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Investigations of techniques for describing and enhancing the accuracy of optical linear algebra processors have been conducted. Significant accomplishments include: 1) showing that error correcting codes can improve processor accuracy and developing criteria which such codes need to possess in order to be suitable for this task; 2) developing a system model incorporating device dynamic range for better quantitative assessment of error correcting code performance; 3) completing a detailed study of the combination of digital partitioning and Modified Multilevel Hamming Codes to achieve high accuracy computation, including scaling properties and effects on processor throughput; 4) obtaining a family of output signal statistics for a generic three-plane

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processor using statistical models for many popular optical sources, modulators and detectors and including crosstalk, background, avalanche gain, flicker and generation-recombination noise effects; 5) applying detection and estimation-theoretic tools and normalizing transforms to this family of statistics to determine accuracy limitations and enhancement possibilities; 6) establishing a general concept of precision for multi-valued numeric processors; 7) constructing a low-noise test facility and the Optical Analysis Simulation Interactive System (OASIS) software for the acquisition, analysis and manipulation of noise measurements in optical computing components/systems; 8) constructing a real-time, simultaneous Stokes polarimeter for measuring complex polarization noise characteristics and 9) using these test facilities to establish the dominant observable noise characteristics of gas and semiconductor laser sources, liquid crystal modulators and PIN and APD photodetectors.

ACCURACY ENHANCEMENT IN OPTICAL COMPUTING

Final Technical Report

on

AFOSR Grant 91-0192

(March 1, 1991 - November 30, 1994)

by

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ABSTRACT

Investigations of techniques for describing and enhancing the accuracy of optical linear algebra processors have been conducted. Significant accomplishments include: 1) showing that error-correcting codes can improve processor accuracy and developing criteria which such codes need to possess in order to be suitable for this task; 2) developing a system model incorporating device dynamic range for better quantitative assessment of error correcting code performance; 3) completing a detailed study of the combination of digital partitioning and Modified Multilevel Hamming Codes to achieve high accuracy computation, including scaling properties and effects on processor throughput; 4) obtaining a family of output signal statistics for a generic three-plane processor using statistical models for many popular optical sources, modulators and detectors and including crosstalk, background, avalanche gain, flicker and generation-recombination noise effects; 5) applying detection and estimation-theoretic tools and normalizing transforms to this family of statistics to determine accuracy limitations and enhancement possibilities; 6) establishing a general concept of precision for multi-valued numeric processors; 7) constructing a low-noise test facility and the Optical Analysis Simulation Interactive System (OASIS) software for the acquisition, analysis and manipulation of noise measurements in optical computing components/systems; 8) constructing a real-time, simultaneous Stokes polarimeter for measuring complex polarization noise characteristics and 9) using these test facilities to establish the dominant observable noise characteristics of gas and semiconductor laser sources, liquid crystal modulators and PIN and APD photodetectors.

SUMMARY OF RESULTS

Considering the significant number of journal publications and conference proceedings resulting from this research, we will present relatively brief summaries of the accomplishments made on each of the three major projects, with references made to the appropriate publications at the end of each project summary. Separate listings will then be presented for journal articles, theses, and other interaction activities covering the entire duration of the grant. In addition, highlights viewgraphs have been sent periodically to our program manager, and a major briefing on the research was presented at Griffiss AFB, Rome, NY in June of 1994.

A. Encoding/Decoding for Error Correction in Optical Computing

This phase of the program involved finding and/or developing error-correcting codes (ECCs) that can be applied to optical linear algebra processors (OLAPs) to enhance their accuracy. Error-correcting codes have been successfully applied to increase the reliability of data transmission systems. The codes introduce a controlled amount of redundant information into the transmitted data. At the receiver, the redundant information allows errors in the received data to be detected and/or corrected, thus improving the reliability of the transmission system. In a similar manner, this idea can be applied to OLAPs.[1,2] Consider an optical matrix-vector multiplier (OMVM). Redundant information can be introduced into the matrix by increasing the row dimension of the matrix. The additional rows in the matrix are formed as linear combinations of the rows of the original matrix. These new rows provide the redundant information. The augmented matrix is now postmultiplied by the input vector to form the product vector. The product vector contains redundant information that can be used to correct errors in the elements of the product vector. Errors can occur during the matrix-vector multiplication due to noise in the system or due to component failures. In general, an OMVM is designed to implement the matrix-vector multiplication $\mathbf{y}=\mathbf{A}\mathbf{x}$, where $\mathbf{A}$ is an M X N matrix and $\mathbf{x}$ is an N X 1 vector. Redundancy is introduced into the matrix by the generator matrix $\mathbf{G}$ for an error code, or $\mathbf{A}^C = \mathbf{GA}$. The encoder performs this operation. The generator matrix $\mathbf{G}$ is an M_C X M matrix with $M_C > M$. Next the product $\mathbf{A}^C\mathbf{X} = \mathbf{GAX} = \mathbf{r}'$ is computed in the OMVM. The product vector $\mathbf{r}'$ may contain errors as discussed earlier. Note that performing the multiplication $\mathbf{GAx} = \mathbf{Gy}$ is equivalent to encoding the vector $\mathbf{y}$ as is done for data transmission. The decoder performs the error detection and correction operations to produce $\mathbf{y}$. If $\mathbf{r}'$ contains more errors than the code can correct, then the output will not be $\mathbf{y}$ in general. Having to compute a higher-dimension matrix-vector product is traded off for the ability to correct errors.

Our first work involved comparing the performance of OMVMs employing error-correction codes to OMVM's not employing the codes through the use of computer simulations. We considered various binary codes, such as convolutional codes[3,4] and the (7,4) Hamming code[3], and various nonbinary codes, such as the weighted checksum code[5] and an extended Reed-Solomon code[6]. Both the presence of signal-independent and signal-dependent noise in the input devices were considered. Our results [7,8] indicated that when the noise is present in the matrix, the codes can improve the performance of the OMVM. The level of improvement is directly related to the error-correcting ability of the code. When the noise is present in the input vector, the codes still improve the performance. However, the level of improvement is not directly related to the error-correcting ability of the code. In other words, using a code that corrects more errors will not necessarily provide a better performance for the OMVM in that case.

New versions and extensions of single-error-correcting ECC's suitable for use on OMVP's were also researched. Several properties which ECC's should possess if they are to be used with OMVP's were developed. First, the code base of the Modified Multilevel Hamming Code (MMHC)[1] should be a power of 2, or 2^n where $n>1$. This requirement for the code base greatly simplifies the encoding and decoding of the code. Codes capable of correcting multiple errors should be based on the ring of integers modulo-m where m is power of 2, or m =

2^n, with m > 1. Several classes of codes satisfying these requirements were found,[9-15] but no simple decoding algorithm for these codes is known.

Extensive simulations employing the single error-correcting MMHC to reduce the rms error and increase the probability of correct detection in OMVP's were performed. The code can significantly improve performance for the cases of noise dominant in the matrix and detectors over a range of matrix and detector signal-to-noise ratios. However, the code only slightly improved performance for the case of noise dominant in the input vector. Therefore, noise in the input vector must be minimized for ECC's to be effective. Several different matrix sizes were considered in the simulations to provide information on the effects of scaling the MMHC to large dimension matrices. In general, the performance improvement provided by the MMHC was fairly constant with matrix size, but the signal-to-noise ratio needed to achieve optimal performance increased with matrix size, as one might expect.

A detailed throughput analysis was performed for OMVP's, both with and without the MMHC. The use of the MMHC caused only a slight reduction in throughput. Larger matrix sizes resulted in better throughputs. The throughput numbers for OMVP's with the MMHC are still competitive with digital electronic computers. However, OMVP's do have an advantage over digital electronic computers in terms of cost and power consumption [16].

Digital partitioning is a promising new technique to achieve high accuracy computations with current technology OMVP's[17] due to its simplicity and power. However, digital partitioning suffers from a sensitivity to errors. The idea of combining ECC's and digital partitioning to reduce this sensitivity to errors was proposed and studied. Extensive simulations showed that the MMHC's can greatly decrease the sensitivity of digital partitioning to errors. Significant improvements in the probability of correct detection are possible when the noise is dominant in the matrix or detectors. When the noise in the input vector dominates, the level of improvement is not as great. The scaling properties are essentially the same as for the case without partitioning, with the signal-to-noise ratio needed for optimal performance being slightly higher.

A detailed throughput analysis of the digital partitioning algorithm was performed. One processor per submatrix is needed so that digital partitioning will be competitive with digital electronics. One processor computing all the subproducts was shown to result in a throughput too low to be competitive. The introduction of the MMHC into the algorithm decreased the throughput, but the resulting throughput is still quite high. Larger matrix sizes result in better throughput performance. The results of the research on the union of digital partitioning and ECC's have been published in [18] and [19].

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B. Statistical Analysis of Optical 3-Plane Processor

Low computational accuracy is an important obstacle for optical processors which blocks their way to becoming a practical reality and a serious challenger for classical computing paradigms. Our goal in this phase of the project was to provide a comprehensive solution approach to the problem of accuracy enhancement in discrete analog optical information processing systems.

In the first step of our solution approach, we carried out a comprehensive statistical analysis of a generic three-plane optical processor by considering the effects of diffraction, interchannel crosstalk, background radiation, photon, excitation, and emission fluctuations in the source array, transmission and polarization fluctuations in the modulator, and photoelectron, gain, dark, shot, and thermal noise in the detector array. This analysis thus accounted for all noise sources of interest, and produced the output signal statistics in terms of those of the input signals. The generality of the approach here makes this analysis widely applicable to processors with fundamentally different architectures and devices as well. In particular, we derived the means, mutual coherence (autocorrelation) and probability density functions (PDFs) of the optical and electrical signals of interest. The analytical form of the signal dependence of the noise at the processor output was established via the variance expression. The most important technical result here pertained to the PDF of the output voltage. We provided an integral equation, with a corresponding series solution, and a convolutional series for the voltage distribution. We also examined, in detail by using Chernoff bounds, the conditions under which this distribution becomes Gaussian. The ability to invoke this assumption played a central role in our subsequent work.

The next step was to bring together results scattered throughout the literature on the statistical and deterministic characteristics of popular optoelectronic devices. The aim here, of course, was to provide the necessary device models to conduct a statistical system modeling effort based on the general analysis described above. We rigorously derived all the relevant models for light-emitting and laser diode sources, an ideal noiseless modulator and a Gaussian random-amplitude-transmittance modulator, p-i-n and avalanche photodiode detectors followed by electronic post-processing, and ideal free-space geometrical-optics propagation and single-lens imaging systems. Unique technical contributions here were the derivation of the laser light statistics, which provided the corrections of some of the erroneous expressions found elsewhere, and the derivation of the impulse response of the separate-absorption-multiplication avalanche photodiode. Well known results on thermal light, photodiode detectors, post-processing electronic circuitry, and simple imaging systems were also rederived in the present notation and formalism. These models are summarized in Table 1.

Naturally, the next step in our development was to determine the output signal statistics for various interesting device combinations by inserting these models into our general formalism. Thus, we combined the efforts described in the above paragraphs to produce results pertaining to specific device combinations within a three-plane configuration. This work was done in a gradual fashion, starting from the simplest possible configuration where only the sources in the system are realistic, and slowly building up the system to its most general and complicated form where every system component is realistic. Consequently, a host of output signal statistics were obtained for certain special cases that are of interest to a number of different problem areas within optics such as photon counting, spectroscopy, imaging through random media, and optical communication as well as optical information processing systems such as correlators, linear-algebra processors, and interconnects. Results involving realistic spatial light modulators are particularly new. Limiting forms of all the results were provided for added insight. These statistics are summarized in Table 2. We also had the opportunity to critically examine the validity of the Gaussian approximation mentioned above in the context of these special cases. This collection of output signal

Table 1 Summary of models for the statistical and deterministic characteristics of popular optoelectronic devices.

COMPONENT	DEVICE	MODEL
Sources	Light-emitting diodes	Circular complex Gaussian random process due to independent, spatially uniform, temporally Poisson, homogeneously broad-ened point emissions; Lorentzian temporal spectrum, narrow circular spatial spectrum (almost perfectly incoherent)
	Laser diodes	Phase-diffused coherent and narrowband chaotic superposition as the output of a nonlinear van der Pol oscillator in the quasi-linear regime; Lorentzian temporal spectrum, constant spatial spectrum (perfectly coherent)
Spatial light modulator	Static screen	Constant transmittance due to lack of spatio-temporal material fluctuations (ideal)
	Random screen	Circular complex Gaussian random process due to inhomogeneously broadened trans-mittance/polarization fluctuations; Gaussian temporal and spatial spectra
Detectors	Ideal photon counter	Unity gain, rectangular impulse response, no dark or thermal noise (ideal)
	p–i–n diodes	Unity gain, exponential (op-amp) impulse response, constant dark excitation rate, Gaussian thermal noise
	Avalanche diodes	Yule–Furry random gain, exponential (op-amp) impulse response, constant dark excitation rate, Gaussian thermal noise
Propagation structures	Near-field free space	Dirac-delta type point-spread functions via geometrical-optics regime propagation (ideal)
	Single-lens imaging system	$\sin(\pi x)/(\pi x)$ or $J_1(\pi x)/(\pi x)$ type point-spread functions whose main-lobe widths are proportional to the mean wavelength

Table 2 Summary of special-case system output signal PDFs (information in the parentheses refer to the limiting forms).

PROCESSOR	***DEVICES***	***OUTPUT DISTRIBUTION***
Ideal	Thermal source	Negative binomial (Poisson)
	Laser source	Multifold Laguerre (Poisson)
Semi-ideal	Thermal source Gaussian SLM	Hypergeometric (Bose–Einstein)
	Laser source Gaussian SLM	Geometric–multifold Laguerre series (Laguerre)
	Source Detector	Gaussian
Semi-real	Source Gaussian SLM Detector	Gauss–Hermite–Laguerre (Gaussian)
Real	Source Gaussian SLM Detector Imaging system	Gauss–Hermite–Laguerre (Gaussian)

statistics then served as the reference frame for our accuracy considerations.

On the heels of our system modeling, we finally turned to the formulation of the accuracy enhancement problem in optical information processing. Specifically, a philosophical as well as operational definition of accuracy was provided first. The concept of precision was also introduced, and its role in relation to accuracy was highlighted. Based on these definitions, we examined the use of detection- and estimation-theoretic tools in search of optimal schemes to enhance the processor accuracy. We first considered a multiple-hypothesis testing approach. We were able here to develop a simple algorithm, similar in vein to the well-known Lloyd-Max quantization algorithm, for the optimal signal space partitioning. Next, turning to parameter estimation techniques, we investigated both the maximum likelihood and the Bayesian strategies. Derivation of classifier structures proved intractable here owing to the signal dependence of the noise. Consequently, we considered a normalizing transform that can potentially remove this dependence, and hence enable us to use the rather simple results obtained for the signal-independent noise case. For the first time, equations determining the accuracy bounds were derived, and potentials for realizing these optimal enhancement techniques were assessed by numerically solving these equations. In particular, we found that while all techniques start out at approximately the same level of accuracy, the performance of the multiple-hypothesis testing approach remains almost constant, exhibiting an extremely slight deterioration with increasing sample number. Meanwhile, the performances of the two parameter estimation techniques, practically indistinguishable from each other, improve considerably as the number of samples is increased. We thus concluded that the detection-theoretic approach is suitable for use with a small number of samples and where a low cost and fast classification scheme is desirable; on the other hand, the estimation-theoretic approach should be used when a large number of samples is available and the speed and/or cost of the classifier is of little concern.

Thus, we have provided a rigorous solution to the problem of accuracy enhancement in discrete analog optical 3-plane processing systems. We have also constructed a formal framework for the analysis, modeling, and performance assessment of a wide variety of optical processors.

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C. Complex Amplitude Noise and Accuracy Analysis of Analog Optical Processors

1. Introduction

During this funding period we have pursued an investigation to determine, both analytically and empirically, the dominant sources of accuracy-limiting noise in analog-based discrete numeric processors. Although elements of this accuracy problem have previously been studied [1,2], upon review of that work, as well as others [3], it was determined that fundamentally new concepts, definitions, and methods were required in order to properly formulate the problem. As a result, a comprehensive method for defining information and uncertainty in these processors has been developed. To augment the analytical accomplishments, experimental methods for measuring and analyzing the noise properties of elemental devices, from which practical systems are constructed, have also been developed. From this analysis three major conclusions have been reached. First, linear analog devices are inappropriate for the development of discrete numeric processors because: 1) they cannot be used to construct generalized regenerative processing elements; 2) slight variations in the operating range characteristics across channels in the processor compromise its ability to realize an exact numerical result; and 3) these devices are highly susceptible to both analog and discrete noise processes. Second, the temporal noise characteristics of commercially available sources, modulators, and detectors are frequently highly deterministic, signal-dependent, and dominated by technological (as opposed to phenomenological) factors and extraneous noise events. Third, the dominant source of temporal noise in liquid crystal-based modulators results from electric drive-induced higher order nonlinear (and possibly chaotic) polarization state dynamics. In the following sections we will expand on the accomplishments achieved, and conclusions reached, within this investigation.

2. Definition of precision [4,5,6]

We defined *accuracy* as the amount of information that can be represented in a numerical result, and *precision* to be the amount of information which can be represented without error in the result. Both the accuracy and precision can be described in terms of a bit resolution, and the bits of precision will always be less than or equal to the bits of accuracy. From a numerical perspective it is obvious that precision, and not accuracy, is the most important performance measure of a numerical processor. Based upon the concept of precision we defined a noise measure, the *bit error risk factor* (BERF), which could be used to quantify the precision of a calculated result. This noise measure is defined relative to the intersection of adjacent signal states, and hence is not simply a statistical moment. In this way, the BERF noise measure can be used without loss of generality for *any* finite noise process.

3. Analysis of the signal space [5,6]

The information represented within a processor is best viewed from the perspective of a signal space. The signal space is represented at each input device, and is transformed by the action of the algorithm into the result. The behavior of the algorithm, and in general the signal space, is dictated by the number system. In our analysis we employ the unsigned normalized radix-R numeric representation (UNRNR). This is a multivalued representation which utilizes radix-R arithmetic rules for addition, subtraction, multiplication, and division. It was established that the UNRNR, being a fixed point representation, provides for the existence of an exact solution under the action of the matrix-vector algorithm.

To aid in the analysis of the signal space we defined two quantities: 1) the region of information (ROI); and 2) the density of information (DOI). By utilizing the concept of a signal space we were able to establish the number of unique information-bearing signal states, their ROI, and their DOI for a generalized ideal (i.e. noiseless) matrix-vector algorithm. It was found that the output signal space is nonuniformly distributed over its domain for uniformly distributed input signal spaces. The quantization-induced uncertainties of this were then established, and discussed in terms of standard significance measures and roundoff errors.

4. Generalized noise analysis [6]

With the ideal signal space understood, and the basic role of quantization induced uncertainty established, we investigated the accuracy and precision implications of a nonideal signal space created by a generalized spatiotemporal signal-dependent noise model. In this analysis we established the extent to which temporal, spatial, signal-independent, and signal-dependent noise components contributed to the resulting uncertainty in the signal space. We determined that spatial uniformity noise (UN) is particularly destructive because it accumulates due to the action of the matrix-vector algorithm. The result is that small spatial nonuniformities result in a large signal offset, thus preventing the algorithm from realizing an exact numerical result. We then established the basic requirements for an *accuracy uncertainty principle* (AUP) which defined the extent to which the spatial domain can be traded off for increased temporal accuracy. It is noted that any attempt to employ accuracy enhancement techniques which exploits the spatial domain, such as digital partitioning or the use of error correcting codes[7], without conforming to the AUP will be inherently flawed if significant spatial uniformity noise is present.

5. Isolation of observable signal components [4,6]

From a practical perspective, the signal space is represented in terms of the physical state of a device. In optoelectronic systems which employ electrooptical modulators the signal states generally originate in electrical form. The electrical signals act within the devices to either emit an optical signal or to change the material state of an optically sensitive medium which in turn interacts with an incident optical field. In general it is the characteristics of the optical signal interactions in which we are most interested. However, the optical signals are not directly measurable and we only have access to the detected electrical signals. Also, within any channel of the processor we have at a minimum one each of a source, modulator, and detector. To isolate the contribution of each device within the observable electronic output, so as to relate the desired signal to the observable electronic inputs, we developed a generalized input-output model for one channel of the system. This model was used extensively in the empirical phase of the investigation to isolate the contribution of the modulator, in particular.

6. Intensity-based analysis [4,6]

Since most systems of interest manipulate the intensity of the optical field, we conducted a comprehensive empirical signal and noise characterization of common sources (HeNe and Ar^+ lasers and laser diodes), liquid crystal-based modulators (twisted nematic, nontwisted nematic, supertwisted nematic, and smectic A*), and PIN photodetectors. To conduct this investigation we developed a low noise test facility described in more detail in section 8. The first major finding was that extraneous noise processes, such as power supply ripple and electromagnetic interference (EMI), were the dominant observable noise process for each device. After these extraneous noise sources were minimized, it was found that the modulator noise significantly dominated the source and detector noise. It was also found that all devices exhibited highly deterministic noise which could be directly traced to the electronic drive signal. Due to the deterministic nature of the noise process on each device, the statistics of the noise processes were generally nonsymmetric, multimodal, and signal-dependent. The noise performances of three nematic liquid crystal devices are shown in Table I.

The modulator is the weak link in the accuracy behavior of the system. To understand what may be the source of this behavior we must realize that liquid crystal-based modulators are fundamentally complex-amplitude devices. They are used in intensity-based systems by placing them between crossed polarizer-analyzer pairs. The information on the device is actually represented by a polarization state, which is induced by an electric field across the liquid crystal material. Due to the fundamentally complex-amplitude nature of the modulator, it became clear that in order to understand the noise process at the modulator plane a new interpretation of the multiplication operation must be established. Traditionally, in dissipative intensity-based systems, the

BERF, ε = 0.1%	LCLV		LCTV		LCVR	
	min ζ(ε)	max ζ(ε)	min ζ(ε)	max ζ(ε)	min ζ(ε)	max ζ(ε)
Linear dynamic range, LDR	0.5 V		0.6 V		0.8 V	
BERF-based dispersion, ζ(ε)	0.007	0.009	0.1	0.25	0.002	0.0035
# levels, L	72	56	6	2	400	228
# Bits, N	6	5	2	1	8	7
Maximum throughput rate	0.2 ms		16.7 ms		0.2 ms	

Table I. The noise performance for three nematic liquid crystal modulators.

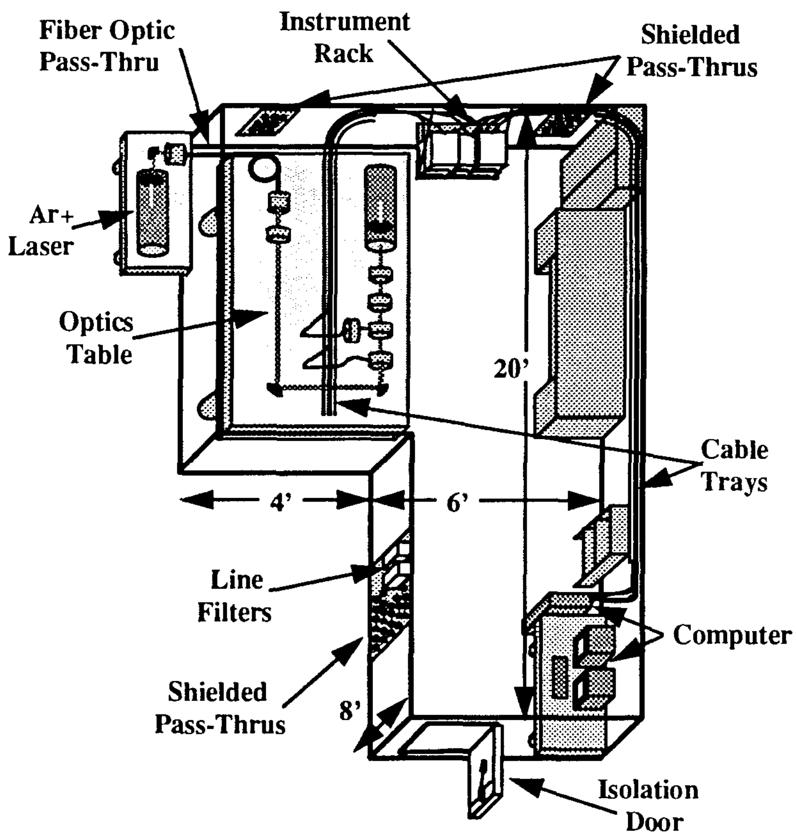

Figure 1. Low noise test facility

interaction of signal states was considered a simple scalar multiplication by a non-negative transmission coefficient which was less than unity. In a liquid crystal device this is obviously not the case, and since the modulator is the dominant source of noise it became necessary to investigate the physical source of this noise.

7. Complex-amplitude analysis [6,8]

Within this phase of the investigation the primary goal was to isolate the amplitude- and polarization- induced noise components from the resulting intensity signal of the modulators. To accomplish this, device models were constructed using both Jones and Mueller techniques. These device models were subjected to amplitude and polarization state perturbations to identify how each dominated different portions of the operating range. It was found that a linear polarization state under the action of a noisy rotation produced an intensity noise signal which peaked when the mean polarization state was oriented at 45^{o} to an analyzer. The amplitude noise dominated when the polarization state was oriented parallel to the analyzer, and fell off linearly with rotation. For the case of an elliptical polarization state, it was found that under the action of increased ellipticity (from linear toward circular) the noise dropped off with ellipticity. With these simple behaviors we established a series of experiments using linear polarizers to qualitatively identify whether the modulator noise processes were dominated by a polarization-based noise or amplitude-based noise process. It was found that the physical noise process within the modulators was almost entirely polarization- based. With this fact in hand we then wanted to understand the nature of this noise process. To accomplish this the polarization state dynamics were measured using a simultaneous Stokes polarimeter. The polarimeter is briefly described in section 9.

It was found that the polarization state dynamics of the modulator were, for the most part, confined to the static polarization trajectory of the device. In these regions it was shown that the noise process could be explained using a simple phenomenological model for the reorientation of the bulk medium. However, it was also found that in regions of peak noise the polarization state dynamics significantly diverged from the static trajectory, thus indicating that higher order physical processes were driving the physical noise process. It was found that this higher order noise was more prevalent in nontwisted nematic devices. Also, it was found that all LC devices possessed a noise component at twice the frequency of the drive signal. This indicated that the basic physical noise process in LC devices, no matter what their construction, is nonlinear.

8. Low noise test facility [4,6,8]

We developed this facility to isolate all components of the observable quantity influencing the experimental outcome so that cause and effect relationships could be established and external influences eliminated. Since the devices and architectures of interest are optoelectronic hybrids, we must not only be concerned with the state of the optical environment but also that of the electrical environment. Optical isolation within the facility, as well as within each experimental apparatus, was achieved using light shields in conjunction with optical laser line filters(LLF's). Experimentally, the problematic signals are electronic and exist as deterministic ripple on drive electronics and EMI. We observe that EMI is not only a prevalent noise source but also the most difficult to define and control. Measurements made of the ambient EMI indicated that it was the dominant noise component in all observables, obscuring any events of interest. Controlling this EMI became a necessary prerequisite to achieving useful experimental results. The primary step in reducing the EMI component was to isolate the experimental apparatus from the ambient EMI. This was achieved by constructed a 1280 cubic foot Faraday cage in which the experimental apparatus could be located (Fig. 1).

This cage maintained EMI isolation from the outside world using a single-point, grounded double copper-screen shell with two single phase isolation filters for power pass-through and several banks of shielded BNC connectors for signal pass-throughs. All experimental equipment resided inside the screen room except for an Argon ion laser, whose beam was brought into the facility via an incoherent multimode fiber bundle. All instruments and components within the screen room were thoroughly shielded and grounded to prevent EMI contamination from within the facility. To contain potential sources of contamination on the power lines inside the screen room two independent 20A, 120V plug circuits and one independent lighting circuit were run from the isolation filters. All power supplies and computer equipment existed on one plug circuit, with amplifiers and meters on the other. Incandescent bulbs controlled by a dimmer switch were used on the lighting circuit. The screen facility sits on a 1/16-inch thick polyethylene sheet to maintain good ground isolation from the laboratory's concrete floor, ensuring a single-point ground (e.g. preventing current loops).

9. Simultaneous Stokes polarimeter [6,8]

To achieve a detailed understanding of the temporal polarization state dynamics we constructed a polarimeter which allowed for the simultaneous measurement of all four Stokes parameters at a rate of up to 250 kHz (Fig. 2). The system utilized a linearly-polarized 15 mW Spectra Physics 124B Helium-Neon laser as an input source. The orientation of the source's polarization state was controlled by a Newport 550 polarization rotator (PR). The beam was spatially filtered, stopped down, and passed through a Meadowlark DPM-1.0-HN32 polarizer (Pol) to ensure that any polarization state noise from the source was eliminated. After passing through the sample the beam was split twice

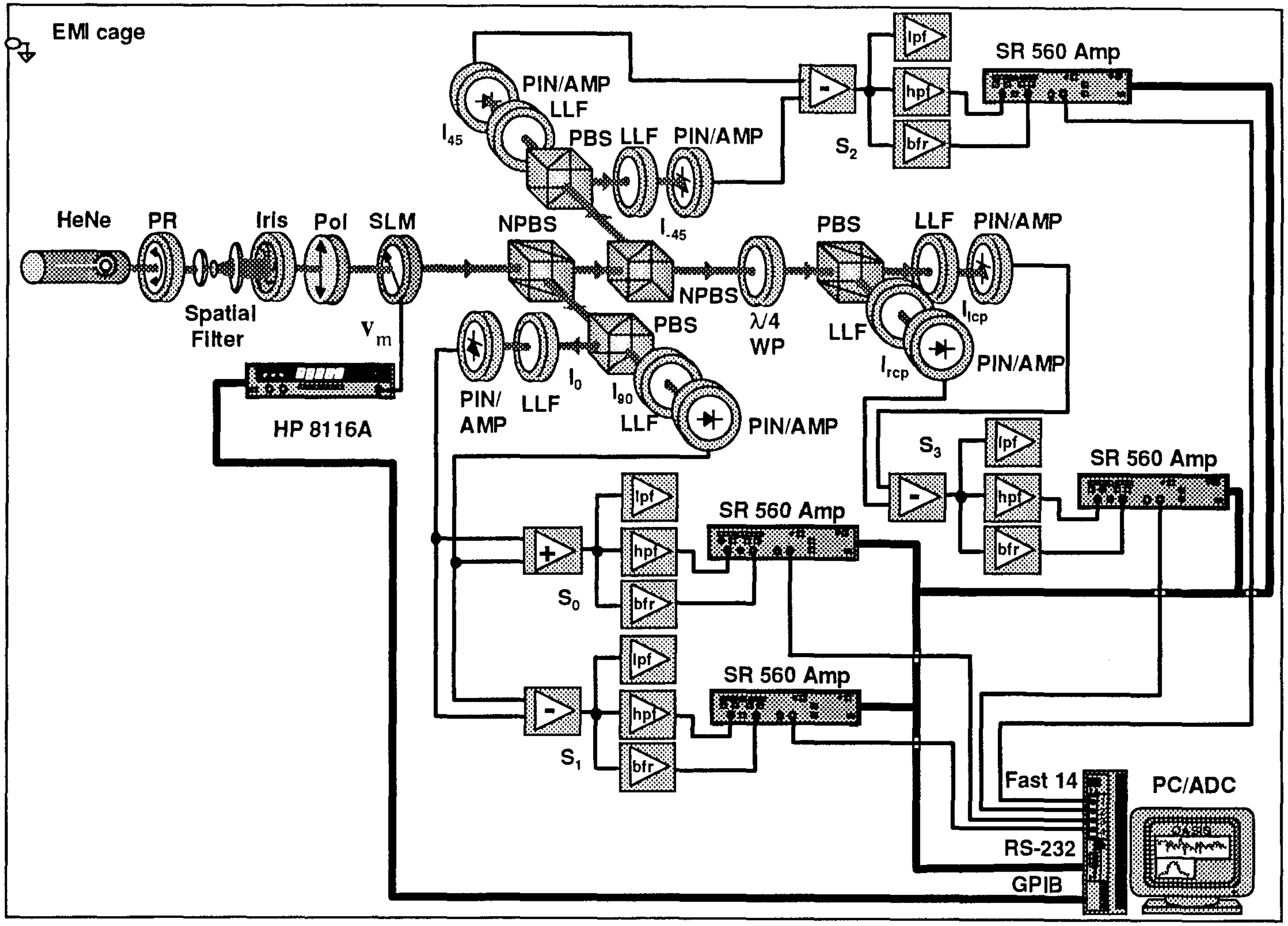

Figure 2. Simultaneous Stokes polarimeter.

using Newport 05BC16NP.4 non-polarizing beam splitters (NPBS). The output from the first NPBS was passed through a Melles Griot 03PPW014/A 20° polarizing beam splitter (PBS) which was oriented to separate the 0° and 90° components of the beam. These components were then detected with Devar 539-1 PIN photodetectors (PIN/AMP) which were light shielded with Newport 10LF10-633 laser line filters (LLF). The reflected beam from the second NPBS was passed through a PBS oriented to separate the +45° and -45° components, and the transmitted NPBS beam passed through a Meadowlark QHM-1.0-633 quarter wave plate (WP) and then a PBS to separate the right circular and left circular components. An electronic subsystem consisting of buffer amps, adders, differencers, and low- and high-pass filters was developed to generate the four Stokes parameters from the output of the six photodetectors in accordance with the relationships:
$S_0 = I_0 + I_{90}$; $S_1 = I_0 - I_{90}$; $S_2 = I_{45} - I_{-45}$; and $S_3 = I_{rcp} - I_{lcp}$.

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1. S. G. Batsell, "Accuracy limitations in optical linear algebra processors", Ph.D. dissertation, Dept. of Electrical Engineering, Texas Tech University (1990).

2. S. G. Batsell, T. L. Jong, J.F. Walkup, and T. F. Krile, "Noise limitations in optical linear algebra processors," Appl. Optics, **29**, 2084-2090 (1990).

3. B. Taylor and D. Casasent, "Error-source effects in a high-accuracy optical finite-element processor," Appl. Optics, **25**, 966-975 (1986).

4. M. V. Morelli, T. F. Krile, and J. F. Walkup, "Temporal intensity noise characteristics and discrete numeric accuracy of analog liquid crystal-based spatial light modulators," Appl. Optics (Special issue), **33**, pp. 2812-2828 (1994).

5. M. V. Morelli, T. F. Krile, and J. F. Walkup, "The concept of precision in analog-based discrete numeric optical computing," SPIE Proc. **2297**, Optical Implementation of Information Processing (1994).

6. M. V. Morelli, "Complex-amplitude noise and accuracy analysis of analog optical processors," Ph.D. dissertation, Dept. of Electrical Engineering, Texas Tech University (1995).

7. S. Ellett, T. Krile, and J. Walkup, "Error correction coding for accuracy enhancement in optical matrix-vector multipliers ," Appl. Optics, **31**, 5642-5653 (1992).

8. M. V. Morelli, T. F. Krile, and J. F. Walkup, "Complex-amplitude noise characteristics of analog liquid crystal spatial light modulators," SPIE Proc., **2265**, Polarization Analysis and Measurement II (1994).

RESEARCH PERSONNEL (1991-1994)

1. Faculty:

   Dr. J.F. Walkup, Co-Principal Investigator, Horn Professor

   Dr. T.F. Krile, Co-Principal Investigator, Professor

   Dr. D.J. Mehrl, Research Associate, Assistant Professor

2. Graduate Students:

   A.V. Huynh
   S.A. Ellett
   D.A. Timucin
   M.V. Morelli

3. Undergraduate Laboratory Assistants:

   M. Mahendra
   W. Lu
   T. Shen
   D. Hammons
   B. Turner

4. Administrative Secretary:

   P. Burtis
   C. Spitz
   E. Gonzales

COMPLETED THESES AND DISSERTATIONS (1991-1994)

1. S.A. Ellett, "Error-Correction Coding for Optical Matrix-Vector Multipliers, M.S. thesis, Dept. of Electrical Engineering, Texas Tech University, August, 1991.

2. D.A. Timucin, "Statistical Analysis of Optical Linear Algebra Processors", M.S. thesis, Dept. of Electrical Engineering, Texas Tech University, December, 1991.

3. A.V. Huynh, "Perceptron-Based Optical Quadratic Neural Network Using Photorefractive Crystal," M.S. thesis, Department of Electrical Engineering, Texas Tech University, December, 1991.

3. S.A. Ellett, "Error-Correcting Codes for Optical Matrix Processors," Ph.D. dissertation, Dept. of Electrical Engineering, Texas Tech University, August, 1994.

4. D.A. Timucin, "Accuracy in Optical Information Processing," Ph.D. dissertation, Dept. of Electrical Engineering, Texas Tech University, December, 1994.

5. M.V. Morelli, "Complex-Amplitude Noise and Accuracy Analysis of Analog Optical Processors," Ph.D. dissertation, Dept. of Electrical Engineering, Texas Tech University, May, 1995.

JOURNAL PUBLICATIONS UNDER AFOSR 91-0192

Journal Articles Published

1. A.V. Huynh, J.F. Walkup, and T.F. Krile, "A $BaTiO_3$-Based Optical Quadratic Neural Network Implementing the Perceptron Algorithm," Opt. Engr. 31, 979-985 (1992).

2. S.A. Ellett, J.F. Walkup, and T.F. Krile, "Error Correction Codes for Accuracy Enhancement in Optical Matrix-Vector Multipliers," Appl.Opt. 31, 5642-5653 (1992).

3. D.A. Timucin, J.F. Walkup, and T.F. Krile, "Accuracy in Analog Optical Processors: Statistical Analysis," J.Opt.Soc.Am A 11, 560-571 (1994).

4. J.D. Downie and J.F. Walkup, "Optimal Correlation Filters for Images with Signal-Dependent Noise," J.Opt.Soc.Am. A 11, 1599-1609 (1994).

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6. S.A. Ellett, T.F. Krile, and J.F. Walkup, "Combining Digital Partitioning and Error-Correcting Codes for High Accuracy Optical Computing," Opt. and Laser Technology 26, 301-311 (1994).

7. M.C. Bashaw, J.F. Heanue, A. Aharoni, L. Hesselink and J.F. Walkup, "Cross-talk Considerations for Angular and Phase-Encoded Multiplexing in Volume Holography," J.Opt.Soc. Am. B, 11, 1820-1836 (1994).

8. "An Optical Pattern Recognition System for Validation & Security Verification," Optics & Photonics News, 5, 13-18 (1994) (with B. Javidi and J.L. Horner).

CONFERENCE PRESENTATIONS AND PROCEEDINGS

1. S.G. Batsell, J.F. Walkup and T.F. Krile, "Temporal Modulation Effects on the Noise Properties of Optical Linear Algebra Processors," Opt. Soc. Am. Annual Mtg., Boston, MA, November, 1990.

2. S.A. Ellett, J.F. Walkup and T.F. Krile, "Encoding for Error Correction in Optical Computing," Opt. Soc. Am. Annual Mtg., Boston, MA, November 1990.

3. A.V. Huynh, J.F. Walkup and T.F. Krile, "Optical Quadratic Perceptron Neural Network," Opt. Soc. Am. Annual Mtg., Boston, MA, November 1990.

4. D.A. Timucin, M.V. Morelli, J.F. Walkup and T.F. Krile, "Statistical Analysis of Optical Linear Algebra Processors," 1991 Gordon Research Conference on Holography and Optical Info. Processing, Plymouth, NH, June 1991.

5. S.A. Ellett, J.F. Walkup and T.F. Krile, "Error Codes Applied to Optical Algebraic Processors," Proc. SPIE 1564, San Diego, July 1991.

6. A.V. Huynh, J.F. Walkup and T.F. Krile, "Optical Perceptron-Based Quadratic Neural Network," Opt. Soc. Am. Annual Mtg., San Jose, CA, November 1991.

7. D.A. Timucin, J.F. Walkup and T.F. Krile, "Accuracy Enhancement in Optical Linear Algebra Processors," Opt. Soc. Am. Annual Mtg., San Jose, CA, November 1991.

8. S.A. Ellett, T.F. Krile and J.F. Walkup, "Accuracy Enhancement of Optical Vector-Matrix Processors," Opt. Soc. Am. Annual Mtg., Albuquerque, NM, September 1992.

9. D.A. Timucin, J.F. Walkup and T.F. Krile, A Decision-Theoretic Approach to Accuracy Enhancement in Optical Processors," Opt. Soc. Am. Annual Mtg., Albuquerque, NM, September 1992.

10. M.V. Morelli, T.F. Krile and J.F. Walkup, "Noise Characterization of Analog Devices for Optical Computing, "LEOS '92" Boston, MA, November 1992.

11. D.A. Timucin, J.F. Walkup and T.F. Krile, Statistical Analysis and Modeling of Analog Optical Processors," Proc. SPIE 2026, 204-215, San Diego, CA, July 1993.

Conference Presentations and Proceedings continued

12. S.A. Ellett, T.F. Krile and J.F. Walkup, "Reduction of Error Effects in Digital Partitioning by Error-Correction Coding," Proc. SPIE 2026, 276-285, San Diego, CA, July 1993.

13. M.V. Morelli, J.F. Walkup and T.F. Krile, "Accuracy Issues for Quantized Analog Optical Computing," Opt. Soc. Am. Annual Mtg., Toronto, Canada, October 1993.

14. M.V. Morelli, T.F. Krile and J.F. Walkup, "Concept of Precision in Analog-Based Discrete Numeric Optical Computing," Proc. SPIE 2297, San Diego, CA, July 1994.

15. M.V. Morelli, T.F. Krile and J.F. Walkup, "Complex-Amplitude Noise Characteristics of Analog Liquid Crystal Spatial Light Modulators," Proc. SPIE 2265, San Diego, CA, July 1994.

16. D. Timucin, J.F. Walkup and T.F. Krile, "Theoretical Results on Accuracy Limitations in Analog Optical Processors," Optical Computing/OC'94, Edinburg, Scotland, August 1994.

17. M.V. Morelli, J.F. Walkup and T.F. Krile, "Electrooptical Noise Characteristics of Devices for Multi-Valued Numeric Optical Processing," Opt. Soc. Am. Annual Mtg., Dallas, TX, October 1994.

18. D. Timucin, J.F. Walkup and T.F. Krile, "Theoretical Limitations on Accuracy in Analog Optical Processors," Opt. Soc. Am. Annual Mtg., Dallas, TX, October 1994.

OTHER INTERACTION ACTIVITIES (1991-1994)

1. Chairman of 1991 Gordon Research Conference on Holography and Optical Information Processing, Plymouth, NH, June 1991 (Dr. J.F. Walkup). Over 100 participants. Dr. Krile and graduate students Michael Morelli and Dogan Timucin also attended.

2. Served as Topical Editor for "optical signal processing and image science" for Journal of the Optical Society of America A, 1992-1994 (Dr. J.F. Walkup).

3. Served as Associate Editor for IEEE Trans. on Neural Networks, 1992-1994 (Dr. T.F. Krile).

4. Co-Organizer of 1991 Texas Systems Day, Texas Tech University, Nov. 1991 (Dr. J.F. Walkup).

5. National Research Council Senior Associateship at NASA Ames Research Center, 1992-1993 (Dr. J.F. Walkup). Research on optimum design of correlation filters in signal-dependent image noise with Dr. J.D. Downie. Also presented talks on AFOSR-funded research at NASA Ames and Stanford University.

6. Visiting Professor, Dept. of Electrical Engineering, Stanford University, 1992-1993 (Dr. J.F. Walkup). Research on cross-talk issues in holographic data storage in photorefractives with members of Dr. L. Hesselink's group.

7. Served on technical program committee for Internat. Conf. on Optical Info. Proc., St. Petersburg, Russia, Aug. 1993. (Dr. J.F. Walkup).

8. Attended OSA's Palm Springs (CA) Topical Meetings, March 1993. Meetings dealt with spatial light modulators and optical computing. (Dr. J.F. Walkup).

9. Presented talk "Optical Matrix Processors: Issues," at Optoelectronics Industry Development Association "Optics in Switching and Computing Technology Workshop," Baltimore, MD, May 1993 (Dr. J.F. Walkup).

10. Attended 1993 Gordon Research Conference on Optical Signal Processing and Holography, Plymouth, NH, June 1993 (Dr. J.F. Walkup).

11. Patent application filed (AF Docket #21069, with J.L. Horner and B. Javidi): "Optical Pattern Recognition System for Verifying the Authenticity of a Person, Product, or Thing,". Idea uses a phase-encoded mask to provide secure identification technique on items such as credit cards, etc.

Other Interaction Activities continued

Developed with J. Horner of Rome Laboratory and B. Javidi of the U. of Connecticut.(Dr. J.F. Walkup).

12. Visited U. of New Mexico's Center for High Technology Materials, Albuquerque, NM, January, 1994. Presented talks on optics research at Texas Tech University (Drs. Walkup, Krile, and Mehrl).

13. Presented briefings on AFOSR Grant 91-0192 to Dr. Alan Craig in Washington, D.C., Lubbock, TX, and Rome, NY (Drs. Walkup, Krile, graduate students S. Ellett, M. Morelli, and D. Timucin).

14. Presented lectures on optical computing research at various institutes and universities in St. Petersburg, Russia, March, 1994 (Dr. J.F. Walkup). These included the Vavilov State Optical Institute, Baltic State University, and St. Petersburg Polytechnic University.

15. Graduate student Michael Morelli traveled to NASA Ames Research Center in May, 1994 to make noise measurements on an acousto-optic-based matrix-vector multiplier system built for NASA Ames by Photonic Systems Inc. The analysis software developed under AFOSR Grant 91-0192 was utilized in making these noise measurements.

16. Graduate student Michael Morelli interacted with engineers at Meadowlark Optics, Inc. on optimizing the design of liquid crystal SLMs based on research results obtained at Texas Tech University.

SIGNIFICANT ACCOMPLISHMENTS

1. Demonstrated that error-correcting codes can improve the accuracy of analog optical matrix-vector multipliers. Determined criteria which make particular codes suitable for this task.

2. Developed system model incorporating device dynamic range for better quantitative assessment of error correcting code performance.

3. Completed detailed study of use of digital partitioning and Modified Multilevel Hamming Codes(MMHCs) to achieve high accuracy computation, including scaling properties and effects on processor throughput. This for the case of single error correcting MMHCs.

4. Derived output statistics for a generic 3-plane optical processor using statistical models for many popular optical sources, modulators, and detectors.

5. Applied detection and estimation-theoretic tools and normalizing transforms to this family of statistics to determine accuracy limitations and enhancement possibilities.

6. Established a general concept of precision for multi-valued numeric processors.

7. Constructed a low-noise test facility and the Optical Analysis Simulation Interactive System (OASIS) software for the acquisition, analysis and manipulation of noise measurements in optical computing components and systems.

8. Constructed a real-time simultaneous Stokes polarimeter for measuring complex polarization noise characteristics.

9. Used low-noise test facility and OASIS software to establish the dominant observable noise characteristics for gas and semiconductor laser sources, liquid crystal modulators, and PIN and APD photodetectors.