FINAL REPORT

Project A-1719

CONCEPTUAL DESIGN OF AN ON-BOARD OPTICAL
PROCESSOR WITH COMPONENTS

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Prepared for
NATIONAL AERONAUTICS & SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER
MARSHALL SPACE FLIGHT CENTER, ALABAMA

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Engineering Experiment Station
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ABSTRACT

This report summarizes the investigation performed on Contract NAS8-31344. The objective of the first part of this investigation was the specification of components for a spacecraft on-board optical processor. The objective of the second part of the research program was the search for a space oriented application of optical data processing and the investigation of certain aspects of optical correlators. The investigation confirmed that real-time optical processing has made significant advances over the past few years, but that there are still critical components which will require further development for use in an on-board optical processor. The most critical component for a real-time optical processor is the real-time optical input device. A major part of the first part of this program was the collection and evaluation of information on these devices. The devices evaluated were the General Electric Coherent Light Valve, the ITEK Pockel's Readout Optical Modulator, the Hughes Liquid Crystal Modulator, and the Image Forming Light Modulator. The ITEK PROM and Hughes Liquid Crystal devices were identified as the primary candidates for the real-time input device of an optical processor although neither device could be judged at this time as completely satisfactory for the subject application.

During the second part of this program contact was made with personnel knowledgeable with future space missions and their data management requirements. The results of these discussions revealed that there is a hesitancy to do any on-board data processing because of the possible loss of some of the available radiometric data. The data handling philosophy is to transmit all of the data to earth and let each investigator reduce the data as he desires. Further, the prevailing thoughts were that if on-board processing were used it would be digital rather than optical at this time. This view is held because of the excellent outlook for on-going development of digital processing technology, and the large amount of support it is currently receiving. Because of formidable ground data storage problems, however, the reluctance toward on-board data processing may be set aside in the near future.

If this turn around occurs, optical processing systems will be competitive with digital systems for some applications because of their potentially lower acquisition cost and smaller input power drain, and their vastly superior processing speed.

Certain aspects of optical correlators are reviewed, and a brief discussion of the techniques for calculation of Fourier transforms by digital methods is presented.

PREFACE

This report covers work performed under Contract NAS8-31344 for the period 9 January 1976 through 9 January 1977 and briefly reviews work performed during the first part of the program from 10 March 1975 to January 1976. It is the culmination of a study of the application of coherent optical processing to on-board satellite data management systems, and represents the final report on the research program under Contract NAS8-31344. This program was performed under the technical cognizance of Messrs. J. H. Kerr and H. F. Smith, Code EF13, NASA-Marshall Space Flight Center, and their interest throughout this study is gratefully acknowledged.

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I. INTRODUCTION

This research program, Conceptual Design of an On-Board Optical Processor with Components, was divided into two parts performed sequentially. Part one dealt with the problems associated with the design of a satellite optical data processor, and part two was concerned with the applications of state-of-the-art optical processors to satellite data acquisition systems.

The results of the phase one effort were reported in the interim report [1-1]. In general that report presented a review of the status of selected components of an optical processor, a general discussion of the mechanical and electronic considerations of an on-board optical processor, and a digital simulation of the operational characteristics of real time optical processors.

Optical data processors derive their usefulness from the fact that a lens system can provide a two dimensional Fourier transform of an input image in the time it takes light to propagate through the optical system. Coherent optical data processing has existed since the early 1950's when many of the basic concepts were published [1-2, 1-3, 1-4, 1-5]. A major drawback to optical data processors in the past has been the limitations imposed by available techniques for inputting an image into the optical system. Photographic film has, for many years, provided the standard input medium. Recent developments in input devices for optical processors have put the optical data processor on the verge of real time operation. Four devices emerge as the principal contenders for real time input devices for optical processors. These are: (1) the General Electric Coherent Light Valve [1-6], (2) the KD*P Light Modulator [1-7], (3) the Hughes Liquid Crystal Modulator [1-8] and (4) the

Itek Corporation's Pockel's Readout Optical Modulator [1-9]. None of these devices function as an ideal input device and their selection must consider the intended application. The interim report discussed each of the devices and also presented a discussion of some of the interface problems presented by various parts of an optical processor.

The second part of the research program which makes up the main portion of this report was concerned with some aspects of optical correlators which apply to satellite data acquisition systems. The major portion of the effort was the search for a space oriented application of optical processors. Laboratory and industrial applications of optical and optical-digital data processors are numerous and many are discussed in this report. Space applications, however, are not as easily identified because of uncertainties in the accuracy and storage requirements of satellite acquired data.

During the second phase of this program project personnel held discussions with many people knowledgeable in future space missions and their data processing requirements. The current feeling toward on-board processing is one of reluctance to reduce the general applicability of the data to a wide range of user interests. There is a strong desire to transmit all the data to earth to be stored since on-board processing would result in the loss of some of the available data. If all data is transmitted, individual investigators can determine which parts of the data may be eliminated for their particular application.

Another strong consideration concerning on-board processing is the general feeling that if on-board processing were to be used it would probably be digital rather than optical for the first generation systems, for reasons discussed in Section II of this report.

There is a strong feeling that many processing applications presently performed by optical processors will in the not to distant future be performed by digital processors. It is our view, however, that economic and technological analysis must be applied to each data processing application to determine the merits of the two general processing techniques, and in so applications the most cost effective system may well be a hybrid optical-digital processor. As a result of this philosophy, a review was made of th digital processing techniques for linear transformations, and the results of recent technology extending optical processing techniques to nonlinear applications was also considered.

In general this report includes a review of the general applications o optical data processors, a brief review of components critical to optical data processors, and a review of competitive digital processing techniques for the generation of Fourier transforms.

II. APPLICATIONS OF OPTICAL DATA PROCESSORS

A. General Applications

Most optical computing systems are based on the Fourier transforming properties of a simple lens [2-1]. The ability of a simple lens to produce a two-dimensional Fourier transform has been known for years. Such processing systems offer the potential of extremely fast processing times and extremely large space-bandwidth products. Optical processing systems, however, do have some performance limitations. Since such systems are analogue in nature they process data with limited accuracy in comparison with the accuracy obtainable with digital systems. Flexibility is also limited since optical processors can perform linear operations such as the Fourier transform and correlation and convolution operations extremely fast but they are not easily modified to perform other computations. Work is presently underway to increase the flexibility of optical processors to include many new types of data processing operations. Among the methods by which the flexibility is being extended are nonlinear data processing operations and space-variant linear data processing systems [2-2].

There are many applications for which the speed and accuracy of optical processing systems make them ideally suited. However, it was not until digital computer technology and optical systems were combined that optical computing systems became of general interest. Early optical-digital computing systems of the late 1960's were used for pattern recognition. For example, Lendaris and Stanley developed a large computer controlled diffraction pattern sampling system during this time period [2-3]. Their system was large, complex, slow, and costly. With the combined decrease in cost of

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minicomputers and lasers a diffraction pattern sampling system can be acquired today at a reasonable cost. In the early 1970's optical computing systems began to be considered for industrial applications. Jensen pointed out some of the potential applications in 1973 [2-4]. The techniques he discusses are based on diffraction pattern sampling rather than the more complicated holographic systems envisioned by many people at that time for optical computers. He points out that even relatively simple optical systems can reveal the precise dimensions of wires, fibers, and spherical objects. Defects in metal, plastic, or glass sheets may also be detected. Particles can be classified, and measurements of sharpness, roughness, hardness, and stress and strain can be made.

With the cost of both optical and digital components such as lasers and integrated circuits being reduced in the early 1970's, many laboratory and industrial applications of optical processors have emerged. Many of these applications have been enumerated by Kasdan and Mead [2-5]. Laboratory applications include various image processing techniques falling in the general categories of aerial image analysis [2-6, 2-7], X-ray analysis [2-8], photomicrograph analysis [2-9] and cell particle scattering [2-10].

Industrial optical digital processing systems now operating include needle point inspection systems, photomask line width measurements, cloth wearing inspections, and paper printability measurements. Noble and Penn point out several additional applications which are well suited for optical processors [2-11]. These include (1) a time waveform spectrum analyzer, (2) a beamformer which reconstructs radio astronomical images from a microwave antenna array, (3) a radar processor matched filter, and (4) a real-time side looking radar image reconstructor. Optical filtering techniques have also been used to advantage in the deblurring of images and image enhancement [2-12].

B. Space Applications

A major part of the effort during the second phase of the project was devoted to the investigation of space applications of optical or optical-digital data processors. With higher data rates expected from future spacecraft, the amount of data to be transmitted to the ground gets to be quite impressive if no on-board data processing is provided. Currently, the Landsat series of satellites, which are earth resource oriented, are expected to have data rates of the order of 10^{12} bits per day. This presents a formidable storage problem for ground-based data collection centers.

To get some feel for the data transmission, data processing, and data storage requirements of future spacecraft missions, the Summarized NASA Payload Descriptions published by Marshall Space Flight Center were reviewed [2-13,2-14]. These summaries cover both automated and sortie payloads. The results of the review which concerned mainly data processing and transmission requirements are shown in Table I and II.

One class of satellites which have extremely high data transmission rates and require image processing are the earth resource satellites of which LANDSAT D is a typical example. The data rate for this satellite is currently quoted as 10^{12} bits per day.

Based on this information, personnel at Goddard Space Flight Center who manage this satellite program were contacted to determine the possibilities for on-board optical processing to reduce the data transmission rate. These

TABLE I

Data Rates - Automated Payloads

Experiment Number	Title	Real Time Data Rate	Real Time Data Volume	Stored Data Rate	Stored Data Volume	Experiment Data Processing Required	Type of Processing
AS-01-A	Large Space Telescope	10^6&TBD	TBD		TBD	TBD	
AS-02-A	Extra Coronal Lyman Exp.	4.3E4	1.779E.9	4.3E4	1.1682E10	Yes	Integrate and Correlate Data
AS-23-A	Medium Aperature Opt. Tel.	1E6 1024	2.048E9 8.85E7	1E6 1024	2.048E9 8.85E7	Yes	Photometric Meas per Star, Resolution enhancement, astrometric readout
HE-01-A	Large X-Ray Telescope Fac.	3.5E4 2E5	3.024E9 5.369E8	5E4 2E5	3.024E9 5.369E8	Yes	Successive Image Integration, enhancement and data correction, diagnosis
HE-03-A	Extended X-Ray Survey	64816 1E6	5.6E9 5.6E9	64816 1E6	5.6E9 5.6E9	Yes	Spatial Image and Dynamic Range Enhan. Rejection of Spurious Radiation Interference
HE-07-A	Small High Energy Satellite	40960	2.123E9	N/A	N/A	Yes	Exp. per. eval. data reduct. and correlation
HE-08-A	Large High Energy Obs. A (Gamma Ray)	2048 12048	4.42E7 1.041E9	2048 12048 2.12E5 1E6	4.44E7 1.041E9	Yes	Radiation and Spurious Count Removal Flux and Spectral vs. Spatial Location
HE-09-A	Large High Energy Obs. B (Magnetic Spectrometer)	12048 51200 1E6	1.041E9	12048 51200 1E6	1.041E9	Yes	Nucleon Identification, Spatial Track Correlation, energy level est. and diag.
HE-11-A	Large High Energy Obs. D (1.2m X-Ray Tel.)	3.5E4 2E5	3.024E9 6.16E9	3.5E4 2E5	3.024E9 6.16E9	Yes	Successive image integration enhancement and data correction; diagnosis
SO-03-A	Solar Maximum Mission (SMM)	1024KHz 9810	8.5E8 9.5E4Hz	768KHz 1.3E5	TBD	Yes	Real time Data evaluation
AP-01-A	Upper Atmos Exp.	1024KHz 9810	8.5E8 9.5E4Hz	768KHz 1.3E5		Yes	Real time data evaluation
AP-02-A	Explorer - Medium Altitude	1024KHz 9810	8.6E8 221Hz	768KHz 1.3E5		Yes	Real time data evaluation
AP-03-A	Explorer - High Altitude	1024KHz 9810	1.3E8 9.5E4Hz	768KHz 1.3E5	TLD	Yes	Real time data evaluation
AP-04-A	Gravity and Relitivity Satellite (LEO)	1000	7.3E6	2300	7.3E6	Yes	Real time data evaluation
AP-05-A	Environ. Perturbation Satelite A	2000 9E4	Analog TBD 1.73E8	TBD	TBD	Yes	Short time data evaluation
EO-08-A	Landsat-D (EOS-D)	4000 1.28E5 2E8 2E8	1.13E11	N/A	N/A	Yes	Image Processing
EO-10-A	Applications Explorer	N/A	N/A	2.8E5	8.6E8	Yes	Produce contour plots time correlated temp. maps, color pictures, etc.
EO-12-A	TIROS-O	VHF 1350Hz 1.2E5 2E8 4000	1.13E11	N/A	N/A	Yes	Image Precessing
EO-57-A	Foreign Sync. Meter Sat.	28E6 194 BPS 50000Hz 14E6	12E11	N/A	N/A	Yes	Meteorological Computations

TABLE I (continued)

Data Rates - Automated Payloads

Experiment Number	Title	Real Time Data Rate	Real Time Data Volume	Stored Data Rate	Stored Data Volume	Experiment Data Processing Required	Type of Processing
EO-58-A	Geosync. Oper. Environ. Satellite	28E6 194 BPS 50000Hz 14E6	12E11	N/A	N/A	Yes	Meteorological Computations
EO-61-A	Earth Res. Survey Oper. Satellite	1.5E8 4.5E6Hz	1E9 A45 Min/D	6E8 4.5E6Hz	1.[illegible]E11 210 Min	Yes	Image Processing
OP-01-A	Geopause	1024	1E6	1.73E4	1.73E8		
OP-02-A	Gravity Gradiometer	400	35E6	N/A	N/A	No	
OP-03-A	Mini-LAGEOS	N/A	N/A	N/A	N/A	No	Totally Passive Laser Reflectors (Earthquake Assessment)
OP-04-A	Gravity Field Satellite	1000	2.9E9	15000	14.4E6	Yes	Support Proc. and Gravity Field Determination (Earthquake Assessment)
OP-05-A	Vector Magnetometer Sat. Satellite	1.5E5	12E7	1.5E5	Combined RT and PB 12E7	Yes	
OP-06-A	Magnetic Field Monitor Satellite	1.5E5	12E7	1.5E5	Combined RT and PB 12E7	Yes	
OP-07-A	SEASAT-B	N/A	N/A	9E7	3.6E10	Yes	
LS-02-A	Biomedical Exper. Scientific Satellite	TBD	TBD	TBD	TBD	No	
ST-01-A	Long Duration Exposure Fac.	N/A	TBD	TBD	TBD	Yes	To effect contamination counter-measures
PL-07-A	Venus Orbital Imaging Radar	TBD	TBD	TBD	TBD	Yes	Instrument Checkout
PL-12-A	Mariner Jupiter Orbiter	1.17E5 1.17E5	6E11	1.1E5	6E11	Yes	Instrument Checkout
PL-22-A	Pioneer Saturn/Uranus/Titan Probe	2048 2048	TBD	N/A	N/A	Yes	For Investigators
PL-28-A	Pioneer Mars Surface Penetrator	2048	TBD	N/A	N/A	Yes	For Investigators
CN-51-A	International Telecommunication Satellite	1000	8.64E7	N/A	N/A	No	
CN-52-A	U.S.-DOMSAT A	1024	8.85E6	N/A	N/A	No	
CN-53-A	U.S.-DOMSAT B	1000	8.64E7	N/A	N/A	No	
CN-54-A	Disaster Warning Satellite	600	5.25E7	N/A	N/A	No	
CN-55-A	Traffic Management Satellite	512	4.4E7	N/A	N/A	No	
CN-56-A	Foreign Communications Satellite- A	1000	8.6E7	N/A	N/A	No	
CN-58-A	U.S.-TDRS-C	1024	9E7	N/A	N/A	No	
LU-01-A	Lunar Orbiter	2E5	1.74E10	TBD	TBD	Yes	Instrumentation C/O and Short Term Data Analysis

TABLE II-1
Data Rates Sortie Payloads

Experiment Number	Title	Data Acquisition & Management — Science Data Acquisition: Rate	Volume	TV	Voice
AS-01-S	1M Shuttle IR Teles. Fac.	251830	1.434E9	24 hrs.	4kHz
AS-03-S	Deep Sky UV Surrey Teles.	(only housekeeping data)		1.6	5kHz
AS-04-S	1M Diffract. Lmtd, UV Opt. Tel.	1E7	2.88E9	1.6	5
AS-05-S	Very Wide Field Galactic Camera	(housekeeping only)		12.8	3
AS-15-S	3M Ambient Temp. IR Teles.	21740	1.468E9	24	Std.
AS-63-S	Sortie Med. Aperature Opt. Tel.	(housekeeping only)		16	5
HE-11-S	X-Ray Angular Structure	20480	8.05E9		
		10240	6.98E11		
		10240	6.98E11		
		43008	3.7E9	1.6	
HE-15-S	Magnetic Spectrometer	10000	8.64E8	-	
HE-19-S	Low Energy X-Ray Teles.	40960	3.54E9	-	-
HE-25-S	Transition Rad-Det. (HE-701)	1500	1.296E8	-	-
SO-01-S	Dedicated Solar Sortie Mission (DSSM)	1.32E7	5.94E11	-	4
SO-11-S	Solar Fine Pointing Payload	1.32E7	5.94E11	-	4
SO-15-S	Solar Activity Early Payload	5.77E6	2.60E11	-	4
SO 17-S	Solar Activity Growth Processes (SO-703)	1E6	8.6E10	1.5	4
AP-06-S	Atmos. Magnetospheric & Plasmas in Space (AMPS)	3.2E6	1.4E11		
		1.E7			
		4.E5	TBD		3200 b/s
AP-08-S	Lidar System (AP-701)	4800	1.1E8	-	-
AP-09-S	Electron Accelerator (AP-702)	D2920	2E5		
		A3000Hz	8.5 hrs.	-	-
			6000 Hz		
AP-10-S	Chemical Release (AP-703)	208	1.7E7	-	-
AP-11-S	Diagnostic Payload (AP-704)	D3E5	6E9	-	-
		A 20 MHz	120 MHz		
AP-12-S	TADS (AP-705)	D TBD	24 hrs.	-	-
		A 10 MHz	20 MHz	-	-

TABLE II-1 (continued)
Data Acquisition & Management (continued)

Experiment Number	Function	Computer Support: Mem(R/A)	Mem(BULK)	Word Length	Operations Per Sec
LS-04-S	Data Formatting	24000	5.E4	16	1E5
LS-09-S	Warefan Analysis Data Comp. Trad				
LS-10-S	" "	24000	5E5	16	1E5
LS-13-S	" "	13000	5E4	16	1E5
EO-01-S	Data Formatting Data Storage	2500	1500	24	1E5
EO-05-S	Formatting and Storage	9000	200	16	30000
EO-06-S	Monitor and Format Data	2000	1500	7	120
EO-19-S	TBD	TBD	TBD	TBD	TBD
EO-20-S	Pointing Central	TBD	TBD	TBD	TBD
EO-21-S	TBD	TBD	TBD	TBD	TBD
EO-22-S	TBD	TBD	TBD	TBD	TBD
OP-02-S	Data Formatting, Storage Commands, Computations	5E3	2000	10	7E4
OP-03-S	Telescope OP-102 Pointing controls	5400	2000	16	29000
OP-04-S	Comm. Exp., Monitor Exp. Format Data For Storage	7.6E3	2000	10	2.9E4
OP-05-S	Data Formatting, Data Storage, Computations	5E3	2000	10	7E4
OP-06-S	" "	5E3	2E6	10	1.9E4
SP-01-S	N/A	N/A	N/A	N/A	N/A
SP-14-S	N/A	N/A	N/A	N/A	N/A
SP-15-S	No	N/A	N/A	N/A	N/A
SP-31-S	N/A	N/A	N/A	N/A	N/A
ST-08-S	TBD	TBD	TBD	16	TBD
ST-31-S	N/A	N/A	N/A	N/A	N/A
CN-05-S	N/A	N/A	N/A	N/A	N/A
CN-08-S	N/A	N/A	N/A	N/A	N/A

TABLE II- 1 (Concluded)
Data Disposition & Communications (Continued)

	Digital (Continued)			Television			
	Dump 1 Day	Shuttle	Sto & Ret	RT	Dump 1 Orbit	Dump 1 Day	Sto & Ret.
AS-01-S	1.844 E9		1.1117E10	26 MHz	26 MHz	26 MHz	26 MHz
				0.174 hrs.	0.858 hrs.	13.3 hrs.	16 hrs.
AS-03-S	2.59E8		1.555E9	26 MHz	26 MHz	26 MHz	26 MHz
				0.1 hr.	0.1	1.6	9.6 hr.
AS-04-S	3.053E9		5.400E9	26 MHz		26	26
				0.1	0	1.6	9.6
AS-05-S	N/A		1.298E9	1E6 Hz			1E6 Hz
				0.8	N/A	N/A	76.7 hr.
AS-15-S	1.88E9		1.117E10	26	26	26	26
AS-63-S	0		1.73E8	0.1	0.1	1.55	9.2
				26		26	26
				0.1	0	1.55	9.1
HE-11-S	3.7E9		2.2817E10	0.1	0.1	1.6	9.6
HE-15-S	1041		6.246E9	N/A	N/A	N/A	N/A
HE-19-S	3.64E9		2.3000E10	N/A	N/A	N/A	N/A
HE-25-S	1.38E8		8.99E8	N/A	N/A	N/A	N/A
SO-01-S	5.94E9		N/A (P/L Tape Rec.)	0	0	0	0
SO-11-S	5.94E10		N/A (P/L Tape Rec.)	0	0	0	0
SO-15-S	2.6E9		N/A (P/L Tape Rec.)	0	0	0	0
SO-17-S	7.3E9		4.400E10	TBD	N/A	N/A	5E6 Hz
AP-06-S	TBD		TBD	TBD	TBD	TBD	9.3 hr.
AP-08-S	TBD		TBD	TBD	TBD	TBD	TBD
AP-09-S	TBD		TBD	TBD	TBD	TBD	TBD
AP-10-S	N/A		1.7E7	N/A	N/A	N/A	N/A
AP-11-S	TBD		TBD	TBD	TBD	TBD	TBD
AP-12-S			20M	TBD	TBD	TBD	TBD

TABLE II-2
Sortie Payloads (continued)

Experiment Number	Title	Data Acquisition & Management — Science Data Acquisition: Rate	Volume	TV	Voice
		Digital And TV Totally Handled By FFTO Systems			
LS-04-S	Free Flying Teleoperator				
LS-09-S	Life Sciences Shuttle Lab'ry.	23.6E3	2.04E9	(1.5) (12.)	TBD
LS-10-S	Life Sciences Mini-Labs	7E3	6.18E8	6E6(COLOR)	INTERM.
LS-13-S	Life Sciences First US/ESRO Spacelab Mission (LS-701)	7E3	50E6	6E6(COLOR)	INTERM.
EO-01-S	Zero-G Cloud Physics Lab. (EO-701)	1E5	160E6	2	-
EO-05-S	Shuttle Imaging Microwave Syst (SIMS-1B)	5ES	9.2E9	0.6	-
EO-06-S	Scanning Spectroradiometer	220	2.61E6	-	-
EO-19-S	Mark II Interferometer-Solar (EO-703)	130E3	5.62E8	-	-
EO-20-S	Earth Resources Shuttle Imaging Radar (EO-704)		1.056E13	-	-
EO-21-S	Shuttle Imaging Microwave System (SIMS-A)	1.5E6	8.7E10	-	-
EO-22-S	Mark II Interferometer-Earth	1.3E5	1.4E9	-	-
OP-02-S	Multifrequency RadarLand Imagry (OP-702)	2.66E5	8.55E9	-	-
OP-03-S	Multifrequency Dual Polarization	4000	1E8		
	Microwave Radiometer (OP-703)	22,000	NIA	-	105 hrs.
OP-04-S	Microwave Scatterometer	2.82E4	7.614E8	-	-
OP-05-S	Multispectral Scanning Imagry	2.64E5	8.55E9	-	-
OP-06-S	Laser Altimeter/Profilometer Exp.	.29340	1.01E9	-	-
SP-01-S	SPA No. 1 Biological (Manned) (B+C)	94	2.44E6	4.2MHz 3 hrs.	-
SP-14-S	SPA No. 14 Manned & Automated (B+G+C+FP+LP)	14300	564E6	4.2 M 3 hrs.	-
SP-15-S	SPA No. 15 Automated Furnace/Levitation (FP+LP+CP)	14000	484E6	-	-
SP-31-S	Biological/Furnace Subelements & Core (SP-701/702)	30	4.08E6	-	-
		30	2.59E6		
ST-08-S	IRTCM (Integrated Real Time Contammation Moniter)	97E3	8.4E9	-	-
ST-31-S	Drop Dynamics Facility (ST-703)	1000	3.6E6	-	-
CN-04-S	Electromagnetic Environ Expt. (CN-701)	Experiment will Transmit 15.E6 b/s of Experiment Data To Ground Via TDRS For Approximately 0.2 hr Per Orbit.			
CN-05-S	CO2 Laser Data Relaylink (CN-703)	3000	5.4E6	3	-
CN-08-S	TWT Opern Envelope Expts. (CN-704)	488	4.21E7	5	-
		72	6.2E6		

TABLE II-2 (Continued)

		Data Acquisition & Management (Continued)				Data Disposition & Communications			
		Computer Support				Digital			
Number	Function	Mem(R/A)	Mem(BULK)	Word Length	Operations Per Sec	RT	Time	Dump	1 Orbit (Cent)
AS-01-S	Data Qual. Comp.		80000	32	80000				
	Auto Mon & Cont.		20000		20000	256000	1.55 hrs.		1.21E8
AS-0S-S	Data Formatting			32		3000	1.5		16.2E6
AS-01-S	Data Formatting, Curuefit, Transformations Etc.	8000	5E5	32	5E4	1E7*	1.5		190.8E6
AS-05-S	G & N Pointing	4000	5E4	32	4000	2500	1.5		N/A
AS-15-S	Comp. Mon. Cont.	8000	5E5	32	50000	21740	1.55		1.21E8
AS-63-S	Transformations pseudo color displays	8000	5E5	32	5E4	2000	1.5		-
HE-11-S	Various Housekeeping	8000	6.4E4	32	2E4	43008	1.5		2.32E8
HE-15-S	Data Qual. Cont. (Normally Done on Earth)	32000	1E6	32	3.6E4	12048	1.5		6.5E7
HE-19-S	Quick look data processing	4000	5E4	32	4000	42120	1.5		2.274E7
HE-25-S	N/A	N/A	N/A	N/A	N/A	1600	1.5		8.64E6
SO-01-S	TBD	TBD	TBD	TBD	TBD	1.32E6	0.833		3.9E9
SO-11-S	TBD	TBD	TBD	TBD	TBD	1.32E6	0.833		3.9E9
SO-15-S	TBD	TBD	TBD	TBD	TBD	5.77E6	0.83		1.7E9
SO-17-S	Pointing Control	8000	5E5	32	10000	1E6	1		N/A
AP-06-S	Prediction Analysis Spectrum nalysis Data Reduction, RT data Storage	300 to 4000	2500 to 12000	32	32000 max.	TBD	TBD		TBD
AP-08-S	Pointing & Control	TBD	TBD	TBD	TBD	TBD	TBD		TBD
AP-09-S	TBD	TBD	TBD	TBD	TBD	TBD	TBD		TBD
AP-10-S	Pointing Calc.	TBD	TBD	TBD	TBD	N/A	N/A		TBD
AP-11-S	TBD	TBD	TBD	TBD	TBD	TBD	TBD		TBD
AP-12-S	Positions Data Analysis	TBD	TBD	TBD	TBD	TBD	TBD		

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TABLE II- 2 (Concluded)

DATA DISPOSITION & COMMUNICATIONS

Experiment Number	Digital					TV			
	RT	Time	Dump 1 Orbit	Dump 1 Day	Shuttle Sto & Rot	RT	Dump 1 Orbit	Dump 1 Day	Sto & Ret.
LS-04-S	3840	.2	N/A	N/A	N/A	2	N/A	N/A	N/A
LS-09-S	14E3	0.5	N/A	2.16E5	1.34E5	6E6Hz 0.5 Hr.	0.75	N/A	6 MHz 7.5 Hr.
LS-10-S	TBD	TBD	N/A	6.18E8	4.2E3	6E6 0.25	N/A	6E6 0.25	6E6 4
LS-13-S	TBD	N/A	N/A	50E6	3.52E7	6E6 Hz 0.25 Hr.	N/A	6E6 0.25	6E6 3
EO-01-S	0	0	0	0	8E8	4E6 Hz 0.25 Hr.	N/A	N/A	N/A
EO-05-S	0	0	0	1E7	4.59E10	0	0	0	4.63E6 3.41 Hrs.
EO-06-S	N/A	N/A	N/A	N/A	1.43E7	N/A	N/A	N/A	N/A
EO-19-S	N/A	N/A	N/A	N/A	3.37E9	N/A	N/A	N/A	N/A
EO-20-S	N/A	N/A	N/A	N/A	1.98E8	N/A	N/A	N/A	N/A
EO-21-S	0	0	1E9	1E7	0	0	TBD	0	0
EO-22-S	N/A	N/A	N/A	N/A	1.404E9	N/A	N/A	N/A	N/A
OP-02-S	2.66E5	0.1	9.6E7	8.62E9	4.3E4	0.2	0.2	0.2	1
OP-03-S	0	0	0	100E6	5.0E8	0	0	0	0
OP-04-S	0	0	0	0	1.242E9	0	0	0	0
OP-05-S	2.66E5	0.1	9.6E7	8.62E9	4.3E4	0.2	-	0.2	1
OP-06-S	3.42E4	0.1	0.7E4	1.4E8	5.54E3	N/A	N/A	N/A	N/A
SP-01-S	94	1.8	N/A	N/A	N/A	4.2M 0.75	N/A	N/A	4.2M 8
SP-14-S	1.43E4	4.0	N/A	6.18E8	2.47E3	4.2M 0.75	N/A	N/A	4.2M 8
SP-15-S	1.4E4	0.2	N/A	5.56E7	2.779E9	N/A	N/A	N/A	N/A
SP-31-S	0	0	0	0	4.57E7	N/A	N/A	N/A	N/A
ST-08-S	N/A	N/A	84E8	8.4E9	5.47E10	N/A	N/A	N/A	N/A
ST-31-S	N/A	N/A	N/A	3.6E6	1.8E7	N/A	N/A	N/A	N/A
CN-05-S	N/A	N/A	N/A	N/A	6.3E7	N/A	N/A	N/A	N/A
CN-08-S	0	0	0	9.7E6	2.988E8	N/A	N/A	N/A	N/A

discussions revealed that at least for this generation satellite, on-board data processing of any type was not being considered. This decision is based on the philosophy that on-board data processing would result in the loss of radiometric information which would reduce the attraction of LANDSAT to some of its potential users. Since the parts of the collected data which may be discarded cannot be determined to suit all the users simultaneously, the philosophy is to transmit all of the data to the ground and store it for future reference and processing at the user's discretion. This allows each investigator to process the data as he desires, discarding parts of the data which are unimportant to him. Such a plan will provide a large data base for many investigators at the expense of a very large data transmission and storage problem.

Even if on-board processing were being considered, the present thoughts are that it would be digital rather than optical. There are several primary reasons cited for this preference; (1) greater dynamic range of digital processors, (2) higher accuracy obtainable with digital processors, (3) flexibility of digital processors, and (4) the future outlook for digital versus optical processors. While these considerations are valid for serial processing applications, the optical processor is still far superior for processing large quantities of data in parallel.

The dynamic range of digital processors is essentially limited by the number of bits used to represent a number and can be very large (typically about 48 dB for 16 bits). Thus, the digital processor can easily be made to have a greater dynamic range than the sensor which is the source of the data.

Processing accuracy of a digital processor can also be made quite good by using such techniques as double precision processing. Care must be taken, however, since the large number of operations required by a fast Fourier transform algorithm, for example, may result in degradation of the accuracy of the calculations.

Flexibility of a digital processor is greater than that of an optical processor. An optical processor essentially performs the Fourier transform operation by making use of the light diffracting property of a lens. Some techniques, such as nonlinear system operations, are presently being used to extend the flexibility of optical processors. Even with these techniques, there is a limited range of flexibility available with optical processors. On the other hand, a stored program digital computer can perform a wide range of operations, depending only on the ingenuity of the programmer to generate the algorithms to perform the desired operations and the storage capacity required to implement them. Over the last two decades a wide variety of algorithms for digital computers have been developed. Although a direct comparison is difficult because of their widely different processing capabilities, an optical processor is potentially much less expensive than a large scale or special purpose digital processor.

One important feature of optical processors should not be overlooked. This feature is the speed and bandwidth available from optical processors. An optical processor using a simple lens can produce the Fourier transform of a high resolution imput image in the time required for light to propagate through the processor. Some of the LANDSAT images, for example, may approach as many as 4000 resolution elements along one scan line of the image. When such high resolution images are involved, the time required to produce a

Fourier transform digitally using the fast Fourier transform and high speed matrix transposition techniques can be excessive. There should be applications where the speed of the transform operation available from the optical systems outweighs the accuracy and dynamic range advantages of digital systems. An example of such an application would be real time image processing for spatial or texture analysis in which both on-board buffer storage and ground storage requirements could be significantly reduced.

Contact with personnel of the Johnson Space Center in regard to the high data transmission requirements of the Space Shuttle Imaging Radar also revealed a preference for digital data processing. The same basic reasons were cited as for LANDSAT processing with one important consideration being a dynamic range of 50 dB. Even though digital data processing is preferred, optical data processing for this application has not been completely ruled out if a system can be shown to be competitive in dynamic range and power requirements.

The future outlook for digital systems appears to be quite good. This is a result of the large amount of money which continues to be put into the development of such systems. By comparison, a very small amount of funding has gone into the development of optical processing systems. In our view, this situation will not change until spacecraft image processing requirements exceed the expectation of digital processing systems. The projected requirements of the LANDSAT follow-on, a maximum information per image of 2×10^9 bits and a maximum accumulation of 10^{12} bits/day, may result in the investigation of alternative processing and storage techniques.

III. REVIEW OF COMPONENTS CRITICAL TO REAL TIME PROCESSORS

A. Introduction

Since the coherent optical processor is an analogue device, its successful application will be found in special purpose processing systems for which definite advantages over digital computing systems can be demonstrated. For on-board satellite applications, desirable system improvements would include reduction in equipment complexity or power requirements, reduction of RF downlink bandwidth through on-board data compression, and improvements in automatic navigational or docking systems.

The coherent optical processor operates in parallel with the number of parallel channels equal to the number of resolution cells at the input modified by the system modulation transfer function (MTF). A linear transformation can be performed on all these parallel inputs simultaneously; however, the most commonly used input recording medium, photographic film, does not allow real time processing. Even the coherent optical synthetic aperture processors, which employ mono-bath processing techniques, require several minutes between exposure of the film and the useable transparency.

It is clear, therefore, that the most critical component in the coherent optical processor is the real time input device. Over the last five years, a number of devices have been developed around electro-optic crystals, liquid crystal films, ferroelectric ceramics, thermoplastic films, and deformable membranes. On-going development of many of these devices has been stopped because of technical barriers which were too costly to overcome or because of the emergence of other clearly superior device technology.

During the course of this investigation, visits were made to ITEK, Hughes, and General Electric to obtain information on the latest developments in coherent modulator technology, and to observe first hand the performance of the respective devices mentioned above. The impressions gained through these visits supplemented with operating experience on an IFLM which was fabricated at Georgia Tech under contract NAS8-27375 [3-1] form a basis for the information contained herein.

In considering the application of coherent optical processors to on-board spacecraft systems, we will assume that the optical components will be required to satisfy the environmental constraints of spacecraft environment, and that the performance of these components will be compatible with the image quality presently obtained from the ERTS MSS sensor. It has been assumed that optical lens fabrication and coating technology is sufficiently advanced to allow realization of the lens components required for the development of the optical processing systems considered in this report. Hence, the primary emphasis of this study has been directed toward the investigation of real time coherent input devices and detector arrays for sampling and processing the optical processor output plane distribution.

B. Real Time Input Devices

An ideal coherent optical input device would spatially modulate a coherent optical beam to create a phase and amplitude image replica of high resolution and very low distortion which could be instantaneously altered to form new images or stored indefinitely to be used as a permanent image transparency. Practical devices deviate from these ideal characteristics in image quality, time interval required to change the image, and length of time the image can be stored without image degradation. Although some of the devices surveyed exhibited excellent performance in one or perhaps more of the desired characteristics, no device was found to perform well in all categories.

Although this study was not oriented toward a specific spacecraft application, the field of candidate devices can be significantly narrowed by relating potential processing tasks to two common image formats. The ERTS multispectral scanner (MSS) sensor generates a complete image frame consisting of 2313 x 2313 resolution cells at the rate of one image every 28.7 seconds. High resolution vidicons, on the other hand, are capable of generating images with about 1000 x 1000 picture elements at a rate of 30 Hz. Very high resolution tubes with large sensor formats are capable of 10,000 line resolution in a 50 by 50 mm format [3-2]. We have, therefore, restricted our attention to devices which appear to have the potential for achieving image quality compatible with multispectral scanners and are capable of operating at television rates.

The first screening of coherent optical input devices for on board satellite optical processing applications yielded five potential device technologies. These potential technologies are represented by the ITEK Pockel's Readout Optical Modulator (PROM) [3-3, 3-4, 3-5, 3-6], the Hughes Photoactivated Liquid Crystal Light Valve [3-7, 3-8, 3-9, 3-10], the Image Forming Light Modulator (IFLM) [3-1], the General Electric Coherent Light Valve (CLV) [3-11, 3-12] and the CBS Lumatron [3-13]. Of these, the IFLM, CLV and the Lumatron are modified cathode ray tubes, whereas the PROM and the Liquid Crystal Modulator are very compact devices which operate in an open environment. The CRT type modulators have the advantage of simple electronic interface with the image signal representation of the TV sensor. In all three devices, spatial modulation results from an electron charge distribution which is deposited on the crystal by a scanning electron beam. The IFLM exploits the Pockel's effect in the electro-optic crystal KD*P, while the CLV and Lumatron are phase modulated by surface deformations in thin thermoplastic films.

The IFLM was initially eliminated from further consideration for this application on the basis of poor image quality, relatively short lifetime, and system complexity; however, it was recently reported by Casasent [3-14] that a lifetime of 3 years was being projected for a KD*P modulator developed at Carnegie Mellon University. Although the response time of the IFLM is excellent and its operating mode is well suited for the TV sensor, its image quality is barely sufficient for this application. The resolution is limited to about 20 lines/mm because of electric field fringing in the KD*P plate. The current state-of-the-art in the crystal technology limits the size of good quality KD*P plates to about 2 inches, which results in a maximum of about 1000 resolution elements along each dimension of the plate. The modulator discussed by Casasent utilized a 1" x 1.5" 6 mil thick plate with a higher spatial resolution (37 lp/mm), but with the same number of resolution cells (1000 x 1000). In addition, this resolution can only be achieved if the crystal is cooled to near its Curie point which is about -55° C. The lifetime of the KD*P modulator is also questionable because of the surface degradations associated with the intense electron beam required for full contrast. The lifetime of the electron gun cathode is severely reduced when operated at the required beam current of $2A/cm^2$. These considerations along with the complexity associated with the modulator cooling requirement cause the IFLM device to be rated well below the leading contenders.

The Lumatron solid film thermoplastic modulator was eliminated from consideration because of its slow recycle time. Although good images are possible with this device, a complete write-erase cycle requires several seconds.

C. Comparison of PROM, CLV, KD*P, And Liquid Crystal Modulators

A comparison of imaging and system performance characteristics for the PROM, CLV, and Liquid Crystal Modulator is given in Tables III-1 and III-2. For a detailed discussion of the physical characteristics and operating modes of these devices see Section III of the Interim report

D. Summary of Optical Input Device Characteristics

In summary, the final choice of a coherent optical input device for on-board spacecraft data processing applications will be strongly influenced by the type of image sensor employed and the processing operations required for the application. In general, the PROM and Liquid Crystal Modulator appear to offer greater potential for spacecraft applications because of their good image quality, compact size, and long lifetime. The CLV, on the other hand, has lower complexity interface requirements, and exhibited the highest image quality of the candidates. Its poor lifetime, large size and questionable adaptability to a space environment form the primary basis for ranking the CLV behind the PROM and the Liquid Crystal Modulator. The KD*P modulator has questionable lifetime, relatively poor image quality, and significant materials problems which, in our view, place it a distance last among the candidate devices which have been considered. A summary of considerations relating to the selection of the PROM or the Liquid Crystal Modulator for a given optical processing application follows.

TABLE III-1

Comparison of Coherent Image Performance for the
PROM, CLV, KD*P, and Liquid Crystal Modulator

	Photometric Sensitivity	Resolution	Active Area	No. of Resolution Cells	Contrast	Gray Scale No. of Steps for $\Delta D=0.15$	Isolation Read-Write	Input Dynamic Range
GE CLV	N.A.	25 lp/mm @ 50% MTF	1"x 1"	625 x 625 @ 50% MTF	10^5:1	14	∞	21 dB
Itek PROM	300 ergs/cm^2 for C=100:1, 10^4 ergs/cm^2 for C=10^4:1	50 lp/mm* @ 50% MTF	1"x 1"	1,250 x 1,250 @ 50% MTF	10^4:1	27	28 dB	40 dB
Hughes Liquid Crystal Modulator	160 μW/cm^2 for C=100:1	60 lp/mm @ 50% MTF	1'x 1"	1,500 x 1,500 @ 50% MTF	10^2:1	9	50 dB	15 dB
KD*P Carnegie Mellon	N.A.	20 lp/mm † @ 50% MTF	2"x 2"	1,000 x 1,000	10^2:1		∞	

* Much greater resolution is possible for images possessing a narrow spatial frequency spectrum.

† Requires cooling to the Curie temperature of KD*P (∿ 50° C).

TABLE III-2

Comparison of System Performance Characteristics for the PROM, CLV, KD*P, and Liquid Crystal Modulator

	Response Time	Cycle Rate	Storage Time	Maximum Light Output	Drive Requirements	Lifetime	Level Slicing	Estimated Cost
GE CLV	4 msec.	30 Hz	<300 msec.	700 Lumens	7000 Vdc @ 10 μA	1,000 hrs.	No	$75 K
Itek PROM	.01-100 * μsec.	60 Hz	<1 hour †	limited by Read-Write Isolation	2000 Vdc	>10,000 hrs.	Yes	$38 K
Hughes Liquid Crystal Modulator	10-250 msec.*	15 Hz	N.A.	1,000 Lumens	6 Vac @ 0.5 mA	>10,000 hrs.	Yes	$25 K
KD*P Carnegie Mellon	5 μsec.	30 Hz	1 hour			?	No	

* Response time is dependent on the writing intensity.

† Maximum storage time cannot be realized for continuous read-out because of image degradation resulting from low read-write isolation.

ITEK PROM

Advantages

1. Compact Size
2. Good Image Quality (High Resolution, High Contrast, High Input Dynamic Range)
3. Compatible with TV Sensor
4. Has Storage Capability
5. High Sensitivity
6. Has Level Slicing Capability
7. Controllable Image Erase Capability

Disadvantages

1. Requires High Voltage Supply for Operation
2. Low Read-Write Isolation
3. Long Range Improvements Depend Primarily on Developing New Electro-Optic Crystals
4. Requires Electrical-to-Optical Interface

Hughes Liquid Crystal Modulator

Advantages

1. Compact Size
2. High Resolution
3. Low Drive Power Requirements
4. Potentially a Low Cost Device
5. High Read-Write Isolation
6. Has Level Slicing Capability
7. Long Range Improvements Depends Primarily on Well Established Thin Film Technology

Disadvantages

1. Low Contrast and Input Dynamic Range
2. Slow Response and Decay Times
3. Cosmetic Quality of Images is Poor
4. Alignment of Liquid Crystal Film can be Destroyed by Mechanical Shock
5. Requires Electrical-to-Optical Interface

E. Correlation-Plane Detector Requirements

There are specific requirements for the physical characteristics of a detector to be used in the correlation plane of an optical processing system. These requirements are reviewed here and a discussion of detector characteristics appears in Section III-F in the Interim report. The correlation plane requirements are then compared with available detector characteristics.

The information in the correlation plane is in the form of a spatial distribution of light intensity. The detector should, therefore, sample at discrete points or scan the area covered by this distribution. For example, the use of an array of discrete elements, the outputs of which can be electronically scanned, enables near real-time processing to be achieved. This mode of operation would be virtually impossible to accomplish by physically scanning the light distribution with a single detector element. Even with electronic scanning of a fixed array, the response time of the detectors must be minimized.

The light intensity can vary large amounts over small distances. Therefore, detector elements with a wide dynamic range and small size are required. Likewise, the intensity patterns of interest may vary by relatively small amounts over large distances. This possibility requires highly stable detectors with a wide dynamic range.

With a laser as the source in an optical processing system there is usually more than enough power available to saturate the detector elements in the high intensity regions of the information plane. However, some incoherent-to-coherent input devices are capable of contrast reversal operations which can be employed to reduce the undiffracted component of the Fourier transform diffraction pattern by a factor of 10^4. In this case, the dynamic range requirements are greatly reduced. The major consideration is then a lack of adequate sensitivity in the regions of low light level. In summary, the requirements for a correlation plane detector are that it consist of an array of very sensitive, highly stable, and fast detector elements that respond linearly with irradiance over a wide dynamic range. The arrays must be capable of being fabricated in a variety of sizes and configurations with adequate resolution for the optical data processing application.

F. Available Detector Arrays

The most promising detectors for use in the correlation plane of an optical processing system are the solid state devices of the following types:

1. Photodiode arrays,
2. FET bucket brigade,
3. Charge coupled devices (CCD's), and
4. Charge Injection Devices (CID's)

G. Comparison of Correlation Plane Detectors

Table III-3 presents a comparison of the correlation plane detection devices.

TABLE III-3

TYPICAL PARAMETERS FOR ARRAY DETECTORS

Device	Array Configuration	Element Spacing	Illumination Sensitivity	Dynamic Range	Response Time	Frame Rate	Random Access
Reticon	Linear and Rectangular-Self Scanning Photodiode Array	linear-1 mil rect.-4 mil	2×10^{-3} ft. cd.	30 dB	1 μsec.	1 kHz	No
RSI	Polar Photo-diode Array	1 mil	<1 $\mu W/cm^2$	60 dB	<1 μsec.	6.3 kHz	Yes
Bucket Brigade	Rectangular	3 mil	1 ft. cd.	18 dB	10 μsec.	60 Hz	No
CCD	Rectangular	2 μm	<10 ft. cd.	30 dB	1 μsec.	<1 kHz	No
CID	Rectangular	3 mil	0.1 ft. cd.	20 dB	<0.3 μsec.	30 Hz	Yes

IV. OPTICAL CORRELATION PROCESSORS

A. Discussion of Optical Correlation Techniques

The devices which hamper the development of real time optical computers at present are the electro-optical input devices. These are devices which transform the electrical signal representation of an image to a coherent optical image in real time. The state-of-the-art in these devices was the subject of the first phase of this program and the results of that investigation were reported in the Interim report [4-1]. A brief review of these devices, which include the General Electric Coherent Light Valve, the Hughes Liquid Crystal Modulator, and the ITEK Pockel's Readout Optical Modulator along with some recent development in other devices, is given in Section III of this report.

Two basic techniques for optical correlation which find wide application are described below. One of these involves joint transform correlation in which both input images are placed side by side in the input plane of an optical processor. The Fourier transforms of the two images are superimposed onto a storage device such as the PROM, which is assumed to have a linear region of the amplitude transmittance versus exposure curve, and the correlation components are then formed by a second Fourier transformation [4-2]. The retransformed image contains the autocorrelation terms on axis and two cross-correlation terms off axis by a distance of twice the input image separation. A digital simulation of this technique is presented in Section VI of the Interim Report.

The second method involves the holographic recording of a filter function produced by one of the input images. Lohmann gives eight different ways in which the hologram may be generated and discusses the advantages and disadvantages of the various methods [4-3]. Figure 1 shows the relation of the input image, the filter and the lens and Figure 2 presents a list of features of the various methods. In the figures u(x) is the complex amplitude transmittance of the unknown object, and v(x) the complex amplitude transmittance of the reference placed in the transform plane of the first of two successive transform lenses in the system. The complex amplitude term incorporated in a Fourier hologram in $\tilde{u}(x/2f)$ or $\tilde{u}^*(x/2f)$ is defined as

$$\tilde{u}(v) = \int u(x)\ \exp(-2\pi i v x)\,dx$$

where * denotes the congugate. For Fresnel holograms at a propagation distance z = f the corresponding terms are $\hat{u}(x)$ and $\hat{u}^*(x)$ where

$$\hat{u}(x) = \int \tilde{u}(v)\exp\ \{2\pi i[vx + (f\lambda)\sqrt{1 - \lambda^2 v^2}]\}\ dv$$

The prepare column having a negative sign indicates that the reference signal, v(x), cannot be used directly and must be made into a hologram before it can be used as the coherent filter. The next two columns for $\Delta\eta$ and Δx_s which contain minus signs indicate stringent coherence either spectrally or spatially. The columns δx_o, δx_R, and δx_D containing minus signs refer to the need for careful lateral adjustment in the object, reference, and detector planes. Adjustments in the reference plane may be on the order of a few microns. The arrows connecting two columns indicate dependent adjustments. The requirement for precise registration of the image transform and its filter does not apply to the joint transform correlation technique. The N_p column refers to the sensitivity to phase noise. The capability of measuring shifts between the object and the reference is indicated by a plus sign in the shift column.

Method No. 1, which is Vander Lugt's coherent matched filtering method has been used to measure the shift between two images of cloud formations.

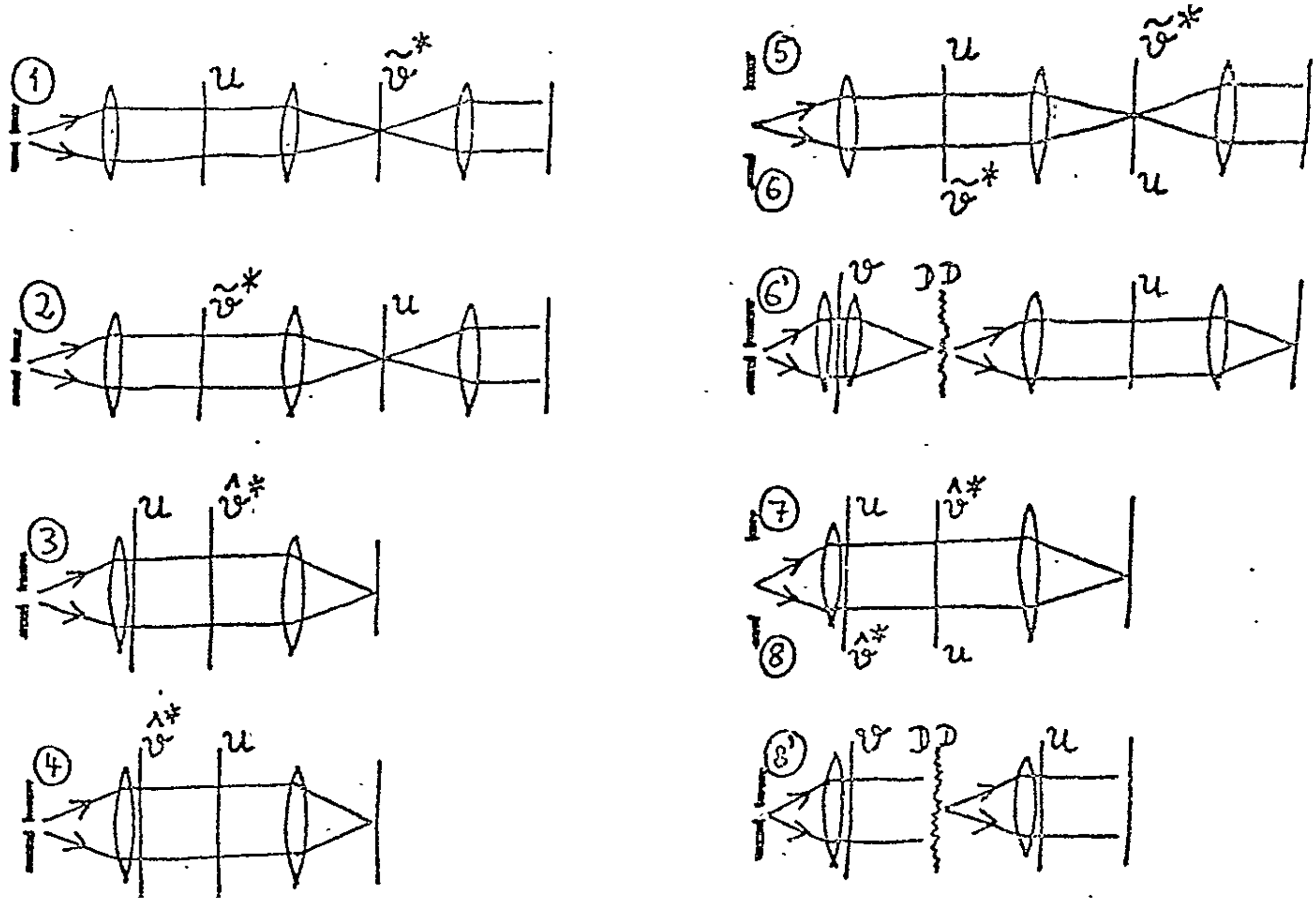

Figure 1. Different arrangements for holographic optical correlation. (From Ref. 4-3)

Nr.	input	reference	prepare	$\Delta\lambda$	Δx_S	∂x_O	∂x_R	∂x_D	N_P	shift
1	u	$\tilde{v}^*$	−	−	−		−		−	+
2	$\tilde{v}^*$	u	−	−	−	−			−	−
3	u	$\hat{v}^*$	−	−	−			−	−	−
4	$\hat{v}^*$	u	−	−	−			−	−	−
5	$\|u\|^2$	$\tilde{v}^*$	−	−	+		+		+	+
6,6'	$\|\tilde{v}\|^2$	u	+	+	(+)'	+	+	−	−	−
7	$\|u\|^2$	$\hat{v}^*$	−	−	+				+	+
8,8'	$\|\hat{v}\|^2$	u	+	+	(+)'				−	+

Figure 2. List of Features of holographic correlation methods. (From Ref. 4-3)

Some of the methods make use of incoherent signals and thus simplify the input device to the optical system. The first four of the methods are old while the last four are new.

The joint transform technique has the advantage that the accurate alignment of the filter is reduced as compared to Vander Lugt filtering. The input objects can be placed anywhere along the optical axis in the input light beam as long as they remain in the beam and are coplanar. The two input images must be coplanar and the correlation results are largely sensitive to rotation and size of the two images.

None of the methods is ideal in all respects, but the method best suited for a particular application must be selected based on the demands of the application.

Some recent developments in the use of Mellin transforms have been claimed to reduce the dependence on image size and rotational orientation between the input images [4-4]. Shift or positional invariance in an input image is eliminated by forming the magnitude of the Fourier transform of the input image. This eliminates the effects of positional shifts in the input function since they appear as phase angles of the complex transform components. The effects of rotation and scale change on the transform components are separated by performing a rectangular to polar transformation on the Fourier transform components. A scale change in the transform coordinates does not effect the angular coordinate in the polar transformation while it scales directly the radial component. This reduces a two dimensional scaling of the input to a one dimensional scaling of the transformed function.

A single dimension Mellin transform on the radial component in the polar transformed data should produce a scale invariant transform due to the scale invariant properties of the Mellin transform. The rotational variations of the input are converted to phase factors by performing a single dimension Fourier transform in the angular dimension of the polar transformed information.

A digital simulation of this technique of eliminating size and rotational variations of the input images was attempted late in the contract period. Time did not allow for the simulation to be developed to a point of producing conclusive results.

Figures 3 and 4 are examples of how a joint transform correlator and a Vander Lugt correlator could be constructed. These two examples do not meet the requirements of a real time optical correlator since they use as input media transparencies which are not real time input devices capable of operation at television frame rates.

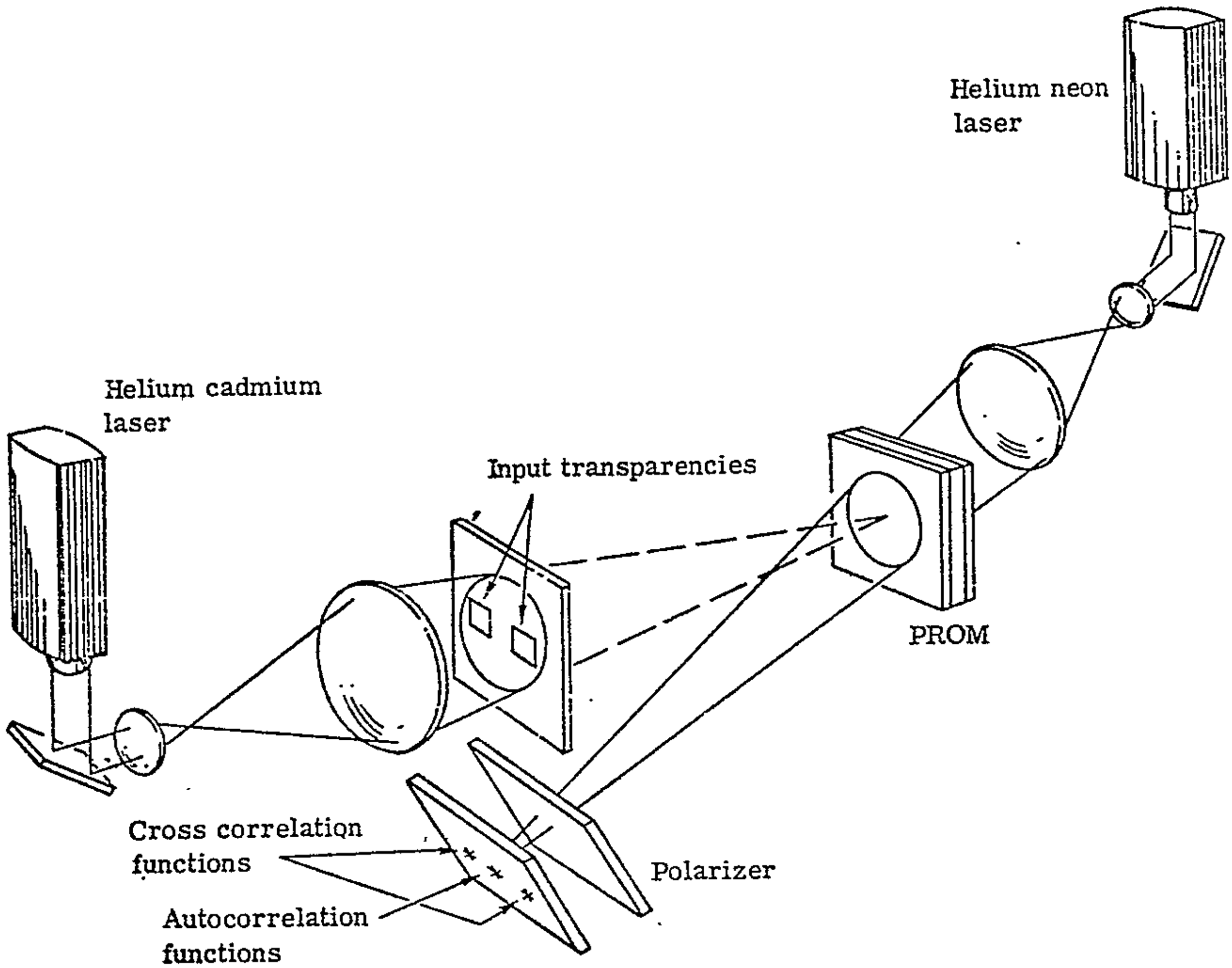

Figure 3. Joint transform correlator using PROM.
(From Ref. 4-2)

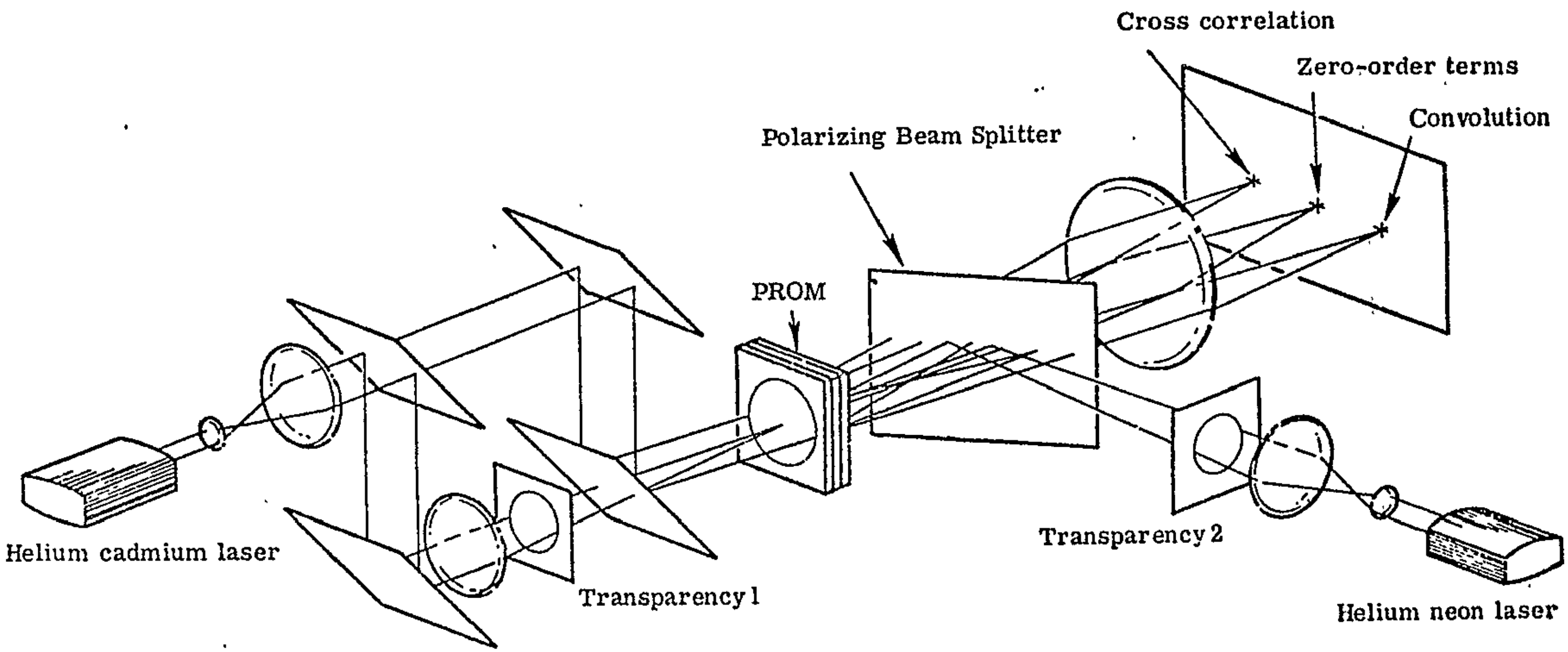

Figure 4. Vander Lugt correlator using PROM.
(From Ref. 4-2)

V. SOME CONSIDERATIONS OF DIGITAL IMAGE PROCESSORS

Many of the personnel with whom discussions regarding optical processing have taken place during the project period have indicated a belief that in a few years, possibly five, digital processors will replace optical processors. This supposition applies to such areas as synthetic aperature radar processing where optical techniques have been developed to a high degree of perfection. This feeling is due, at least in part, to the very rapid advancement in digital systems and in the techniques of using these systems. The following is a brief review of some of the present considerations in digital image processing so that the trade-offs between digital and optical processing can be better appreciated.

The time required to perform a one dimensional fast Fourier transform, (FFT), using the Cooley-Tukey method and using a general purpose computer performing calculations serially is [5-1]

$$T_c = 2kN \log_2 N \text{ (seconds)}$$

where N = number of points in transform,

k = constant depending on particular computer and program.

The indicated reference gives $k = 30 \times 10^{-6}$ seconds for an IBM 7094 computer.

To perform a two dimensional FFT requires that the single dimension transform be taken in one of the dimensions of the input data, say along the rows of an image - which corresponds to the normal method of generation of a TV picture - and that the transform then be taken along all the columns of the row transformed data.

If the number of rows is represented by N and the number of columns by M, the time required to transform the entire picture using the Cooley-Tukey algorithm is

$$T_{2c} = (2kM \log_2 M)N + (2kN \log_2 N) M$$
$$= 2 k MN (\log_2 M + \log_2 N)$$
$$= 2 k MN \log_2 MN \text{ (seconds)}$$

If the picture is square N = M

$$T_{2c} = 2 k N^2 \log_2 N + 2 kN^2 \log_2 N$$
$$= 4 kN^2 \log_2 N \text{ (seconds)}$$

Applying a filtering operating in the transform or spatial frequency plane requires that the transform be multiplied by the transfer function involving N^2 operations, and the time $T_f = k_1 N^2$, where k_1 is the time required to read the memory, perform the multiplication, and write into memory. Retransforming the filtered spatial frequency plane to obtain the filtered input function would again require a number of operations equal to

$$T_{2c} = 4 kN^2 \log_2 N$$

The total time involved in the digital computation of the filtered function, with the exception of the k's representing the computation time, agrees with that given by Hall [5-2]

$$T_{2cf} = 4k N^2 \log_2 N + k_1 N^2 + 4 k N^2 \log_2 N$$
$$= 8 k N^2 \log_2 N + k_1 N^2$$
$$= N^2 (8k \log_2 N + k_1)$$

The time required to compute a single dimension transform by the direct method is

$$T_d = kN^2$$

The time required to perform a two dimensional transform of an N x N matrix by the direct method transform is

$$T_{2d} = kN^2(2N)$$
$$= 2kN^3$$

The time required to perform two dimensional filtering (transform, filter and retransform) by direct "brute force" methods would be

$$T_{2df} = 2kN^3 + k_1N^2 + 2kN^3$$
$$= N^2(4kN + k_1)$$

Using the constant k given for the IBM 7094 computer some representative times may be calculated for the computation of the two dimensional transform of several sized N x N images.

CALCULATION TIMES

Single Dimension Transforms			No. of Single Dimension Transforms	Two Dimensional Transforms	
N	T_d(sec)	T_c(sec)		T_{2d}(sec)	T_{2c}(sec)
32	0.031	0.010	64	1.97	0.61
64	0.123	0.023	128	15.7	2.95
128	0.492	0.054	256	126	13.8
256	1.97	0.123	512	1009	62.9
512	7.86	0.276	1024	8053	283
1024	31.5	0.614	2048	64425	1258
2048	126	1.35	4096	515396	5536
4096	503	2.95	8192	4123169	24150
8192	2013	6.39	16384	3.30×10^7	1.05×10^5
16384	8053	13.8	32768	2.64×10^8	4.51×10^5

Our experience on the Univac 1108 computer with a single dimension FFT of length 256 was that the computation time was approximately 0.12 sec and for a 1024 point transform was 0.6 sec [5-3]; these times agree well with the above calculations based on the IBM 7094 computer calculation times.

The General Radio (GenRad) time series analyzer can perform a single dimension 1024 FFT in 12.2 msec. It is a special purpose analyzer vintage early 1970's [5-4].

For the filtering operation for large dimension images the computation times would be approximately double those indicated above for the two dimensional transforms since the transform would have to be taken twice and the time for the spatial filtering operation for large dimension arrays would be small compared to the transform times involved.

The above estimated times assume that the computer memory is large enough to contain the entire image data set. The image data set is an N x N array of brightness level each requiring two computer words since the transform process produces complex transform components. An N of 128 which produces a 128 x 128 array was the largest that could be used in the 65K main memory of the U-1108. This represents $2^7 \times 2^7 \times 2 = 32K$ words of memory for the image data and storage must also be allocated in the main memory for the program used for the calculations.

In most practical situations and for large images all the image data could not be present in the main memory at the same time. Future semiconductor memory developments will probably make possible such large memories. Presently, for large images, the data must be brought into the main memory piecemeal. This is efficient for the first transform operation for a two dimensional transform since the data is generated serially (in rows). A problem is then encountered when the input data matrix must be transposed so that the second transform operation can be performed (along the columns of the transformed data). This in the past has consumed more computer time than actual transform operations. Billingsley [5-5] states that the expenditure of computer time for a two dimensional transform is primarily for the 90^{o} rotation for the x, y separate transform processes and that the transform process is "neatest" if the data arrays contain a number of samples which is a power of two, which restricts the image size increments.

Techniques have been developed which reduce the matrix transposition time (for a 1024 x 1024 matrix) from several tens of minutes to several minutes by performing the matrix transposition on subelements of the data array and storing the results of these operations in extended memory. These subelements are of dimensions which are power of two factors of the larger array [5-6]. The times indicated are for a CDC 6600/7600 computer and make use of a sizable extended core memory.

Another technique which requires no extended memory is presented by Eklundh [5-7]. This technique reads in the row oriented data and performs the row transforms. The number of rows read in depends on the size of the central memory available. As few as two rows can be processed in main memory to obtain the transpose matrix at the expense of having to read the data set more than one extra time. The more rows which can reside in main memory at one time the shorter the computation time of the transpose matrix. Eklundh states the time required to transpose a 1024 x 1024 matrix of data points for 32 rows in main memory at one time is:

Central Processor Time =	23 sec
Estimated Input-Output Time =	134 sec
Total Time	157 sec

Special purpose pipeline and parallel FFT processors can speed up the time required for calculation of the transforms considerably but restrict the flexibility of the digital processors.

Several techniques are used to speed up the calculation of the FFT. One splits the single dimension transform into a two dimension transform of a size which is an integer factor of the transform size N. The transform is then computed on the smaller radix set of data points. For example a 64 point transform can be split into four rows of 16 points each, the transform of the rows taken, the columns then arranged as four 4 x 4 matrices and the transform of each row again obtained [5-8]. The "elementary computation" element in a "decemation in time" algorithm for a radix 2 transform involves the calculation of

$$A' = A + CW^i$$

$$C' = A - CW^i$$

where A and C are complex input data points and $W = \exp(j2\pi/N)$, and i is an index which is a function of how many steps have been completed in the algorithm. A radix 2 algorithm would require eight memory cycles, four multiply cycles, and six add cycles for each of the $(N/2)\log_2 N$ elementary calculations. The number of elementary calculations required in the FFT computation is given by

$$C_r = \frac{N}{r} \log_r N$$

where N is the number of points in the transform and r is the radix. If $r=n$, $C_r = 1$, but the complexity of the elementary calculations increases with r. Thus this technique appears to increase the FFT computation speed by possibly a factor or two or four before the complexity of the hardware becomes prohibitive.

Some examples of the speed of higher radix designs are given by Corinthios [5-9]. He gives the computation time and maximum sampling rate of the input data for the calculation of a 4096 point transform as a function of radix as:

Radix	Computation Time (Msec)	Maximum Sampling Rate (Samples/Sec)
2	9.5	430,000
4	3.6	1,080,000
8	1.85	2,100,000

Later developments led to a further increase in the processing speed of r + 1 where r is the radix [5-10]. Here assuming that the operations can be performed at the data shifting clock period of 100 nsec a 1024 point radix 4 transforms can be obtained in 64 msec which amounts to a maximum sampling frequency of 16 MHz. This time is obtained from Corinthios' expression for the time for transforming N real valued data in real time as

$$t = \frac{1}{2}(n)\left(\frac{N}{r}\right) t_{sh}$$

where $N = r^n$ with r the radix of the transform, and t_{sh} is the minimum data shifting period. A two pass fast Fourier transform processor for image processing applications is described by Buijs, et al. [5-11]. The processing rate is one clock cycle per input point for the N-point transform regardless of the value of N chosen. The implementation uses two radix $N^{\frac{1}{2}}$ passes carried out in parallel and in which each $N^{\frac{1}{2}}$ point transform is carried out via a serial input parallel output transform circuit. The processing rate is expected to be nearly 5 MHz. This technique appears to be relatively advantageous for small N (a 64 x 64 transform being implemented). For a clock rate of 200 nsec the processing rate should be approximately 200 msec for a 1024 point transform.

A new hardware realization of higher speed Fourier transforms described by Liu and Peled [5-12] should make possible a throughput of complex data points at a 25 MHz rate using standard available TTL integrated circuits. Their approach should offer an "attractive alternative" up to transform lengths of 1024 points.

VI. CONCLUSIONS AND RECOMMENDATIONS

Part one of this investigation was carried out to determine the feasibility of an optical processor for on-board spacecraft operation. The investigation revealed that although real time optical processing is much nearer a reality than it was several years ago, there are still components critical to real time operation which need further developing and refinement. Among these critical components are the incoherent-to-coherent optical input devices for the object and filter planes, and the high resolution detector arrays for the output plane. Much of part one of this effort was directed toward an investigation of the impact of the operating characterisitics of these devices on system performance, since these are, at present, the critical components of a real time optical processor.

The final success of a real time optical processor will depend in large part on the performance of the image input devices, which will be employed in both the input plane and the frequency domain filter plane. Photographic transparencies have traditionally been used for these functions; however, because of processing time delays, photographic film can hardly be classed as a real time input medium. While devices to provide the function of image inputting and filter function insertion in the transform plane display some similar characteristics, the demands on each of these devices are different. It would be desirable for the input plane device to be capable of inputting high contrast images at television rates, with erasure or write-over capabilities such that an image written on the input device at a television rate would be independent of previously written images. The input plane device should also be able to accomodate high resolution television images or images generated from multispectral scanners. The filter plane devices should also be capable of inputting high contrast, high resolution images to the filter plane of a Fourier optical processor, and in addition be capable of storing the image over an appreciable time interval. The filter function storage interval would be dependent on the application for which the processor is intended.

Four devices were considered in this investigation for the role of image input device. These were: (1) the General Electric Coherent Light Valve, (2) the electron-beam-addressed KD*P Light Modulator, (3) the ITEK Pockel's Readout Optical Modulator, (4) and the Hughes Liquid Crystal Modulator. Of these four devices the PROM and the Liquid Crystal Modulator appear at this time to be the best candidates for the real time optical processing applications because of their inherent operational simplicity, compactness, extended life-time, and future development prospects. However, neither of these devices is completely satisfactory in its performance of the desired functions for an image input device and additional development work is required. Techniques for optimum systems applications of these devices should also be investigated.

Output plane detection devices provide another optical processor interface where device characteristics are important. The information in the output plane of an optical processor is in the form of a spatial distribution of light intensity. The detector should sample at discrete points or scan the output plane with sufficient resolution to extract the details of the processing operation. A review of solid state detection devices was carried out. The exact specification of an output plane device is dependent on the processor application, and should be selected on the basis of operational compatibility.

The mechanical design of an on-board optical processor is important to successful operation in a spacecraft mission. The general mechanical design considerations for an on-board optical processor were discussed. Guidelines have been suggested for establishing the mechanical specifications for an on-board optical processor designated for a specific mission.

The electronic interface with the optical processor is also not specifically defined at this time. Since it appears highly probable that the input to the optical processor will be an electrical signal in the form of a time waveform, and not a direct optical input, some unique electro-optical interface problems arise with the potential image input devices. The excitation for the input devices is generally an incoherent light image which must be generated from the time waveform representing the input signal to the processor. A discussion was presented of potential electrical-to-optical interface devices such as cathode ray tubes, storage tubes, and modulated laser beams. Imaging of these electrical-to-optical interface devices in the input plane of the incoherent-to-coherent input devices is also discussed. Recommendations concerning the interface electronics at this time are, that since there are so many unknowns in both the electrical-to-optical and optical input devices, a laboratory breadboard should be constructed to provide a test bed for the evaluation of real time input techniques.

A preliminary digital simulation of several potential problems relating to real time operation of an optical processor was presented. Specifically considered were the optical correlation of two input images by the spatial heterodyning technique, and the effects of image decay on the correlation plane light intensity distribution. The results of this preliminary investigation strongly suggest that additional simulation studies be performed to evaluate the correlation signal degradation for complex coherent images which are subject to image decay resulting from the short relaxation times characteristic of some coherent input devices. These advanced studies would also serve to define the required parameters for the correlation plane detector.

From the results of part one of this study it is recommended that a program leading to the development of an on-board coherent optical processing system be mission-oriented, and include the following elements: (1) select a specific spacecraft mission for which an on-board optical processor would significantly improve data management operations, and provide additional benefits in the reduction of system cost and complexity, (2) continue digital simulation of optical processing operations to define system requirements, (3) initiate the development of or modification to a real time optical input device which would be compatible with the spacecraft sensors for the selected mission, and (4) assemble a breadboard optical processor to allow experimental evaluation of the complex electrical-to-optical and optical-to-electrical interfaces.

Part two of the investigation was concerned with the applications of optical data processors, specifically those systems relating to satellite data acquisition. Discussions with personnel knowledgable with future space missions have revealed that on-board data processing of any kind which would eliminate some of the available data is not acceptable at this time. Returning all the available data to the earth and letting each investigator perform whatever data processing techniques he desires is the method of operation for space missions of the immediate future. This method of operation creates severe data storage problems. It is possible, however, that the severe technological problems associated with transmission, processing and storage of projected data acquisition systems will have a moderating influence on the currently held views which oppose preprocessing.

In addition, if on-board processing were to be considered, the general opinion at present is that it would be digital rather than optical. The reasons cited for this are (1) greater accuracy offered by digital processors, (2) greater flexibility of digital processors, (3) future developments appear better for digital as opposed to optical processors and (4) greater dynamic range of digital processors. A major disadvantage of digital processing is the time required to process a two dimensional image, and the high acquisition cost of these systems. It should be pointed out, however, that the preference for digital processing is due in part to its relatively mature hardware technology, and the general feeling that optical processing is still a laboratory technique.

Systems employing optical data processing may well find applications for on-board processing when spacecraft are designed for operational rather than research purposes. For such an application the exact nature of the data of interest would be known, and the redundant parts of the data could be eliminated without significant loss of information. Optical data processors may also find applications for purposes of "quick look" capabilities not requiring all the precision available from various sensors.

From the results of part two of the investigation it was determined that: (1) on-board data processing for the space craft missions now being designed is generally not considered desirable, (2) if on-board processing were to be considered it would probably be digital rather than optical at this time, (3) the exact configuration of an optical correlator would be determined by the specific application to be satisfied and (4) there have been significant advances in device technology relating to real time data processing system implementation.

Although the current concensus is that preprocessing or high speed optical spatial processing is not desirable for spacecraft data acquisition systems, pressures resulting from technological difficulties with advanced mission concepts may force a change in this opinion in the near future. It is our view that NASA should continue to look at optical processing technology as a potential component of a new generation of data acquisition and processing systems. When properly utilized, both optical and digital technology could be combined to form a hybrid system with increased flexibility and processing speed for applications in earth resources and space systems technology.

VII. REFERENCES

SECTION I

1-1. J. R. Walsh, R. G. Shackelford, R. D. Wetherington and R. Sheppard, "Conceptual Design of an On-Board Optical Processor With Components," Interim Report on Contract NAS8-31344, Georgia Inst. of Technology, January 9, 1976.

1-2. D. Gabor, MIT Electronics Research Laboratory Technical Report, Rept. No. 238, 1952.

1-3. E. L. O'Neill, "Spatial Filtering in Optics," IRE Trans on Infor. Theory IT-2, 1956.

1-4. P. Elias, D. S. Grey and D. Z. Robinson, "Fourier Treatment of Processes," J. Opt. Soc. Am., 42, 1952.

1-5. E. L. O'Neill (ed.), "Communication and Information Theory Aspects of Modern Optics," General Electric Co., Electronics Laboratory, Syracuse, NY., 1962.

1-6. M. L. Noble, "Coherent Light Valve, Real Time Information Processing," General Electric Technical Document R7SELS-12, February 1975.

1-7. R. G. Shackelford and J. R. Walsh, Jr., "Design and Fabrication of an Experimental Image Forming Light Modulator," Final Report on Contract NAS8-27375, Georgia Inst. of Technology, June 1972.

1-8. J. Grinberg, et al., "A New Real Time Non-Coherent - to-Coherent Converter. The Hybrid Field Effect Liquid Crystal Light Valve," Optical Eng. 14, 1975. NASA, GSFC, Contract NAS5-23192.

1-9. P. Nisenson, et al., "Characteristics and Optimization of an Electro-Optic Imaging Device for Real-Time Map Profiling," Report No ETL-CR-74-18 for the U. S. Army Engineer Topographic Laboratories, prepared by Itek Corp., December 1974.

SECTION II

2-1. J. W. Goodman, Introduction to Fourier Optics, McGraw-Hill Book Co., New York, NY., 1968.

2-2 J. W. Goodman, "Operations Achievable With Coherent Optical Data Processing," Proc. of the Technical Program Electro-Optical Systems Design Conference 1975, Anaheim, CA., November 11-13, 1975.

2-3. G. G. Lendaris and G. L. Stanley, "Diffraction-Pattern Sampling for Automatic Pattern Recognition, Proceeding of the IEEE, Vol. 58, No. 2, February 1970.

2-4. N. Jensen, "Practical Jobs for Optical Computers," Machine Design, February 23, 1973.

2-5. H. L. Kasdan and D. C. Mead, "Out of the Laboratory and into the Factory - Optical Computing Comes of Age," Proc. of the Technical Program Electro-Optical Systems Design Conference 1975, Anaheim, CA., November 11-13, 1975.

2-6. K. Preston, "Analogue and Digital Pattern Recognition," Proc. IEEE, Vol. 60 , No. 10 , October 1972.

2-7. N. Jensen, R. Schindler and H. B. Peake, "Optical Power Spectrum Measurements for Image Quality," SPSE Proc. on Recent Developments in Image Analysis, May 1972.

2-8. P. Kruger, W. B. Thompson and A. F. Turner, "Computer Diagnosis of Pneumoconiosis," IEEE Trans. on Systems, Man and Cybernetics, Vol. SMC-4, No. 1, January 1974.

2-9. R. E. Kopp, et al., "The Use of Coherent Optical Processing Techniques for Automatic Screening of Cervical Cytologic Samples," The Journal of Histochemistry and Cytochemistry, Vol. 22, No. 7, 1974.

2-10. G. C. Salzman, et al., "A Flow-System Multiangle Light Scattering Instrument for Cell Characterization," Clinical Chemistry, Vol. 21, No. 9, 1975.

2-11. M. L. Noble and W. A. Penn, "Applications of Coherent Light Valve Systems to Optical Signal Processing," Proc. of the Technical Program Electro-Optical Systems Design Conference 1975, Anaheim, CA., November 11-13, 1975.

2-12. G. W. Stroke, "Optical Computing," IEEE Spectrum, Vol. 9, No. 12, December 1972.

2-13. Payload Descriptions, Vol. I, Automated Payloads, NASA, Marshall Space Flight Center, Huntsville, AL., July 1975.

2-14. Payload Descriptions, Vol. II , Books 1 and 2, Sortie Payloads, NASA, Marshall Space Flight Center, Huntsville, AL., July 1975.

SECTION III

3-1. R. G. Shackelford and J. R. Walsh, Jr., "Design and Fabrication of an Experimental Image Forming Light Modulator," Final Report on Contract NAS8-27375, Georgia Inst. of Technology, June 1972.

3-2. O. H. Schade, Sr., "Television Cameras" International Workshop on Earth Resources Survey Systems, NASA SP-283, 1972.

3-3. P. Nisenson, et al., "Real Time Optical Processing," Proc. of the Soc. of Photo-Optical Inst. Engrs., Vol. 45, March 1974.

3-4. S. Iwasn, and J. Feinleib, "The PROM Device in Optical Processing Systems," Opt. Eng., Vol. 13, No. 3, May/June 1974.

3-5. S. G. Lipson and P. Nisenson, "Imaging Characteristics of the Itek PROM," Appl. Optics, Vol. 13, No. 9, Sept. 1974.

3-6. P. Nisenson, et al., "Characterization and Optimization of an Electro-Optic Imaging Device for Real-Time Map Profiling," Report No. ETL-CR-74-18 for the U. S. Army Engineer Topographic Laboratories, prepared by the Itek Corp., December 1974.

3-7. J. Grinberg, et al., "A New Real Time Non-Coherent-to-Coherent Light Converter - The Hybrid Field Effect Liquid Crystal Light Valve," Opt. Eng. 14, 1975. NASA, GSFC, Contract NAS5-23192.

3-8. A. D. Jacobson, "The Photoactivated Liquid Crystal Light Valve," Hughes Program Summary, June 1, 1975.

3-9. A. D. Jacobson, et al., "The Liquid Crystal Light Valve, An Optical-to-Optical Interface Device," Pattern Recognition, March 1973.

3-10. T. D. Beard, et al., "AC Liquid Crystal Light Valve," Appl. Phys. Letters, Vol. 22, No. 3, February 1973.

3-11. M. L. Noble, "Coherent Optical Processing," General Electric Technical Brochure, August 1, 1974.

3-12. M. L. Noble, "Coherent Light Valve, Real Time Information Processing," General Electric Technical Document R7SELS-12, February 1975.

3-13. R. J. Doyle and W. E. Glen, "LUMATRON: A High-Resolution Storage and Projection Device," IEEE Trans. Elect. Dev., Vol. ED-18, 1971.

3-14. D. Casasent, "Use of DKDP Light Valves in Optical Information Processing," Proc. of the Soc. of Photo-Optical Inst. Engineers, Vol. 83, August 1976.

SECTION IV

4-1. J. R. Walsh, R. G. Shackelford, R. D. Wetherington and R. Sheppard, "Conceptual Design of an On-Board Optical Processor With Components," Interim Report on Contract NAS8-31344, Georgia Inst. of Technology, January 9, 1976.

4-2. P. Nisenson, J. Feinleib, R. A. Sprague and S. Iwasa, "Characterization and Optimization of an Electro-Optic Imaging Device for Real-Time Map Profiling," Final Technical Reprot Contract DAAK02-74-C-0029, Itek Corp., October 17, 1974.

4-3. A. W. Lohmann, "Several Optical Correlation Methods," Digest of Papers International Optical Computing Conference 1975, Washington, DC., April 23-25, 1975.

4-4. D. Casasent and D. Psaltis,"Position, Rotation, and Scale Invariant Optical Correlation," Applied Optics, Vol. 15, No. 7, July 1976.

SECTION V

5-1. T. S. Haung, W. F. Schreiber and O. J. Tretiak, "Image Processing," Proc. IEEE, Vol. 59, No. 11, November 1971, pp. 1586-1609.

5-2. E. L. Hall, "Comparison of Computations for Spatial Frequency Filtering," Proc. IEEE, Vol. 60, No. 7, July 1972, pp. 887-891.

5-3. J. R. Walsh and R. D. Wetherington, "CCS Down-Link Spectral Studies" Tech. Rept. No. 7, Proj. A-852, Contract No. NAS8-20054, Georgia Tech, Engineering Experiment Station, Atlanta, May 29, 1976.

5-4. General Radio Catalog 73, p. 70.

5-5. F. C. Billingsley, "Review of Digital Image Processing," Presentation paper for presentation at EUROCOMP 75, London, September 1975.

5-6. B. R. Hunt, "Data Structures and Computational Organization in Digital Image Enhancement," Proc. IEEE, Vol. 60, No. 7, July 1972, pp. 884-887.

5-7. J. O. Eklundh, "A Fast Computer Method for Matrix Transposing," IEEE Trans on Computers, July 1972, pp. 801-803.

5-8. B. Gold, and T. Bially, "Parallelism in Fast Fourier Transform Hardware," IEEE Trans on Audio and Electroacoustics, Vol. AU-21, No. 1, February 1973, pp. 5-16.

5-9. M. J. Corinthios, "The Design of a Class of Fast Fourier Transform Computers," IEEE Trans. on Computers, Vol. C-20, No. 6, Junes 1971, pp. 617-623.

5-10. M. J. Corinthios, "A Fast Fourier Transform for High-Speed Signal Processing," IEEE Trans. on Computers, Vol. C-20, No. 8, August 1971, pp. 843-846.

5-11. H. L. Buijs, A. Pomerleau, M. Fourier, and W. G. Tam, "Implementation of a Fast Fourier Transform (FFT) for Image Processing Application," IEEE Trans. on Acoustics, Speech, and Signal Processing, Vo. ASST-22, No. 6, December 1974, pp. 420-424.

5-12. B. Liu and A. Peled, "A New Hardware Realization of High-Speed Fast Fourier Transformers," IEEE Trans. on Acoustics, Speech, and Signal Processing, Vol. ASSP-23, No. 6, December 1975, pp. 543-547.