is insufficient parallelism in the optical systems to warrant replacing all-electronic preprocessors. The resonant piezo-electro-optic modulator approach considered shows promise for other signal processing applications where complex arithmetic must be performed. In particular, it shows promise for adaptive beamforming in cases where high accuracy is not required or where analog and digital coprocessors work side by side.

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1. William T. Rhodes, "Optical Matrix-Vector Processors: Basic Concepts," Proceedings of the SPIE, vol. 614, pp. xxx-xxx (1986).

PROFESSIONAL PERSONNEL

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Mr. Robert W. Stroud, doctoral candidate in electrical engineering

INTERACTIONS

Participated in AFOSR optical signal processing technical discussions held in connection with Optical Society of America Topical Meeting on Optical Computing held at Incline Village, Nevada, March 1985.

Met with Jacques Ludmann, RADC, Hanscom Field, June 1985, for general discussions on optical signal processing.

Presentations on related research made at SDI/ONR optical computing program reviews in San Diego (August 1985) and Washington, D.C. (October 1985).

Meeting with Captain Greg Swietek, HQ AFSC/DLAC, Andrews AFB, 7 November 1986, to discuss optical signal processing research.

Meeting with P. Denzil Stilwell, Radar Division, Naval Research Laboratory, 6-8 November 1985, to discuss fiber-optic-feed phased array radar system.

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