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Optical and Electronic Techniques for Sonar Signal Processing

T. J. CURRY
Ocean Systems Division
and
D. J. DeSANTIS
Target Development Division

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NAVAL UNDERWATER SYSTEMS CENTER
NEWPORT, RHODE ISLAND

TECHNICAL REPORT

OPTICAL AND ELECTRONIC TECHNIQUES FOR SONAR SIGNAL PROCESSING

Prepared by Thomas J. Curry
Thomas J. Curry
David J. DeSantis
David J. DeSantis

C.A. SPERO,JR.
Associate Director,
Weapons

18 June 1971

R.T. LUNDY
Captain, U.S. Navy
Commanding Officer

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FOREWORD

Requirements for signal processing systems for underwater acoustic signals are becoming increasingly demanding. Test and evaluation centers, specifically AUTEC, demand systems that can process larger amounts of data in shorter times.

A study of optical techniques for solving signal processing problems related to real time three dimensional tracking schemes and torpedo acoustic systems was conducted for more than a year, encompassing both extensive laboratory tests and research. This report summarizes the results of the investigation, enumerating the possible strengths and the current weaknesses of optical signal processing for the class of signal processing problems related to real time tracking and torpedo development.

This work was accomplished under Task Assignment Number NSSC RDT&EN Sub Project SF 1990301, Element 6520209N.

ABSTRACT

The possibility of employing optical techniques in acoustic signal processing is explored. The strengths and weaknesses of optical systems are examined and significant developments in electronic systems are noted.

Some state-of-the-art inadequacies of optical devices are discussed. Indications are that, for the signal processing related to three-dimensional tracking for test and evaluation, electronic techniques are presently the preferred approach. However, research findings indicate that extensive technological advances in optics may be experienced. If these are realized, the potential advantages of optical signal processing may become realizable in the future.

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INTRODUCTION

Modern underwater detection systems require sophisticated acoustic signal processors. As the state-of-the-art in these systems develops, the functions of acoustic signal processors become more complex, since larger amounts of data must be processed in shorter times.

Electronic systems function in a serial fashion; in order to process large amounts of data, several serial systems are usually operated simultaneously, or in parallel. This configuration has several disadvantages, all of which stem from the necessity for parallel operation. First, the number of necessary components could be too large; second, power consumption could be prohibitive; finally, the physical dimensions could be excessive.

An optical system, on the other hand, is inherently parallel. Since it operates in two dimensions, it avoids some of the problems of the serially functioning electronic system. High resolution in certain types of optical storage media could allow for processing large amounts of data (reference 1). The ease with which complex mathematical functions can be implemented optically is attractive; however, technological advances must be made before this advantage can be realized to an extent that would make the optical system for the stated applications competitive on all fronts. Four of the main considerations in evaluating state-of-the-art of optical systems are light modulators, light deflectors, real time storage media, and detectors.

LIGHT MODULATORS

One of the requirements in the realization of real time optical data processing is a device that converts electrical signals directly into optical signals. A compilation of data on light modulators was made (reference 2), paying particular attention to those that could have application to real time sonar signal processing. Three such schemes suitable for this application are ultrasonic light modulators (ULM), electro-optic light modulators (EOLM), and membrane light modulators (MLM).

Ultrasonic Light Modulators

The function of a ULM is to mix a laser beam with an acoustic beam in a suitable medium. This mixing results in modulation of the polarization, phase, frequency, or amplitude of the optical energy.

Ideally, the ULM will have a large operation bandwidth; high frequency of operation; large information storage capacity; low optical insertion loss; minimum phase distortion of the optical beam; and high power acoustic beam generation, with low propagation attenuation, resulting in good modulation efficiency. The developmental status of the ULM currently is:

1. Frequency range (electrical)	100 kHz to 2000 mHz
2. Bandwidth - B	up to 1000 mHz
3. Processing time - T (usec)	up to 20 usec
4. Transducer insertion loss	4 to 20 dB
5. Nominal impedance	10 to 50 ohms
6. TB product*	3000

*This TB product is for a ULM used in a typical correlator with a processing time of 10 usec and a bandwidth of 300 mHz. (Although from items 2. and 3. above, a TB product of 20,000 would be expected, physical constraints on the optical processing system limits the parameters such that the simultaneous achievement of the upper limits is not practical (reference 2)).

These parameters look promising for many of the modulator applications of optical engineering such as real time data analysis and correlation of antennae patterns, radar data processing, pulse expansion and compression for improved radar range and radar resolutions, and pattern recognition. However, most of these applications use typical frequency ranges from 10 to 500 mHz. Obviously, these are not the frequencies encountered in sonar; it would be impractical, therefore, to condition sonar signals for interfacing with the ULM.

Development of new lasers, new materials, and new applications may extend the capabilities of the ULM. There are devices, although not yet commercially available, which are operational in the kilohertz frequency range with insertion losses of less than 5 per cent. Further advances will bring lower drive powers and lower cost. This type of optical modulator could then be adequate for signal processing at sonar frequencies. But for the present, the ULM is limited to high frequency applications; it is therefore unsuited for acoustic processing.

Electro-optic Light Modulators

The EOLM changes the incident light parameters as a function of an applied voltage. This device has not been developed to the extent that the ULM has. One of the main drawbacks to the EOLM is the driving voltage necessary for modulation, usually in the range of 1000 volts. Those that do have low driving ranges suffer from limited optical apertures, usually approximately 5 mm. Also, the EOLM is presently undesirable for writing on dry-processed film because the limited optical apertures (when low driving voltages are desired) require a well-collimated ultraviolet laser. Although such lasers are available, they are prohibitively expensive.

EOLM development is directed towards obtaining contrast ratios of 500:1, low driving voltages ($< 80V$), and larger optical apertures (12 mm). If cost can be kept reasonably low, and if crystal growth technology increases satisfactorily, then good EOLMs capable of multichannel operation will be commercially available. With these developments, the EOLM is a possibility for future use in acoustic signal processing.

Membrane Light Modulators

An MLM in the unactivated state is a mirror. The laser beam that reflects from this device will be unchanged and unmodulated when the MLM is quiescent. When the device is activated, its mirror surface deforms in a microscopic polka-dot pattern, and the MLM becomes a spatial-phase modulator capable of modulating light striking the mirror surface on a point-by-point basis.

Power requirements for the MLM are modest, on the order of 10 to 100 milliwatts per membrance element. Frequency ranges of direct current (DC) to several megaHertz are possible; response times range between 50 and 500 nanoseconds.

Some of the disadvantages of the MLM are a need for critical alignment into a coherent optical system, high cost, and limited dependability due to the mechanical nature of its operation. Probably, the limited dependability and high cost of the MLM will be brought to suitable levels. However, the need for optical precision and accurate alignment will continue to render MLMs unsuitable for rugged, field type operations for some time. Furthermore, MLMs are not now commercially available; their use in a coherent optical processing system for sonar frequencies is not likely in the near future.

LIGHT DEFLECTORS

Design and selection of a scanner for an optical signal processing system is not a simple task, since state-of-the-art is not yet at the point where off-the-shelf scanners have broad application potentials. For high resolution (above 400 spot diameters) the only practical method for deflecting a laser beam in the foreseeable future is with rotating mirror scanners. These rotating devices do have operational problems; however, with careful control, satisfactory results are possible.

Multi-faceted rotating mirrors, usually six-sided polygons, have been developed in recent years which have overcome many of the mechanical problems of optical interfaces. These problems have included angular tolerances, flatness, deformation under rotation, high strength, scanning jitter, spot wobble and bearing runout. Rotating scanners also have a specific advantage in that deflection sensitivity is independnt of wavelength.

There are many other types of scanning and deflection systems; each has distinct limitations to practical implementation. Refraction techniques, for example, electro-optical devices using birefringent crystals, or acoustic-optical devices such as the ULM, inject phase distortions at higher frequencies and introduce high insertion losses of 10 to 40 per cent. Such losses become important when total power is a constraint such as in a torpedo, or when detector sensitivity is a premium. Deflection sensitivities of refraction devices vary with wavelength and, at high frequencies, power and heat problems may develop. Deflection techniques, such as ballistic scanners, do not have these limitations but they are not practical for most systems.

Although the rotational scanner is one type of light deflector which does possess good operational parameters, many varieties (polygonic scanning types) do not provide a linear motion of the recording spot across the film. This disadvantage is due to a rotation as well as a translation of the laser beam, since the mirror is not located on the center of the rotational axis. Correctional elements can remove these inherent nonlinearities. However, both reflective and refractive optics must be used. These are difficult techniques, and the necessary equipment is both expensive and in constant need of accurate and precise alignment. Other recorder-scanner systems which produce a true linear scan are available, but the correction for their sensor nonlinearities is as complex as the process necessary for the polygon.

If a simple and economic way can be found to correct inherent problems of the rotating mirror scanner, then it is feasible that this device could be used in an optical signal processing system for underwater application.

REAL TIME STORAGE MEDIA

The selection of a suitable recording media is mainly based upon the resolution, bandwidth, dynamic range, and exposure power desired for a particular application. Many silver halide films commercially available are sensitive over the entire visible spectrum and have a wide range of exposure sensitivities and resolutions. Resolution capabilities for these media can vary from 100 line pairs/mm to 2000 line pairs/mm. (The latter is for spectroscopic No. 649 film.) Typical recording beam powers necessary for writing on these media range from 4×10^{-6} milliwatts to 50 milliwatts. These are relatively small amounts of power and are readily obtained from most commercially available lasers.

The disadvantages to these films is that they all require wet processing chemical baths; even with the fastest processing techniques, there is a 10-15 second delay. Obviously, for real time operation, this is not practical.

Dry processed media, then, seem better suited to real time use. Most of them require only the application of heat or light to process the film. Their limitation, however, is the necessity for an extremely large amount of exposure power. This may be prohibitive because of certain limitations in system design, i.e., application, size, and cost. Two of the most promising types of dry processed films are Kalvar KDR and photochromics. Kalvar films can be developed in approximately .5 seconds, at temperatures of 280°F, and then erased with ultraviolet light. Photochromics, on the other hand,can be exposed instantaneously. Three further advantages to photochromic films are that they have unlimited resolution capabilities, they can be written on using ultraviolet light, and they can be erased with infrared light. The state-of-the-art in photochromic research has presently reached specific limitations in film capabilities, the most important of which is the need for at least .01 joules/cm^2 to bring the film from an optical density of 0.0 to an optical density of 1.0. Since exposure is accomplished with ultraviolet light, laser sources and high pressure Hg-Arc lamps are virtually the only choices. Ultraviolet lasers are expensive; high pressure Hg-Arc lamps are not easily implemented into an optical processing system because of size and safety regulations. Thus, again, size and cost are limitations of system design.

Recently, there has been considerable interest in the development of simple, inexpensive, and reliable devices with built-in memories that are capable of giving a bright, continuous, and readily erasable display. One solution currently being investigated by many industries is cathodochromism, using the reversible optical absorption bands produced by creating color centers in crystalline solids (reference 3). This interest in cathodochromism is due in part to the ease with which electrons can be generated, modulated, and deflected, relative to light beams.

At present, the occurrence of fatigue and the lack of an efficient way to produce a rapid erasure are the main drawbacks to the use of these materials. These problems are also inherent in photochromics. Solutions may be found to these problems within the next few years, but one problem that will remain with the use of films in optical processing systems is the need for appropriate film drive subsystems. Although commercially available, these subsystems usually create more problems than they solve. More development directed toward reduction in size and weight must be done before a practical film drive subsystem can be made useful for the class of applications indicated.

DETECTORS

The data in the optical processing system must eventually be reinterpreted to electrical signals so that the post-processing can be accomplished. This transduction must also be done in real time. State-of-the-art of light detectors indicates that several may be applicable to the present need.

Two fundamental forms of solid-state detectors are the photoconductor and the p-n junction. In both, hole-electron pairs are produced in the semiconductor when entering photons have an energy greater than the band gap. In the p-n junction detector, external quantum gains on the order of 0.3 are possible. A wide variety of parameter combinations in this device are available with frequency response as high as several thousand megaHertz and sensitivity to wavelength as large as several microns. The frequency response is dependent on active detector area. Obtaining a 1,000 megaHertz response requires extremely small apertures of approximately several mils. At 100 megaHertz response, effective areas as large as .1 inch in diameter are possible.

The photoconductors have response times typically from 2 to 2000 microseconds, spectral responses in the region of 40 microns, and extremely good environmental rigidity.

A new type of detector, the avalanche PIN diode, has recently been introduced. Gains of 1000 with response times in nanoseconds have been recorded. This device achieves its quantum gain by means of avalance multiplications. That is, for each photon absorbed within the depletion layer, several current carriers will be generated. Some of these devices have peak response and gain that is a function of light intensity. The devices are not commercially available yet, but warrant investigation because of

their possibilities as an adequate light detector. Phototransistors, another type of solid-state detector, combine the p-n junction with the transistor gain in one device. The response time is relatively small, about 0.1 usec, with current gains of ten.

Most detectors require some sort of cooling. This necessity creates additional system constraints which must be considered. Most of the detector manufacturers sell a standard detector package, but will design and build detectors in glass or metal evacuated packages for specific applications. Many build special detectors in cryogenic packages which require only electrical power to obtain the detector temperatures. The sizes, shapes, and weights of available detectors and detector-cooler packages are numerous. However, specially-designed packages for detectors of complex design are expensive and may not be available at any price when as few as one or two are needed.

In summary, the state-of-the-art of photomultiplier tubes can yield spectral responses from S-1 through S-20, and pulse rise times typically less than several nanoseconds, with quantum efficiencies as high as 45 per cent. The final problem is that of size and weight. Some detectors require vacuum housing, cryogenic cooling systems, and cumbersome power equipment.

LIMITATIONS ON OPTICAL ELEMENTS

The historically important parameters in an imaging lens which affect its performance are limiting resolution, speed, and the degree to which basic lens distortions are corrected. The theoretical limiting resolution of a lens is a function of its optical aperture; however, lens performance can better be defined in terms of spatial bandwidth.

Spatial bandwidth, or resolution capability, of a lens is a function of both the wavelength of the illuminating light and the focal length-to-aperture ratio. The smaller this ratio, the higher the resolution capabilities of the lens. The maximum practical spatial bandwidth of a lens depends largely on the application. If light loss is not important, low speed lenses, such as those used in optical comparators and photocopying machines can provide spatial bandwidths of 3000 or more cycles. The speed of a lens is directly related to the amount of light it can collect. The faster the lens, the more light it collects.

However, achieving a large spatial bandwidth with a fast lens (yielding maximum light transmission with low ' numbers) is difficult because correction must be made for lens distortions or aberrations over a much wider angular field. Theoretical limiting resolution is an upper limit on the lens performance as the lens speed (aperture) decreases.

A fundamental problem in attempting to apply optics to signal processing is the change in optical needs. Traditionally, lenses have been matched to the performance of the human eye; in recent years, however, the demand for optical components for other applications has occasioned a look into new fields of optical component requirements. Better machining techniques are crucial to producing better optical devices. As these improve, so will lens quality and, ultimately, usefulness. Presently, industry can produce, at a high price, excellent quality lenses good enough for almost any application. Eventually, machining techniques will make these excellent lenses more radily available and, thus, more practical. Such development will then close the gap between the technological demand for sophisticated lenses and the industrial supply of relatively simple ones.

CONCLUSIONS

A study of the optical system for acoustic signal processing was undertaken because of the inherent ability of the system to process information in parallel. However, the attendant areas of technological difficulty, described in this report, indicate that this virtue alone does not warrant further investigation into the technique at this time. When further developments in modulators, deflectors, storage media, and detectors are made, reconsideration of the optical system in this application will be warranted.

Furthermore, integrated circuit technology has progressed to the point that the electronic system can perform fast enough to simulate the advantages of parallel processing. Developments in large scale integration (LSI) means faster, more compact systems. With breakthroughs in read-only memories (ROM), arithmetic operations can now be performed with economical power consumption and in a small unit by applying table look-up techniques. Multiplication has been the traditional consumer of time in arithmetic units. Multiplication speeds as fast as addition speeds are now possible; using the new LSI devices, access times in nanoseconds are common.

In summary, electronic techniques for acoustic signal processing have these main advantages: small size, low cost, speed of performance, and ease of integration with existing techniques. The final advantage is familiarity. Its limitations and stengths are already known; expertise in the field already exists. Since the immediate goal is dependable techniques for in-service hardware, electronic techniques are currently the most practical.

Optical techniques continue to look promising. However, the technique is still in its youth. More research and development is required to make optics compete with electronics on all fronts. Continuing research conducted by others indicates that such development is likely. When it is accomplished, further comparative examination of optical and electronic techniques will be useful. But for the present, electronics techniques continue to be the most practical, efficient, and economical method of solving acoustic signal processing problems for applications in three dimensional tracking.

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13. ABSTRACT

The possibility of employing optical techniques in sonar signal processing is explored. The virtues and weaknesses of optical systems are examined, and significant developments in electronic systems are noted.

State-of-the-art inadequacies of the optical system are discussed. Indications are that at the present and for the immediate future, electronic techniques remain the preferred appraoch to solving sonar signal processing problems. However, technological advances in the state-of-the-art in optical techniques may justify reconsideration of optics in the future.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Serial Processing vs Parallel Processing						
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